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Search for a low-mass $\tau^-\tau^+$ resonance in association with a bottom quark in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

Abstract

A general search is presented for a low-mass $\tau^-\tau^+$ resonance produced in association with a bottom quark. The search is based on proton-proton collision data at a center-of-mass energy of 13 TeV collected by the CMS experiment at the LHC, corresponding to an integrated luminosity of 35.9 fb^{-1}. The data are consistent with the standard model expectation. Upper limits at 95% confidence level on the cross section times branching fraction are determined for two signal models: a light pseudoscalar Higgs boson decaying to a pair of τ leptons produced in association with bottom quarks, and a low-mass boson X decaying to a τ-lepton pair that is produced in the decay of a bottom-like quark B such that B → bX. Masses between 25 and 70 GeV are probed for the light pseudoscalar boson with upper limits ranging from 250 to 44 pb. Upper limits from 20 to 0.3 pb are set on B masses between 170 and 450 GeV for X boson masses between 20 and 70 GeV.

*See Appendix B for the list of collaboration members

1 Introduction

The observation of a Higgs boson by the ATLAS and the CMS Collaborations [1–3] represents a major step towards the understanding of the mechanism for electroweak symmetry breaking [4–6]. All measurements within the Higgs boson sector have so far been in general agreement with the predictions of the standard model (SM) [7, 8]. However, the SM cannot address several crucial issues, such as the hierarchy problem, the origin of the matter-antimatter asymmetry in the universe, and the nature of dark matter [9–12]. Theories beyond the SM have been proposed to address these open questions. Many of these predict the existence of more than one Higgs boson, or new resonances that preferentially decay to a pair of third-generation fermions, including τ leptons.

In this analysis, a search for several scenarios of low-mass resonances that decay to a pair of τ leptons of opposite charge is performed. In particular, we define multiple signal regions that are optimized based on two benchmark models that have final states with different kinematic properties. We consider a mass range between 20 and 70 GeV, as we are bounded below by our kinematic requirements, and above 70 GeV by the background of the Z boson mass peak.

The first model describes a low-mass pseudoscalar Higgs boson A, produced in association with two bottom quarks (b$\bar{\text{b}}$A), and decaying to a τ-lepton pair. This is one of the preferred scenarios in the Two-Higgs-Doublet Models (2HDMs) [13–17]. Searches for signatures of b$\bar{\text{b}}$A or A pair production containing τ leptons in the final state have been performed using pp collision data at a center-of-mass energy of 8 TeV collected by CMS [18, 19] and ATLAS [20], as well as with data at 13 TeV by CMS [21, 22]. Other searches by CMS and ATLAS for low-mass bosons exploit final states containing muons and b quarks [23–25], but also electrons [26, 27] or photons [28]. For this model, we choose events with a τ-lepton pair and a central jet that is consistent with the decay of a b hadron ("b-tagged jet"). A Feynman diagram of this signal process at leading order (LO) is shown in Fig. 1 (left panel).

The second model describes a low-mass boson X decaying to a τ-lepton pair in a process where the X boson is created through the decay of a vector-like quark (VLQ) [29–32]. In the scenario considered here, a heavy bottom-like quark B is produced in a t-channel process in association with a light quark, where an X boson acts as the propagator. It then decays via B → bX, so that the final state topology is qbX. The B is typically scattered in the forward direction, and two categories of event selection are optimized to target this signature. Both categories require
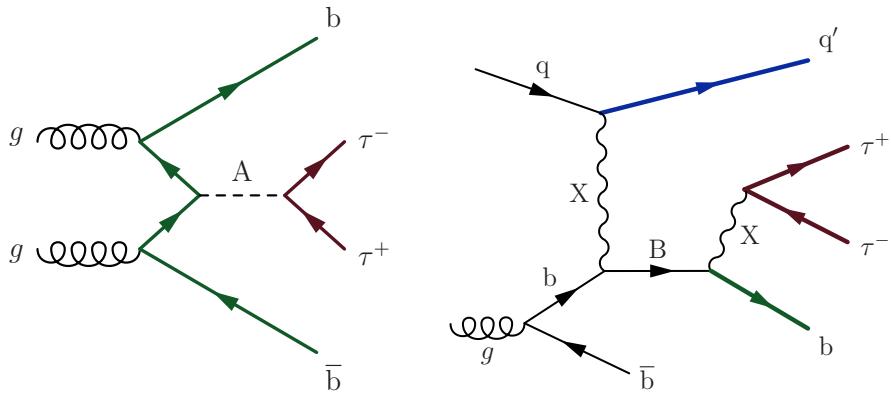

Figure 1: Feynman diagrams of (left) a low-mass pseudoscalar Higgs boson (A) produced in association with bottom quarks, and (right) a bottom-like quark produced in t channel, which decays into X and a bottom quark. The particle X decays into a τ-lepton pair.

a jet consistent with the decay of a b hadron, with one category requiring an additional central jet with pseudorapidity $|\eta| < 2.4$, and one category requiring an additional forward jet with $|\eta| > 2.4$. With this selection, the analysis provides new sensitivity to vector-like quarks by targeting previously unexplored decays of heavy bottom-like quarks. The Feynman diagram of this signal process that is dominant at LO is also shown in Fig. 1 (right panel).

A number of other scenarios beyond the SM produce signatures similar to the two models considered. For example, Hidden Valley models [33, 34] predict a spin-one resonance decaying to lepton pairs; dark-force models [35] include the decay of a top quark to a bottom quark and two GeV-scale bosons, W$'$ and Z$'$, that decay to leptons [36, 37]; and new flavor changing neutral current interactions of the top quark, in which a new light X boson is produced in association with a single top quark and decays to lepton pairs [38]. Although these new physics scenarios are not considered in this analysis, the results can be applied to most of these cases in the kinematic regions explored in this work.

A previous analysis of proton-proton (pp) collision data taken at a center-of-mass energy of 8 TeV, exploring a similar final state focusing on dimuon resonances, has observed excesses at an invariant mass of 28 GeV that correspond to local significances of 4.2 and 2.9 standard deviations in the two event categories defined by the analysis [39]. Reference [39] also reports an analysis of data with a center-of-mass energy of 13 TeV, and finds both a 2.0 standard deviation excess and a 1.4 standard deviation deficit in the same two event categories, respectively. If there were a new heavy particle that had Yukawa-like couplings proportional to mass, the rate would be enhanced in the $\tau\tau$ final state considered in this work, and would provide additional information on the couplings of such a new particle. Therefore, the results of this analysis are compared to those of Ref. [39].

This analysis is based on pp collision data delivered by the LHC at CERN at a center-of-mass energy of 13 TeV. The data set corresponds to an integrated luminosity of 35.9 fb^{-1}, collected by the CMS detector during 2016. Only the semileptonic final states $e\tau_h$ and $\mu\tau_h$ are considered, where one of the τ leptons decays into light leptons (electron or muon), and the other decays hadronically, denoted as τ_h.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume, there are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors from $|\eta| < 3.0$ to $|\eta| < 5.2$. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

Events of interest are selected using a two-tiered trigger system [40]. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than 4 μs. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to about 1 kHz before data storage.

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [41].

3 Simulated samples

Samples of simulated events are used to devise selection criteria, and estimate and validate background predictions. The main sources of background are the pair production of top quarks ($t\bar{t}$), single top quark production, W and Z boson production in association with jets, denoted as "W + jets" and "Z + jets", diboson (WW, WZ, ZZ) production, and quantum chromodynamics (QCD) production of multijet events. The W + jets and Z + jets processes are simulated using the MADGRAPH5_aMC@NLO [42] generator (2.2.2 and 2.3.3) at LO precision with the MLM jet matching and merging scheme [43]. The same generator is also used for diboson production simulated at next-to-leading order (NLO) precision with the FxFx jet matching and merging scheme [44], whereas POWHEG [45–47] 2.0 and 1.0 are used for $t\bar{t}$ and single top quark production at NLO precision, respectively [48–51]. The Z + jets, $t\bar{t}$, and single top processes are normalized using cross sections computed at next-to-next-to-leading order (NNLO) in perturbative QCD [52–54].

The $b\bar{b}A$ samples are produced with the PYTHIA 8.212 [55] generator with the pseudoscalar mass (m_A) ranging from 25 to 70 GeV.

The qbX signals are generated with MADGRAPH5_aMC@NLO, using the same production mechanism as for producing single top quarks in the t-channel. The b quark that initiates the qbX process is predominantly produced in gluon splittings, and is modeled by the four-flavor scheme (4FS), such that the b quark is not contained in the proton parton distribution functions. A previous comparison with data has shown that the absolute value of the transverse momentum ($p_T = |\vec{p}_T|$) and η distributions of the top quark in simulated t-channel events is better modeled in the 4FS than in the five-flavor scheme [56]. Several samples with different values of m_X, ranging from 20 to 70 GeV, are generated. Mass values of 170, 300, and 450 GeV are considered for the B particle.

The event generators are interfaced with PYTHIA to model the parton showering and fragmentation, as well as the decay of the τ leptons. The PYTHIA parameters affecting the description of the underlying event are set to the CUETP8M1 tune [57]. The NNPDF3.0 parton distribution functions [58] with the order matching that of the matrix element calculations are used with all generators. Generated events are processed through a simulation of the CMS detector based on GEANT4 [59], and are reconstructed with the same algorithms used for data. The simulated samples include additional pp interactions per bunch crossing, referred to as "pileup". The effect of pileup is taken into account by generating concurrent total inelastic collision events with PYTHIA. The simulated events are weighted such that the distribution of the number of pileup interactions matches that in data, with an average of approximately 23 interactions per bunch crossing [60].

4 Event and object reconstruction

The reconstruction of observed and simulated events relies on the particle-flow (PF) algorithm [61], which combines information from the CMS subdetectors to reconstruct and identify the particles emerging from the pp collisions: charged and neutral hadrons, photons, muons, and electrons. This section describes how these PF objects are combined to reconstruct other physics objects such as jets, τ_h candidates, or missing transverse momentum ($\vec{p}_T^{\text{miss}}$). The primary pp interaction vertex of an event is taken to be the reconstructed vertex with the largest value of summed physics-object p_T^2.

After being reconstructed by the PF algorithm, electrons are identified with a multivariate anal-

ysis (MVA) [62] discriminant that combines several quantities describing the track quality, the shape of the energy deposits in the ECAL, and the compatibility of the measurements from the tracker and the ECAL [63]. Selected electrons must pass a discriminant requirement that rejects electrons coming from photon conversions. Muons are identified with requirements on the quality of the track reconstruction and on the number of measurements in the tracker and the muon system [64]. To reject nonprompt or misidentified leptons, a relative lepton isolation I_ℓ ($\ell = $ e, μ) is defined as follows:

$$I_\ell \equiv \frac{\sum_{\text{charged}} p_{\text{T}} + \max\left(0, \sum_{\text{neutral}} p_{\text{T}} - \frac{1}{2} \sum_{\text{charged, PU}} p_{\text{T}}\right)}{p_{\text{T}}^\ell}.$$

In this expression, $\sum_{\text{charged}} p_{\text{T}}$ is the scalar p_{T} sum of the charged hadrons originating from the primary vertex, and located in a cone of size $\Delta R = 0.3$ (0.4) centered on the electron (muon) direction, where $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$, $\Delta \eta$ is the difference in pseudorapidity, and $\Delta \phi$ is the difference in azimuthal angle in radians. The sum $\sum_{\text{neutral}} p_{\text{T}}$ represents the same quantity for neutral hadrons and photons. The contribution of pileup photons and neutral hadrons is estimated from the scalar p_{T} sum of charged hadrons originating from pileup vertices, $\sum_{\text{charged, PU}} p_{\text{T}}$. This sum is multiplied by a factor of $1/2$, which corresponds approximately to the ratio of neutral- to charged-hadron production in the hadronization process of inelastic pp collisions, as estimated from simulation. In this analysis, $I_{\text{e}} < 0.10$ ($I_\mu < 0.15$) is used as the isolation requirement for the electron (muon).

Jets are reconstructed from PF candidates using the anti-k_{T} clustering algorithm with a distance parameter of 0.4, implemented in the FASTJET library [65–67]. Charged PF candidates not associated with the primary vertex of the interaction are not considered when reconstructing jets. An offset correction is applied to jet energies to take into account the contribution from additional pp interactions within the same or nearby bunch crossings [68]. The energy of a jet is calibrated based on simulation and data through correction factors [68]. Further identification requirements are applied to distinguish genuine jets from those arising from pileup [69], and additional selection criteria on the energy fractions and multiplicity of charged and neutral particles are applied to each event to remove spurious jet-like features originating from isolated noise patterns in certain HCAL regions [70]. In this analysis, jets are required to have $p_{\text{T}} > 30\,\text{GeV}$ and $|\eta| < 4.7$, and must be separated from the selected leptons by $\Delta R > 0.5$. Jets originating from the hadronization of bottom quarks are identified using the combined secondary vertex algorithm [71], which exploits observables related to the long lifetime and large mass of b hadrons. The chosen b-tagging working point corresponds to an identification efficiency of approximately 60% with a misidentification rate of approximately 1% for jets originating from light quarks or gluons, and about 13% for jets originating from charm quarks.

The τ_{h} candidates are reconstructed with the hadron-plus-strips algorithm [72], which is seeded with anti-k_{T} jets. This algorithm reconstructs τ_{h} candidates based on the number of charged hadrons and on the number of strips of ECAL crystals with energy deposits in the one-prong, one-prong + π^0, and three-prong decay modes. An MVA-based discriminant, including the isolation and lifetime information, is used to reduce the incidence of jets being misidentified as τ_{h} candidates. The typical working point of this MVA-based isolation discriminant, as used in this analysis, has an efficiency of about 60% for a genuine τ_{h}, with about a 0.1% misidentification rate for quark and gluon jets. Electrons and muons misidentified as τ_{h} candidates are suppressed using dedicated criteria based on the consistency between the measurements in the tracker, calorimeters, and muon system.

The vector $\vec{p}_{\text{T}}^{\text{miss}}$ is defined as the negative vectorial sum of the $\vec{p}_{\text{T}}$ of all PF candidates [73, 74]

originating from the primary vertex. The $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is adjusted for the effect of jet energy corrections. Recoil corrections are applied to account for the mismodeling of $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ in simulated events of the $Z + \mathrm{jets}$ and $W + \mathrm{jets}$ processes. The corrections are performed on the variable that is defined as the vectorial difference between the measured $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ and the total $\vec{p}_{\mathrm{T}}$ of neutrinos originating from the decay of the W or Z boson. On average, this reduces the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ obtained from simulation by a few GeV.

5 Event selection

The search is performed in events containing $e\tau_{\mathrm{h}}$ or $\mu\tau_{\mathrm{h}}$ (collectively $\ell\tau_{\mathrm{h}}$) candidates, produced in association with a b-tagged jet.

In order to select the $e\tau_{\mathrm{h}}$ ($\mu\tau_{\mathrm{h}}$) final states of the τ-lepton pair, the trigger requirements are at least one isolated electron (muon) with $p_{\mathrm{T}} > 25$ (22) GeV, or the combination of at least one isolated electron (muon) with $p_{\mathrm{T}} > 24$ (19) GeV and one τ_{h} candidate with $p_{\mathrm{T}} > 20$ GeV. In addition to the trigger requirements, a common "baseline selection" is applied, requiring the events to be consistent with the $\ell\tau_{\mathrm{h}}$ signature. Additional event selections to target the $b\bar{b}A$ and qbX signatures are described in the following sections.

5.1 Baseline selection

The $e\tau_{\mathrm{h}}$ channel requires one electron candidate with $p_{\mathrm{T}} > 25$ GeV, $|\eta| < 2.1$, and relative isolation (defined in Section 4) less than 0.10. The electron should be within a longitudinal distance d_z of 0.2 cm and a radial distance d_{xy} of 0.045 cm with respect to the primary vertex. One τ_{h} candidate is required to have $p_{\mathrm{T}} > 20$ GeV, $|\eta| < 2.3$, and to pass the working point of the MVA-based isolation, as detailed in Section 4. The selected electron and τ_{h} should have an opening angle of $\Delta R > 0.5$ and have opposite-sign (OS) electric charges. If multiple τ_{h} candidates are found, the one with the best MVA-based isolation is selected.

Similarly, $\mu\tau_{\mathrm{h}}$ events are selected by requiring one muon candidate with $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.1$. The relative isolation is taken to be less than 0.15. The same d_z and d_{xy} requirements as those imposed on electron candidates are applied to muons. The τ_{h}-candidate selection is the same as for $e\tau_{\mathrm{h}}$ events.

For both the $e\tau_{\mathrm{h}}$ and $\mu\tau_{\mathrm{h}}$ channels, events with additional isolated electrons (or muons) with $p_{\mathrm{T}} > 10$ GeV and $|\eta| < 2.5$ (2.1) that pass the same d_z and d_{xy} requirements, but a looser identification requirement, are discarded to reduce $Z + \mathrm{jets}$, $t\bar{t}$ production, and diboson backgrounds, as well as to keep orthogonality between the $e\tau_{\mathrm{h}}$ and $\mu\tau_{\mathrm{h}}$ channels.

5.2 Additional selection for the $b\bar{b}A$ search

Signal events of the $b\bar{b}A$ process are characterized by a τ-lepton pair and two bottom quarks. In order to increase the signal purity, candidate events are required to have at least one b-tagged jet with $p_{\mathrm{T}} > 30$ GeV and $|\eta| < 2.4$. To further remove $t\bar{t}$ background, events are required to have a transverse mass (m_{T}) less than 40 GeV, where m_{T} is defined as

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} |\vec{p}_{\mathrm{T}}^{\mathrm{miss}}| (1 - \cos \Delta\phi)},$$

in which p_{T}^{ℓ} is the p_{T} of the lepton and $\Delta\phi$ is the azimuthal angle between the lepton direction and the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ vector, which here is assumed to be due to the momenta of undetected neutrinos.

In addition, events are required to satisfy $p_\zeta^{\text{miss}} - 0.85 p_\zeta^{\text{vis}} > -40\,\text{GeV}$, where p_ζ^{miss} is the component of the $\vec{p}_T^{\text{miss}}$ along the bisector of the $\vec{p}_T$ of the lepton and τ_h, while p_ζ^{vis} is the sum of the parallel components of the lepton and τ_h-candidate $\vec{p}_T$ [75]. This variable quantifies the compatibility of events with the topology wherein the direction of neutrinos from the τ-lepton decays are aligned with the direction of the visible τ-lepton decay products. This requirement is optimized to remove a substantial amount of $t\bar{t}$ as well as $W + \text{jets}$ events.

5.3 Additional selection for the qbX search

The final-state bottom quark from $qb \to q'B \to q'bX$ tends to be more centrally produced with a hard p_T spectrum, whereas the final-state light quark tends to be more forwardly scattered. This motivates two mutually exclusive categories of events. The first category requires one forward jet and one b-tagged jet, and is labeled as "1b1f". Namely,

- one b-tagged jet with $p_T > 30\,\text{GeV}$ and $|\eta| < 2.4$;
- at least one forward jet with $p_T > 30\,\text{GeV}$ and $2.4 < |\eta| < 4.7$;
- no other jets with $p_T > 30\,\text{GeV}$ and $|\eta| < 2.4$.

The second category, labeled as "1b1c", has only two central jets:

- one b-tagged jet with $p_T > 30\,\text{GeV}$, $|\eta| < 2.4$;
- exactly one other central jet with $p_T > 30\,\text{GeV}$ and $|\eta| < 2.4$;
- no forward jets with $p_T > 30\,\text{GeV}$ and $2.4 < |\eta| < 4.7$.

In order to further reduce the dominant $t\bar{t}$ background, an additional requirement of $m_T < 60\,\text{GeV}$ is applied to events in both categories. This selection helps to reduce the $t\bar{t}$ background by a factor of five in 1b1f, and by a factor of two in the 1b1c category, while maintaining a signal acceptance of 91 and 98%, respectively. Of all selected data events, 18% fall into 1b1f, and 82% into 1b1c.

After applying the event selection, an excess of events over the SM backgrounds is searched for using the distribution of the invariant mass of the τ-lepton pair, constructed using the SVFIT mass algorithm [76, 77]. This algorithm approximates the invariant mass of the $\tau\tau$ system by exploiting information on the four-vectors of the lepton and τ_h, combined with the xy-components of $\vec{p}_T^{\text{miss}}$ and its covariance matrix. For better energy resolution, the τ_h decay modes (one-prong, one-prong $+ \pi^0$, and three-prong) are treated separately. Although the visible mass of the lepton and τ_h system, defined as the invariant mass of the sum of four-vector from the visible particles, can be also used as a discriminant, the SVFIT mass $m_{\tau\tau}$ is preferred since its peak position locates the resonance mass, while performing equally well in terms of the expected sensitivity. Considering that the typical resolution of the $m_{\tau\tau}$ distribution is 10–15% [76, 77], a bin width of 5 GeV is chosen. The maximum likelihood fit method [78] is performed for the signal extraction, as detailed in Section 8.

6 Background estimation

The dominant background in all search channels and categories comes from $t\bar{t}$ production because of the presence of genuine electrons, muons, τ leptons, and bottom quark jets from $t\bar{t}$ decays. At lower masses, the QCD multijet background also becomes relevant, while around 90 GeV, there is a considerable $Z + \text{jets}$ contribution. Additional small backgrounds are $W + \text{jets}$, diboson, and single top quark events.

For the b$\bar{\text{b}}$A search, simulated events are used to model t$\bar{\text{t}}$ backgrounds, both for the normalization and the shape of the SVFIT mass distribution. The normalization of the t$\bar{\text{t}}$ background is checked by defining a control region with a high t$\bar{\text{t}}$ purity and little signal contamination by requiring $|\vec{p}_{\text{T}}^{\text{miss}}| > 60\,\text{GeV}$ and $m_{\text{T}} > 60\,\text{GeV}$. All other selection requirements stay the same. The data and simulation show close agreement within statistical uncertainty. Therefore, simulated events are used to predict the yield of t$\bar{\text{t}}$ background processes in the signal region without scaling, as well as the associated uncertainties in the cross section.

For the qbX search, on the other hand, additional requirements on the jet multiplicity can cause mismodeling of the t$\bar{\text{t}}$ background. A control region is defined with the same jet category selections as described in Section 5.3, as well as $|\vec{p}_{\text{T}}^{\text{miss}}| > 60\,\text{GeV}$ and $m_{\text{T}} > 60\,\text{GeV}$ requirements. The data-to-simulation scale factors for the t$\bar{\text{t}}$ events are then calculated such that the simulated number of events agrees with data in these sidebands. In the eτ_{h} ($\mu\tau_{\text{h}}$) channel, the scale factor is found to be 0.82 (0.85) for the 1b1f category, and 1.02 (0.97) for the 1b1c category. The statistical uncertainties in these scale factors are up to 6% and considered as nuisance parameters in the combined fit.

The QCD multijet background, in which one jet is misidentified as a τ_{h} candidate and another as a lepton, is small and is estimated using a control region where the lepton and the τ_{h} candidate have same-sign (SS) electric charges. In this control region, the QCD multijet yield is obtained by subtracting from the data the contribution from the $Z + \text{jets}$, t$\bar{\text{t}}$, $W + \text{jets}$, and other SM background processes, as determined from simulation. The expected contribution of the QCD multijet background in the OS signal region is then derived by rescaling the yield obtained in the SS control region by a factor of 1.1, which is measured using a high-purity QCD multijet sample obtained by inverting the lepton isolation requirement. The QCD multijet background estimation results in up to 20% rate uncertainties, accounting for the statistical precision in the region where the extrapolation factor from the SS to OS region is measured. This uncertainty also covers potential dependencies of the OS/SS extrapolation factors on the invariant $\tau\tau$ mass.

For the $W + \text{jets}$ background, the shape is modeled on the basis of simulated events, while its normalization is determined from data using a sideband with $m_{\text{T}} > 80\,\text{GeV}$. The $W + \text{jets}$ simulation is normalized such that the overall yield of the simulated events, including the QCD contribution estimated above, matches the data yield in the sideband with $m_{\text{T}} > 80\,\text{GeV}$ after the baseline selection but before any jet selection. The scale factor necessary for the $W + \text{jets}$ simulated events is found to be 0.95. The uncertainties in the $W + \text{jets}$ event yields estimated from data are as large as 5%. This uncertainty accounts for the statistical limitation of data in the high-m_{T} sideband, the statistical limitation of the simulated $W + \text{jets}$ sample, the systematic uncertainties of other processes in the same region, and the extrapolation from high- to low-m_{T} regions.

Minor backgrounds, such as diboson and single top quark processes, are estimated from simulation.

7 Systematic uncertainties

A binned maximum likelihood fit of the observed $m_{\tau\tau}$ distribution is used to search for a possible signal over the expected background. The $m_{\tau\tau}$ range from 0 to 350 GeV is used, such that the backgrounds can be constrained by data in the high mass sideband, where the signal is not expected.

Systematic uncertainties may affect the normalization or the shape of the $m_{\tau\tau}$ distribution of the signal and background processes. These uncertainties are represented by nuisance parameters in the fit, as described below, and summarized in Table 1. We note that systematic uncertainties play a small role in this analysis, as the measurement is ultimately limited by the size of the data sample.

7.1 Normalization uncertainties

The uncertainty in the integrated luminosity amounts to 2.5% [60] and affects the normalization of the signal and background processes that are based on simulation. Uncertainties in the electron or muon identification and trigger efficiency amount to 2% each [79]. The τ_h identification and trigger efficiency have been measured using the "tag-and-probe" technique [72] and an overall rate uncertainty of 10% is assigned. For events where electrons or muons are misidentified as τ_h candidates, predominantly $Z \to ee$ events in the $e\tau_h$ channel and $Z \to \mu\mu$ events in the $\mu\tau_h$ channel, a rate uncertainties of 12 and 25% [80], respectively, are applied, as determined by a tag-and-probe method. The acceptance uncertainty because of the b tagging efficiency (mistag rate) has been determined to be 3 (5)%. The momentum scale uncertainty in $|\vec{p}_T^{\text{miss}}|$ [73, 74] affects the event yields due to selection requirements on the m_T variable and is estimated to be up to 4%. The uncertainties in the W + jets event yields estimated from data can be as large as 5%, as detailed in Section 6. The QCD multijet background estimation is found to have rate uncertainties up to 20%. The normalization uncertainty on the Z + jets yield is estimated using a dedicated control region in events with two τ_h candidates and at least one b-tagged jet. A 20% uncertainty is assigned to the Z + jets normalization on the basis of the expected fluctuations in the total number of data events in this control region. For the $t\bar{t}$ background, an uncertainty of 6% in the cross section is computed for the 1 b tag category [53], while in the 1b1f and 1b1c categories, a 6% uncertainty is determined from a control region, as previously described. The uncertainties in the cross section for the diboson and single top quark processes are 6 and 5.5%, respectively.

Finally, theoretical uncertainties in the $b\bar{b}A$ cross section calculation due to NNLO corrections for A masses below 50 GeV increase significantly, as is shown in Fig. 263 of Ref. [81]. Therefore, a conservatively estimated uncertainty of 50% is assigned to the $b\bar{b}A$ signal yield.

7.2 Shape uncertainties

The stability of the shape and the normalization of the $m_{\tau\tau}$ distribution are tested with respect to the uncertainties in the τ_h and jet energy scales for the signal and background processes. The uncertainty is estimated by varying the τ_h and jet energies within their respective uncertainties and recomputing $m_{\tau\tau}$ after the final selection. The uncertainty in the τ_h energy scale amounts to 3% [72], and the uncertainties in the jet energy scale are up to 4%, depending on the jet p_T and η [68]. However, the variation of the $m_{\tau\tau}$ distribution due to the jet energy scale is found to be negligible, and therefore, only normalization uncertainties of 4% are considered. Similarly, for events where a jet, muon, or electron is misidentified as a τ_h candidate, a shape uncertainty is derived by varying the reconstructed p_T of the τ_h candidate by 3%, and recomputing $m_{\tau\tau}$ after the final selection. The variations due to the electron and muon momentum scales are found to be negligible.

Finally, uncertainties related to the limited number of simulated events are taken into account. They are considered for all bins of the distributions that are used to extract the results. They are uncorrelated across the different samples and across the bins of a single distribution.

Table 1: Sources of systematic uncertainties and their effects on the acceptance or shape resulting from a variation of the nuisance parameter equivalent to one standard deviation.

Systematic source	Involved processes	Change in acceptance or shape	
		$e\tau_h$	$\mu\tau_h$
Integrated luminosity	Simulated processes	2.5%	
Electron ident. & trigger	Simulated processes	2%	—
Muon ident. & trigger	Simulated processes	—	2%
τ_h ident. & trigger	Simulated processes	10%	
e misidentified as τ_h	$Z \to ee$	12%	—
μ misidentified as τ_h	$Z \to \mu\mu$	—	25%
b tagging efficiency, mistag rate	Simulated processes	3–5%	
$|\vec{p}_T^{\,miss}|$ scale	Simulated processes	Up to 4%	
W + jets normalization	W + jets	5%	
QCD multijet normalization	QCD multijet	20%	
Z + jets normalization	$Z \to \tau\tau$	20%	
$t\bar{t}$ normalization	$t\bar{t}$ (1b1f, 1b1c only)	6%	
$t\bar{t}$ cross section	$t\bar{t}$ (b$\bar{b}$A only)	6%	
Diboson cross section	Diboson	6%	
Single top quark cross section	Single top quark	5.5%	
b$\bar{b}$A cross section	Signal (b$\bar{b}$A only)	50%	
τ_h energy scale	Simulated processes	Shape	
$e/\mu \to \tau_h$ energy scale	Simulated processes	Shape	
Jet energy scale	Simulated processes	4%	
Jet misidentified as τ_h	Z + jets	Shape	
Limited event count	All processes	Shape	
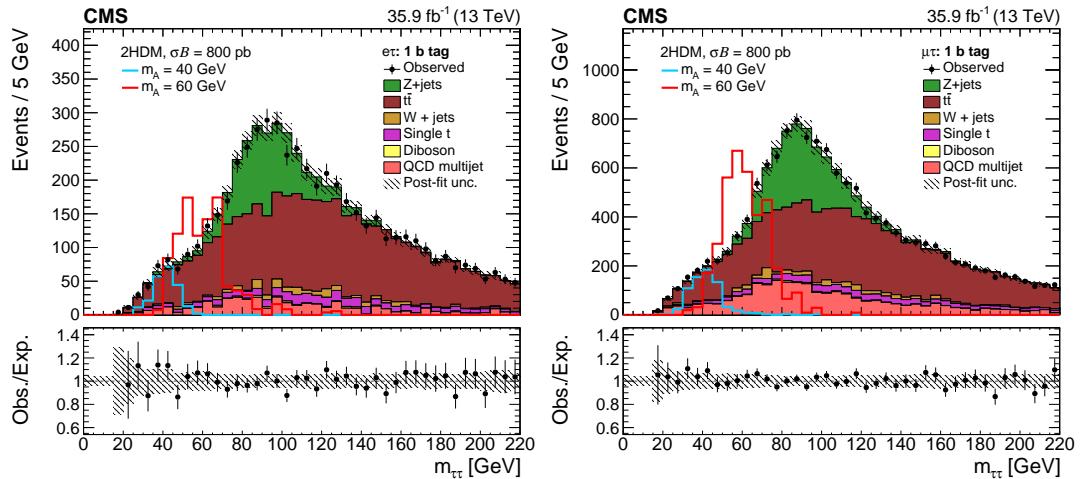
Figure 2: Measured $m_{\tau\tau}$ distribution in the $e\tau_h$ (left), and $\mu\tau_h$ (right) channel, compared to the expected SM background contributions. The signal distributions for b$\bar{b}$A with a pseudoscalar mass of 40 and 60 GeV are overlaid to illustrate the sensitivity. They are normalized to the cross section times branching fraction of 800 pb. The uncertainty bands represent the sum in quadrature of statistical and systematic uncertainties obtained from the fit. The lower panels show the ratio between the observed and expected events in each bin.
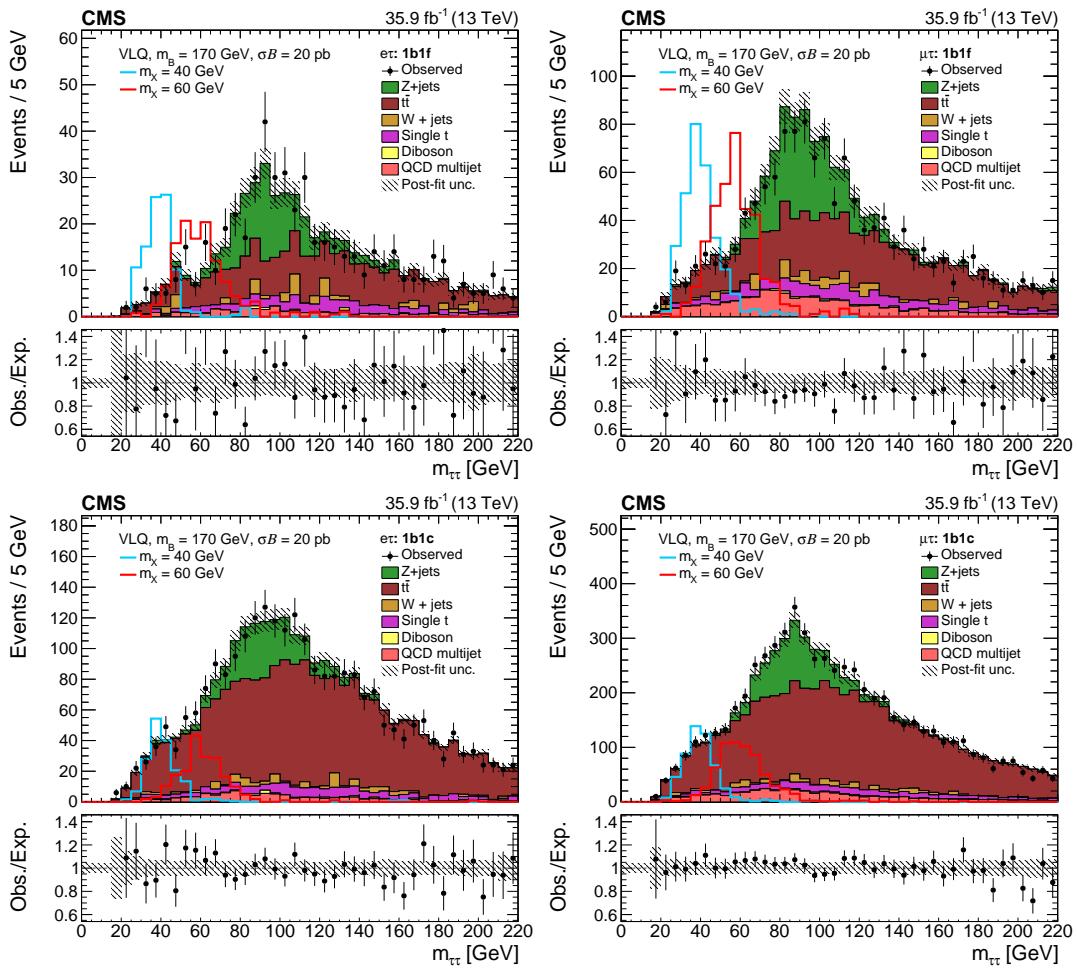
Figure 3: Measured $m_{\tau\tau}$ distribution in the $e\tau_h$ (left), and $\mu\tau_h$ (right) final states, for the 1b1f (upper) and 1b1c (lower) categories, compared to the expected SM background contributions. The signal distributions for the VLQ model with X boson masses of 40 and 60 GeV are overlaid to illustrate the sensitivity. They are normalized to the cross section times branching fraction of 20 pb. The uncertainty bands represent the sum in quadrature of statistical and systematic uncertainties obtained from the fit. The lower panels show the ratio between the observed and expected events in each bin.

8 Results

Figure 2 (3) shows the SVFIT mass distributions in the $e\tau_h$ and $\mu\tau_h$ channel for the $b\bar{b}A$ (qbX) search. Two signal contributions from a pseudoscalar (an X boson) are overlaid assuming a mass of 40 or 60 GeV, normalized to an arbitrary cross section times branching fraction. The uncertainty bands on the histograms of simulated events represent the sum in quadrature of statistical and systematic uncertainties, taking the full covariance matrix of all nuisance parameters into account. However, uncertainties related to simulated events play a small role as the measurement is ultimately limited by the size of the data sample.

The data are consistent with the background-only hypothesis of the SM, therefore, we set an upper limit on the cross section by using the asymptotic CL_s modified-frequentist criterion [78, 82–84]. Figure 4 shows the observed and expected upper limits, at 95% confidence level, on the cross section of $b\bar{b}A$ production times branching fraction of $A \to \tau\tau$ as a function of the pseudoscalar mass, m_A. Representative 2HDMs with varied sets of the $\tan\beta$ and m_A parameters are
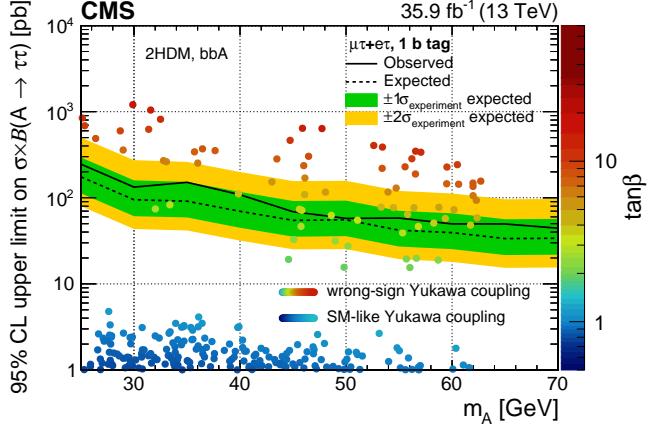
Figure 4: Observed (solid) and expected (dashed) limits at 95% confidence level on the product of cross section for the production of the $b\bar{b}A$ signal and branching fraction $A \rightarrow \tau\tau$, obtained from the combination of the $e\tau_h$ and $\mu\tau_h$ channels. The green and yellow bands represent the one and two standard deviation uncertainties in the expected limits. Representative 2HDMs with varied sets of the $\tan\beta$ and m_A parameters are overlaid for two types of Yukawa couplings to the down-type fermions: one which is SM-like, and one in which the Yukawa coupling is negative ("wrong-sign").
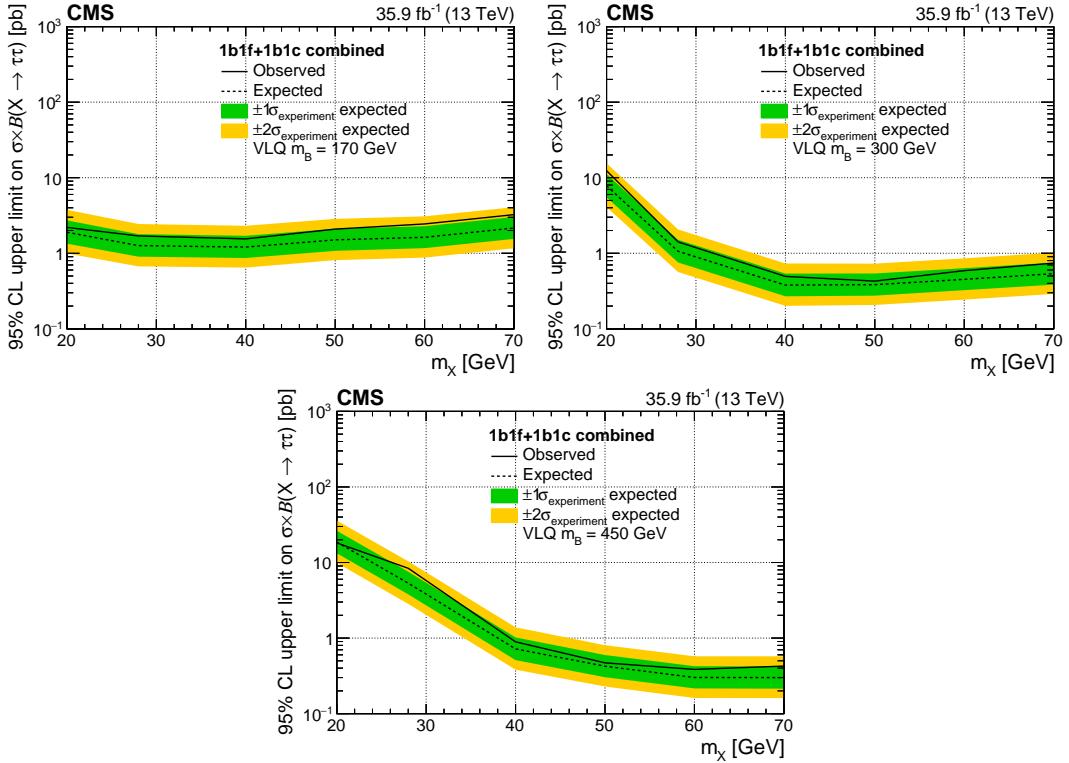
Figure 5: Observed (solid) and expected (dotted) limits at 95% confidence level on the product of cross section for the production of the qbX signal and branching fraction $X \rightarrow \tau\tau$, obtained from the combination of the $e\tau_h$ and $\mu\tau_h$ channels. The m_B values of 170 (upper left), 300 (upper right), and 450 GeV are considered. The green and yellow bands represent the one and two standard deviation uncertainties in the expected limits.

also shown for two types of Yukawa couplings to the down-type fermions: one which is SM-like, and one in which the Yukawa coupling is negative and referred to as "wrong-sign" [85]. We consider a $\tan \beta$ range of 0.6 to 2.0 (1.6 to 37) for the SM-like (wrong-sign) Yukawa coupling scenario with $m_A < 65\,\text{GeV}$. The cross sections for the wrong-sign Yukawa couplings are up to several orders of magnitude larger and have larger $\tan \beta$. Most of the cross sections for these models with $\tan \beta > 3$ are excluded by the current data. For signal events with an m_A ranging from 30 to 70 GeV and A decaying to a pair of τ leptons, the efficiency to pass the final selection criteria of the 1 b tag category of the $\mu\tau_h$ final state, including detector acceptance, selection efficiency, and branching fraction of A $\to \tau\tau$, ranges from 0.002 to 0.022%. Figure 5 shows the same for the qbX process in the VLQ model, but as a function of the X boson mass m_X, for B masses of 170, 300, and 450 GeV. For both searches, the sensitivity is lower in the low-mass region because of the soft p_T spectrum of the τ_h candidate yielding a lower signal detection efficiency. In addition, as the boson mass decreases, the trajectories of the two τ leptons are in close vicinity and start to spoil each other's isolation requirement. For the qbX search, the 1b1f category drives the sensitivity, as can be inferred from Fig. 3. For signal events in which $m_B = 170\,\text{GeV}$, with an X mass ranging from 30 to 70 GeV and decaying to a pair of τ leptons, the efficiency to pass the final selection criteria of the 1b1f category of the $\mu\tau_h$ final state ranges from 0.03 to 0.06%. These values range from 0.02 to 0.10% for the same final state of the 1b1c category.

We proceed to make a comparison with Ref. [39], that is based on the same data set as this paper, and defines two similar signal event categories, but with a dimuon pair in the final state instead of a τ-lepton pair. Upper limits are set at 95% confidence level on the fiducial cross section for the production of a 28 GeV particle decaying to two muons. Because the analysis does not consider a signal model that specifies the kinematic acceptance, it defines the fiducial cross section as

$$\sigma_{\text{fid}} = \frac{N_S}{L \epsilon_{\text{reco}}^{\mu\mu}},$$

where N_S is the number of signal events extracted from the fit to the dimuon mass spectrum, L is the integrated luminosity, and $\epsilon_{\text{reco}}^{\mu\mu} = 0.28$ is the reconstruction efficiency, which takes into account the muon trigger, identification and isolation, as well as the b-tagging efficiency. To compare these results to the present analysis with a τ-lepton pair in the final state, we consider only the most sensitive final state, $\mu\tau_h$. The reconstruction efficiency $\epsilon_{\text{reco}}^{\mu\tau_h}$ for this final state is estimated to be 0.10. This includes the muon trigger, identification and isolation, as well as the τ_h identification and b tagging efficiency. Taking into account $\epsilon_{\text{reco}}^{\mu\tau_h}$, the upper limit on the fiducial cross section is 0.029 (0.057) pb for 1b1f (1b1c), while for the dimuon search, the upper limit is 0.0037 (0.0032) pb for similar event categories. As expected, this analysis is less sensitive than the dimuon search to a hypothetical signal that decays equally to all flavors of leptons. However, if there were a Yukawa-type enhancement between the signal and the τ leptons, then the constraints on the signal production cross section by this analysis would improve by a factor of m_τ^2/m_μ^2.

9 Summary

This paper presents a general search for a low-mass $\tau^-\tau^+$ resonance produced in association with a bottom quark. After defining the signal region by the presence of an electron or muon consistent with the decay of a τ lepton, a hadronically decaying τ lepton, and a jet originating from a bottom quark, an excess over standard model background is searched for in the reconstructed invariant mass distribution of the inferred $\tau\tau$ system. The data are consistent with the standard model background. We set upper limits at 95% confidence level on the cross section

times branching fraction for two signal models: a light pseudoscalar Higgs boson decaying to a pair of τ leptons produced in association with a bottom quark, and a low-mass boson X decaying to a τ-lepton pair that is produced in the decay of a bottom-like quark B as B $\rightarrow$ bX. For both scenarios, X boson masses between 20 and 70 GeV are probed. Upper limits at 95% confidence level ranging from 250 to 44 pb are set on the light pseudoscalar, and from 20 to 0.3 pb on B masses between 170 and 450 GeV. This is the first search for an X resonance in this final state using the center-of-mass energy of 13 TeV. Since many extensions of the standard model have similar event kinematics as this analysis, these results could also be applied to put constraints on other low-mass $\tau\tau$ resonances. If there were a Yukawa-type enhancement between the signal and the τ leptons, then the constraints on the signal production cross section by this analysis would improve by a factor of m_τ^2 / m_μ^2.

The optimized selection of this analysis targets previously unexplored decays of heavy bottom-like quarks, providing new sensitivity to vector-like quarks.

Acknowledgments

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A Supplementary material
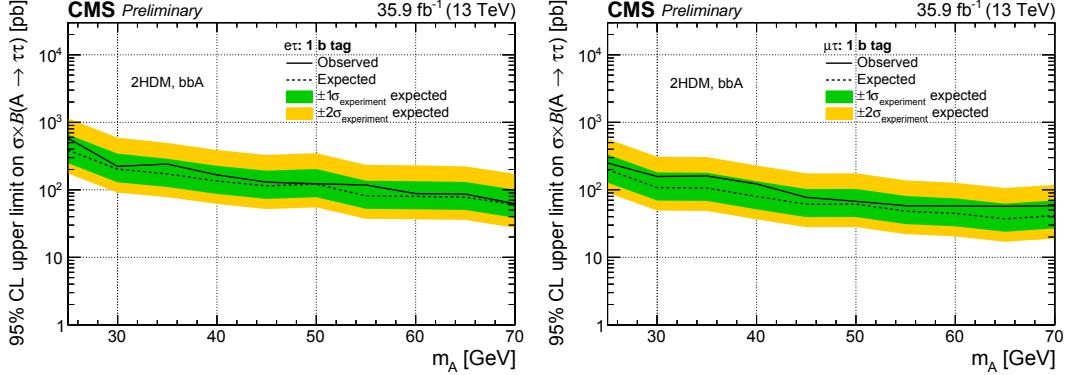
Figure A.1: Observed (solid) and expected (dashed) limits at 95% confidence level on the product of cross section for the production of the b$\bar{\text{b}}$A signal and branching fraction A $\rightarrow$ $\tau\tau$, obtained for the eτ_h (left) and $\mu\tau_\text{h}$ (right) channels. The green and yellow bands represent the one and two standard deviation uncertainties in the expected limits.

Table A.1: The product of acceptance, efficiency, and branching fraction of the b$\bar{\text{b}}$A signal with A $\rightarrow$ $\tau\tau$ in the $\mu\tau_\text{h}$ and eτ_h channels of the 1 b tag category, for different A boson mass values. The selections are as described in Section 5. The uncertainty refers to the statistical uncertainty only.

| m_A [GeV]	eτ_h [%]	$\mu\tau_\text{h}$ [%]
25	0.00025 ± 0.00002	0.00097 ± 0.00005
30	0.00066 ± 0.00004	0.00226 ± 0.00008
40	0.00160 ± 0.00006	0.0043 ± 0.0001
50	0.00229 ± 0.00008	0.0078 ± 0.0001
60	0.0046 ± 0.0001	0.0144 ± 0.0002
70	0.0087 ± 0.0001	0.0222 ± 0.0002
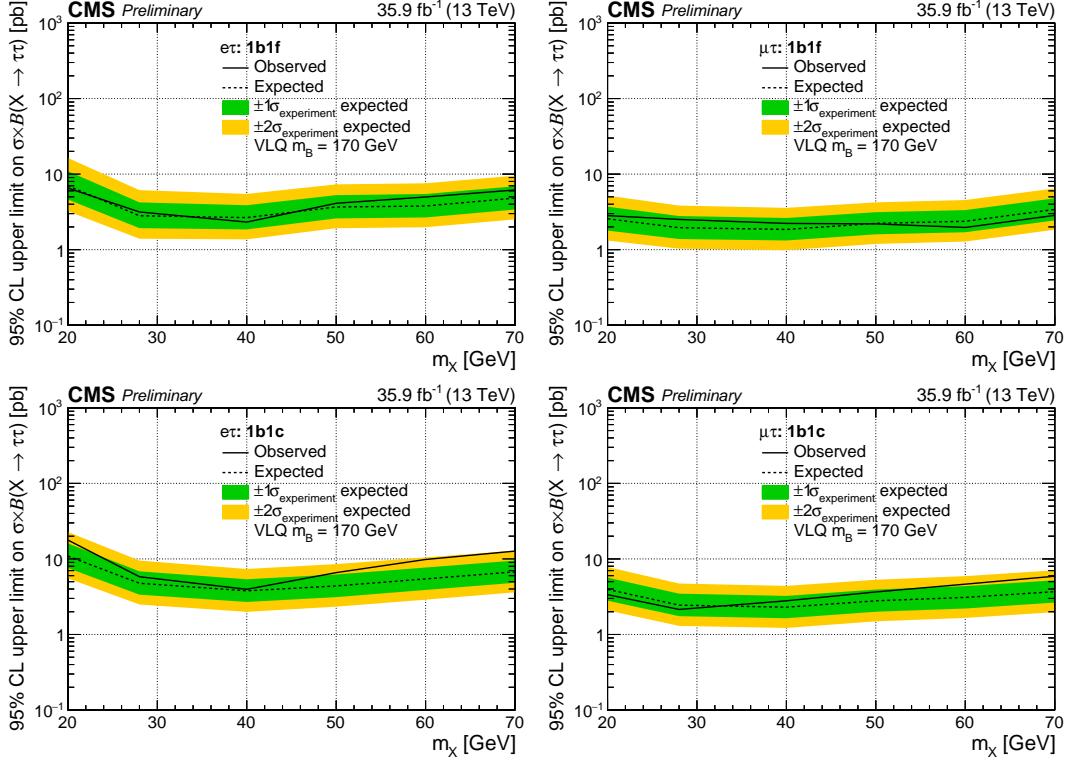
Figure A.2: Observed (solid) and expected (dotted) limits at 95% confidence level on the product of cross section for the production of the qbX signal and branching fraction $X \rightarrow \tau\tau$, obtained for the $e\tau_h$ (left) and $\mu\tau_h$ (right) channels in the 1b1f (top) and 1b1c (bottom) categories. The scenario with $m_B = 170\,\text{GeV}$ is considered. The green and yellow bands represent the one and two standard deviation uncertainties in the expected limits.

Table A.2: The product of acceptance, efficiency, and branching fraction of the qbX signal with $X \rightarrow \tau\tau$ in the $\mu\tau_h$ and $e\tau_h$ channels of the 1b1f and 1b1f categories, for different X boson mass values. The selections are as described in Section 5. The uncertainty refers to the statistical uncertainty only.

m_X [GeV]	1b1f		1b1c	
	$e\tau_h$ [%]	$\mu\tau_h$ [%]	$e\tau_h$ [%]	$\mu\tau_h$ [%]
20	0.0037 ± 0.0001	0.0146 ± 0.0001	0.0044 ± 0.0001	0.0181 ± 0.0001
30	0.0098 ± 0.0001	0.0293 ± 0.0001	0.0165 ± 0.0001	0.0496 ± 0.0002
40	0.0162 ± 0.0002	0.0466 ± 0.0003	0.0307 ± 0.0002	0.0765 ± 0.0004
50	0.0183 ± 0.0002	0.0494 ± 0.0003	0.0321 ± 0.0002	0.0844 ± 0.0004
60	0.0212 ± 0.0002	0.0531 ± 0.0003	0.0331 ± 0.0003	0.0957 ± 0.0004
70	0.0225 ± 0.0003	0.0562 ± 0.0004	0.0375 ± 0.0003	0.0991 ± 0.0005

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