

# Search for Heavy Higgs Bosons Decaying into Two Tau Leptons with the ATLAS Detector Using $pp$ Collisions at $\sqrt{s} = 13$ TeV

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A search for heavy neutral Higgs bosons is performed using the LHC Run 2 data, corresponding to an integrated luminosity of  $139 \text{ fb}^{-1}$  of proton-proton collisions at  $\sqrt{s} = 13$  TeV recorded with the ATLAS detector. The search for heavy resonances is performed over the mass range 0.2–2.5 TeV for the  $\tau^+\tau^-$  decay with at least one  $\tau$ -lepton decaying into final states with hadrons. The data are in good agreement with the background prediction of the standard model. In the  $M_h^{125}$  scenario of the minimal supersymmetric standard model, values of  $\tan\beta > 8$  and  $\tan\beta > 21$  are excluded at the 95% confidence level for neutral Higgs boson masses of 1.0 and 1.5 TeV, respectively, where  $\tan\beta$  is the ratio of the vacuum expectation values of the two Higgs doublets.

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The ATLAS and CMS collaborations discovered in 2012 a new boson with a mass of 125 GeV [1,2]. Current measurements [3,4] indicate that the new particle is compatible with the Higgs boson predicted by the standard model (SM) [5–7]. This discovery opens the way for studies of the structure of the Higgs sector. Many theoretical models beyond the SM, such as two-Higgs-doublet models (2HDMs) [8], extend the Higgs sector to include a second Higgs doublet which implies the existence of new heavy pseudoscalar ( $A$ ) and scalar ( $H$ ) states, while the observed scalar particle would correspond to the lightest Higgs boson ( $h$ ). The decay probability of these scalar states into  $\tau^+\tau^-$  pairs can be enhanced relative to other decay modes in 2HDMs of type II, such as the minimal supersymmetric SM (MSSM) [9,10], the minimal extension of the SM that realizes supersymmetry [11–16].

At tree level, the properties of the MSSM Higgs sector depend only on two non-SM parameters, which can be chosen to be the mass of the pseudoscalar Higgs boson,  $m_A$ , and the ratio of the vacuum expectation values of the two Higgs doublets,  $\tan\beta$ . Beyond tree level, the Higgs sector is affected by additional parameters, the choice of which defines various MSSM benchmark scenarios. In the  $M_h^{125}$  scenario [17], the parameters are such that the mass of the lightest  $CP$ -even Higgs boson,  $m_h$ , is close to the measured mass of the Higgs boson discovered at the LHC [18] and the masses of all superparticles are heavy enough to only

mildly affect the production and decays of the MSSM Higgs bosons. The couplings of the MSSM heavy Higgs bosons to down-type fermions are enhanced with respect to the SM for large  $\tan\beta$  values, resulting in increased branching fractions to  $\tau$  leptons and  $b$  quarks, as well as a higher cross section for Higgs boson production in association with  $b$  quarks ( $bbH$ ). For the mass range considered in this Letter, the mass difference between the  $A$  and  $H$  bosons is much smaller than the experimental resolution and they are treated as degenerate in mass.

This Letter describes a search for massive scalar and pseudoscalar resonances decaying into a  $\tau$ -lepton pair (throughout this Letter the inclusion of charge-conjugate decay modes is implied). The search is conducted on a sample of proton-proton collision data with an integrated luminosity of  $139 \text{ fb}^{-1}$  at a center-of-mass energy of  $\sqrt{s} = 13$  TeV, collected with the ATLAS detector [19–21] during the Run 2 of the LHC (2015–2018) [22]. The  $\tau_{\text{lep}}\tau_{\text{had}}$  and  $\tau_{\text{had}}\tau_{\text{had}}$  decay channels are considered, where  $\tau_{\text{lep}}$  denotes the decay of the  $\tau$  lepton into neutrinos and an electron ( $\tau_e$ ) or into neutrinos and a muon ( $\tau_\mu$ ) and  $\tau_{\text{had}}$  denotes the decay into a neutrino and hadrons. This search improves on the results obtained by previous searches performed by the ATLAS and CMS collaborations at a center-of-mass energy of  $\sqrt{s} = 13$  TeV [23–25] by about a factor of 4–5 for a scalar boson in the mass range 700–2500 GeV, thanks to improvements of the modeling of the top-quark background and of the backgrounds estimated from data, of the reconstruction of high- $p_T$   $\tau$  leptons and the increase of integrated luminosity.

The ATLAS detector at the LHC covers nearly the entire solid angle around the collision point [26]. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters,

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TABLE I. Generators used to describe the signal and background processes, parton distribution function (PDF) sets for the hard process, and models used for parton showering, hadronization and the underlying event (UEPS). The orders of the total cross sections used to normalize the events are also given.  $V$  represents either  $W$  or  $Z$  gauge bosons.

Process	Generator	PDF	UEPS	Cross section order
ggF	POWHEG-BOX v2 [65–69]	CT10 [70]	PYTHIA 8.1 [71]	See text
$bbH$	MG5_aMC@NLO 2.1.2 [72,73]	CT10	PYTHIA 8.2 [74]	See text
$W + \text{jets}$	SHERPA 2.2.1 [75]	NNPDF 3.0 NNLO [76]	SHERPA 2.2.1 [77]	NNLO [78]
$Z + \text{jets}$	POWHEG-BOX v1 [65–67,79]	CT10	PYTHIA 8.1	NNLO [78]
$VV/V\gamma^*$	SHERPA 2.2	NNPDF 3.0 NNLO	SHERPA 2.2	NLO
$t\bar{t}$	POWHEG-BOX v2 [65–67,80]	NNPDF 3.0 NLO	PYTHIA 8.2	NNLO + NNLL [81–87]
Single $t$	POWHEG-BOX v2 [65–67,88–90]	NNPDF 3.0 NLO	PYTHIA 8.2	NNLO + NNLL [91,92]

and a muon spectrometer incorporating three large superconducting toroidal magnets.

Samples of Monte Carlo (MC) simulated events are used to optimize the event selection, estimate the signal efficiencies, and model some of the background processes. The generators and parton showers used to simulate the different MC processes are summarized in Table I. The production cross sections and branching fractions for the various MSSM scenarios are calculated using procedures described in Refs. [27,28]. The cross sections for gluon-gluon fusion (ggF) production calculated with SUSHI [29,30] include next-to-leading-order (NLO) supersymmetric-QCD corrections [31–36], next-to-next-to-leading-order (NNLO) QCD corrections for the top quark [37–41], and light-quark electroweak effects [42,43]. The  $bbH$  cross sections are calculated in the five-flavor [44] and four-flavor schemes [45,46], and the predictions are combined as described in Refs. [47–50]. The other production modes contribute negligibly in the  $M_h^{125}$  scenario and are not considered. The masses and mixing (and effective Yukawa couplings) of the Higgs bosons are computed with FEYNHIGGS [51–58]. Branching fractions of Higgs bosons are computed using a combination of results calculated by FEYNHIGGS, HDECAY [59,60], and PROPHECY4F [61,62], following the procedure discussed in Ref. [27]. The samples were produced with the ATLAS simulation infrastructure [63] using the full detector simulation performed by the GEANT4 [64] toolkit, with the exception of  $bbH$  production of the MSSM Higgs boson signal, for which the ATLASTH [63] fast simulation framework was used.

In this search, the leptonic  $\tau$  decays are identified by their charged decay product, either an electron or a muon. Electron candidates are reconstructed from energy deposits in the electromagnetic calorimeter associated with a charged-particle track measured in the inner detector [93]. They are required to have  $|\eta| < 2.47$ . The transition region between the barrel and end cap calorimeters ( $1.37 < |\eta| < 1.52$ ) is excluded.

Muon candidates are reconstructed in the range  $|\eta| < 2.5$  by matching tracks found in the muon spectrometer to tracks found in the inner detector [94]. The selected leptons in the  $\tau_{\text{lep}}\tau_{\text{had}}$  channel are required to have a transverse

momentum  $p_T > 30$  GeV, pass the “medium” quality requirement for both the electrons [93] and muons [94] and satisfy a  $p_T$ - and  $\eta$ -dependent isolation criterion called “Gradient”, which uses calorimetric and tracking information. The efficiencies for the identification and isolation criteria are given in Refs. [93,94].

Jets are reconstructed from topological clusters [95] of energy depositions in the calorimeter using the anti- $k_t$  algorithm [96], with a radius parameter value  $R = 0.4$  [97]. The average energy contribution from pileup is subtracted according to the jet area and the jets are calibrated as described in Ref. [98]. Jets are required to have  $p_T > 20$  GeV and  $|\eta| < 2.5$ . The effect of pileup is reduced by using tracking information associated with the calorimeter-based jets to reject those not originating from the primary vertex [99]. The primary vertex is chosen as the proton-proton vertex candidate with the highest sum of the squared transverse momenta of the associated tracks.

In order to identify jets containing  $b$  hadrons ( $b$  jets), a multivariate algorithm (MV2) is used [100]. The algorithm has an average efficiency of 70% for  $b$  jets and rejections of approximately 9, 36, and 300 for  $c$  jets,  $\tau$  decays with hadrons, and jets initiated by light quarks or gluons, respectively, as determined in simulated  $t\bar{t}$  events. Correction factors are applied to the simulated event samples to compensate for differences between data and simulation in the  $b$ -tagging efficiencies for  $b$  jets,  $c$  jets and light-flavor jets.

Hadronic  $\tau$  decays are composed of a neutrino and a set of visible decay products ( $\tau_{\text{had-vis}}$ ), typically one or three charged pions and up to two neutral pions. The  $\tau_{\text{had-vis}}$  candidates reconstructed from seeding jets [101] must have  $p_T > 25$  (65) GeV in the  $\tau_{\text{lep}}\tau_{\text{had}}$  ( $\tau_{\text{had}}\tau_{\text{had}}$ ) channel,  $|\eta| < 2.5$  excluding  $1.37 < |\eta| < 1.52$ , one or three associated tracks and an electric charge of  $\pm 1$ . A boosted-decision-tree identification procedure, based on calorimetric shower shapes and tracking information, is used to reject jets.

The  $\tau_{\text{had-vis}}$  candidates must satisfy “loose” or “medium”  $\tau$  identification criteria [101] with efficiencies of about 85% (75%) and 75% (60%) for one-track (three-track)  $\tau_{\text{had-vis}}$  candidates, respectively. The rejection factors of “loose” and “medium”  $\tau$  identification in multijet events are about

20 (200) and 30 (500) for one-track (three-track)  $\tau_{\text{had-vis}}$  candidates, respectively.

The missing transverse momentum,  $\mathbf{E}_T^{\text{miss}}$ , is calculated as the negative vectorial sum of the  $\mathbf{p}_T$  of all fully reconstructed and calibrated physics objects [102]. In addition, this procedure includes a soft term, which is calculated using the inner-detector tracks that originate from the hard-scattering vertex but are not associated with reconstructed objects.

Events in the  $\tau_{\text{lep}}\tau_{\text{had}}$  channel are selected using single-electron and single-muon triggers with  $p_T$  thresholds ranging from 20 to 26 GeV and various isolation criteria [103,104]. The events must contain at least one  $\tau_{\text{had-vis}}$  candidate passing the medium identification and exactly one isolated lepton ( $\ell$ ). The  $\tau_{\text{had-vis}}$  candidate must have  $|\eta| < 2.3$  to reduce misidentified-electron background [105]. The isolated lepton and the  $\tau_{\text{had-vis}}$  candidate must have opposite electric charge and be back to back in the transverse plane:  $|\Delta\phi(\mathbf{p}_T^\ell, \mathbf{p}_T^{\tau_{\text{had-vis}}})| > 2.4$  rad. To reduce background from  $W + \text{jets}$  production the transverse mass  $m_T(\mathbf{p}_T^\ell, \mathbf{E}_T^{\text{miss}}) = \sqrt{2p_T^\ell E_T^{\text{miss}}[1 - \cos \Delta\phi(\mathbf{p}_T^\ell, \mathbf{E}_T^{\text{miss}})]}$ , calculated with the lepton  $p_T$  and the event  $\mathbf{E}_T^{\text{miss}}$ , must be less than 40 GeV. To reduce background from  $Z \rightarrow ee$  production in the  $\tau_e\tau_{\text{had}}$  channel, events in which the isolated lepton and the  $\tau_{\text{had-vis}}$  candidate have an invariant mass between 80 and 110 GeV are rejected. The background contribution from  $Z \rightarrow \mu\mu$  in the  $\tau_\mu\tau_{\text{had}}$  channel is found to be negligible. The signal acceptance times efficiency for each of the  $\tau_e\tau_{\text{had}}$  and  $\tau_\mu\tau_{\text{had}}$  channels varies between 2% and 7% for signals with masses of 0.2–2.5 TeV (the acceptance is calculated with respect to the sum of all  $\tau$  decay modes; the efficiency is calculated taking into account detector acceptance, reconstruction and selection efficiencies).

Events in the  $\tau_{\text{had}}\tau_{\text{had}}$  channel are selected by single- $\tau$  triggers with  $p_T$  thresholds of 80 GeV (5.4 fb $^{-1}$  from June 2015 to May 2016), 125 GeV (9.3 fb $^{-1}$  in May–June 2016) and 160 GeV (124 fb $^{-1}$  from June 2016 to October 2018). Events must contain at least two  $\tau_{\text{had-vis}}$  candidates and no electrons or muons. The  $p_T$  of the leading  $\tau_{\text{had-vis}}$  candidate must exceed the trigger  $p_T$  threshold by 5 GeV. The leading (subleading)  $\tau_{\text{had-vis}}$  candidate must satisfy the medium (loose) identification criteria. The two  $\tau_{\text{had-vis}}$  must have opposite electric charge and be back to back in the transverse plane:  $|\Delta\phi(\mathbf{p}_T^{\tau_{\text{had-vis}}^1}, \mathbf{p}_T^{\tau_{\text{had-vis}}^2})| > 2.7$  rad. The signal acceptance times efficiency varies between 2% and 20% for signals with masses of 0.35–2.5 TeV, and it decreases rapidly for lower mass values due to the selection criteria imposed on the  $p_T$  of the decay products of the  $\tau$  leptons.

Events satisfying the selection criteria of either channel are divided into categories to exploit the different production modes in the MSSM: the  $b$ -tag category for events containing at least one  $b$ -jet and the  $b$ -veto category for events containing no  $b$  jets. These categories are the signal regions used by the analysis.

The  $\tau\tau$  mass reconstruction is crucial for good separation between signal and background events. However, its reconstruction is challenging due to the presence of neutrinos from the  $\tau$ -lepton decays. The mass reconstruction used for both channels is the total transverse mass, defined as  $m_T^{\text{tot}} = \sqrt{(p_T^{\tau_1} + p_T^{\tau_2} + E_T^{\text{miss}})^2 - (\mathbf{p}_T^{\tau_1} + \mathbf{p}_T^{\tau_2} + \mathbf{E}_T^{\text{miss}})^2}$  for either  $(\ell, \tau_{\text{had-vis}})$  or  $(\tau_{\text{had-vis}}^1, \tau_{\text{had-vis}}^2)$  as  $(\tau_1, \tau_2)$ .

The dominant background contribution in the  $\tau_{\text{lep}}\tau_{\text{had}}$  channel arises from processes where the  $\tau_{\text{had-vis}}$  candidate originates from a jet. Such background events are divided into those where the selected lepton is correctly identified, mainly from  $W + \text{jets}$  ( $t\bar{t}$ ) production in the  $b$ -veto ( $b$ -tag) category, and those where the selected lepton arises from a jet, mainly from multijet production. These contributions are estimated using a data-driven technique, which is similar to that described in Ref. [24]. Three orthogonal control regions are defined using the same selection as for the signal region, except that the lepton candidate fails isolation requirements in CR-0, the  $\tau_{\text{had-vis}}$  candidate fails  $\tau$  identification in CR-1, and both fail these conditions in CR-2. The multijet background events are estimated from CR-0 weighted with lepton correction factors, called fake factors, which are ratios of the numbers of lepton candidates passing and failing the isolation requirements [24] (hereafter, fake factors refer to ratios of the number of candidates passing a certain identification requirement to the number of candidates failing the requirement). The  $W + \text{jets}$  ( $t\bar{t}$ ) background events are estimated from CR-1 after subtracting the multijet background contributions estimated from CR-2 corrected with lepton fake factors. Real  $\tau$ -lepton contributions in CR-1 are subtracted using MC simulation. The  $\tau$ -lepton fake-factor weights measured in data are then applied to the events in CR-1 to estimate the  $W + \text{jets}$  ( $t\bar{t}$ ) background in the signal region. Backgrounds where both the lepton and  $\tau_{\text{had-vis}}$  candidates originate from electrons, muons or  $\tau$  leptons arise from  $Z/\gamma^* \rightarrow \tau\tau$  production in the  $b$ -veto category and  $t\bar{t}$  production in the  $b$ -tag category,

TABLE II. Relative increase in the expected 95% C.L. upper limits for the production cross section times branching fraction relative to the statistical only expected limit for each systematic uncertainty under consideration, shown for scalar bosons with mass of 400 GeV and 1 TeV produced via ggF and  $bbH$  production.

Source	ggF (400 GeV)	ggF (1 TeV)	$bbH$ (400 GeV)	$bbH$ (1 TeV)
Tau id. efficiency	0.14	0.16	0.12	0.08
Tau energy scale	0.33	0.09	0.22	0.03
$Z + \text{jets}$ bkg. modeling	0.27	0.19	0.08	0.04
Mis-id. $\tau_{\text{had-vis}}$ bkg.	0.22	0.01	0.14	0.03
Others	0.09	0.04	0.11	0.02
Total	0.54	0.28	0.45	0.13

with minor contributions from  $Z/\gamma^* \rightarrow \ell\ell$ , diboson and single top-quark production. These contributions are estimated using MC simulation. To constrain the normalization of the  $t\bar{t}$  contribution, a top-quark control region enhanced in  $t\bar{t}$  events is defined by substituting the transverse mass requirement with  $m_T(\mathbf{p}_T^\ell, \mathbf{E}_T^{\text{miss}}) > 110$  (100) GeV in the  $b$ -tag category of the  $\tau_e\tau_{\text{had}}$  ( $\tau_\mu\tau_{\text{had}}$ ) channel. This region is included in the fitting procedure. Other major background contributions can be adequately constrained in the signal regions.

The dominant background contribution in the  $\tau_{\text{had}}\tau_{\text{had}}$  channel is from multijet production, which is estimated using a data-driven technique described in Ref. [24]: the

background is estimated from a control region whose events pass the same selection as for the signal region, except the subleading  $\tau_{\text{had-vis}}$  candidates fail  $\tau$  identification. Then the events are weighted with fake factors measured in a region enriched with multijet events to obtain the multijet background estimation in the signal region. The other nonnegligible backgrounds contributions are  $Z/\gamma^* \rightarrow \tau\tau$  production in the  $b$ -veto category,  $t\bar{t}$  production in the  $b$ -tag category, and to a lesser extent  $W(\rightarrow \tau\nu, \ell\nu) + \text{jets}$ , single top-quark, diboson, and  $Z/\gamma^* (\rightarrow \ell\ell) + \text{jets}$  production. These contributions are estimated using MC simulation. To improve the modeling of jets faking hadronic  $\tau$  decays (fake  $\tau$  leptons), events in the simulation that contain quark- or

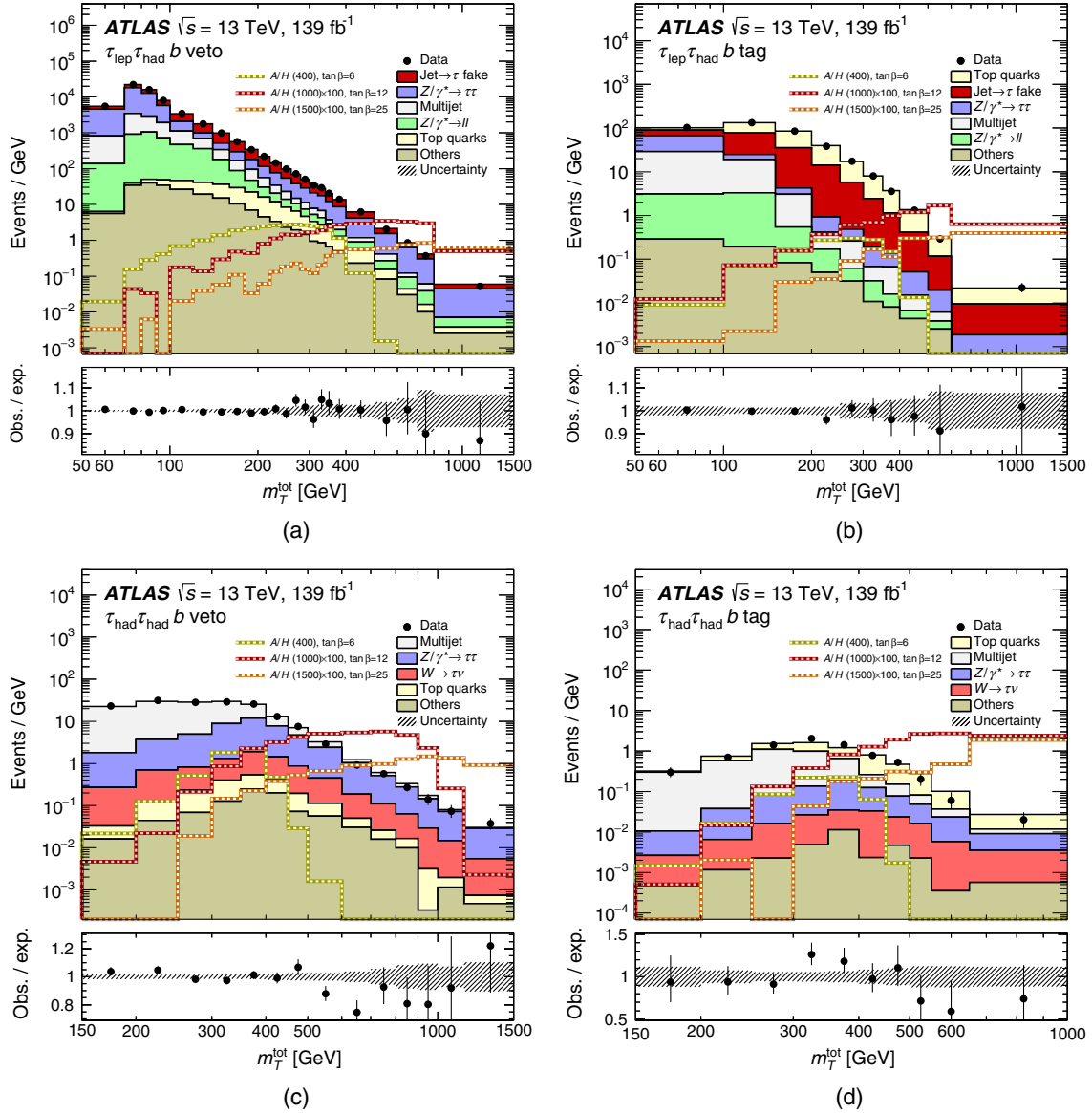


FIG. 1. The  $m_T^{\text{tot}}$  for the  $b$ -veto (left) and  $b$ -tag (right) categories of the  $\tau_{\text{lep}}\tau_{\text{had}}$  channel (top) and  $\tau_{\text{had}}\tau_{\text{had}}$  channel (bottom). The binning displayed is that entering into the fit. The predictions and uncertainties for the background processes are obtained from the fit assuming the background-only hypothesis. Expectations from signal processes are superimposed. Overflows are included in the last bin of the distributions.

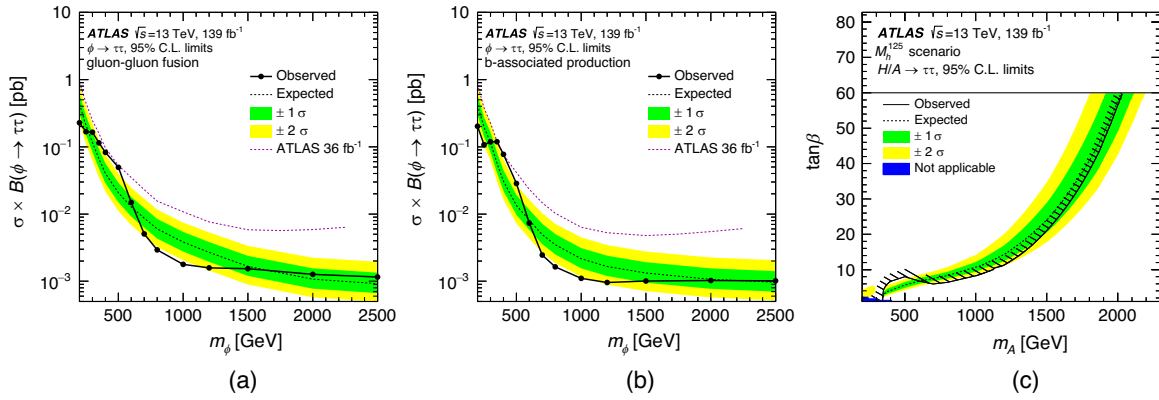


FIG. 2. The observed and expected 95% C.L. upper limits on the production cross section times branching fraction for a scalar boson ( $\phi$ ) produced via (a) ggF and (b)  $b$ -associated production. The limits are calculated from a statistical combination of the  $\tau_{\text{lep}}\tau_{\text{had}}$  and  $\tau_{\text{had}}\tau_{\text{had}}$  channels. The excluded region from the 2015–2016 data ATLAS search [24] is depicted by the dotted pink line. The 95% C.L. upper limits on  $\tan\beta$  as a function of  $m_A$  in the  $M_h^{125}$  scenario is shown (c). The lowest value of  $\tan\beta$  considered for the  $M_h^{125}$  scenario is 0.5. In the small lower-left region shown in solid blue, the mass splitting between  $A$  and  $H$  bosons is above 50% of the mass resolution and therefore the simple addition of the cross sections is not valid. However, this region of parameter space in the  $M_h^{125}$  scenario provides predictions that are incompatible with the measured mass value of the observed Higgs boson by more than  $3\sigma$ . The exclusion limit around  $m_A = 350$  GeV reflects the behavior of the  $A \rightarrow \tau\tau$  branching fraction close to the  $A \rightarrow t\bar{t}$  kinematic threshold for low  $\tan\beta$ . The hatched area defines which side of the curve is excluded by the search.

gluon-initiated jets that are misidentified as  $\tau_{\text{had-vis}}$  candidates are corrected to follow rates of fake  $\tau$  leptons measured in  $W$  + jets and  $t\bar{t}$  enhanced regions in data.

Uncertainties affecting the simulated signal and background contributions are considered in the statistical analysis. These include uncertainties associated with the determination of the integrated luminosity [106,107], the detector simulation, the theoretical cross sections, and the background modeling. For MSSM Higgs boson samples, various sources of uncertainty which affect the signal acceptance are considered, such as the impact of varying the factorization and renormalization scales and uncertainties in the modeling of initial- and final-state radiation, as well as multiple parton interactions. The sensitivity of the search is limited by statistical uncertainties, especially for scalars with mass values above 600 GeV. The main systematic uncertainties are shown in Table II. They are related to the determination of the  $\tau_{\text{had-vis}}$  identification efficiency and energy scale, estimation of the backgrounds with misidentified  $\tau_{\text{had-vis}}$  and modeling of  $Z$  + jets background. The uncertainty in the  $\tau_{\text{had-vis}}$  identification efficiency is determined from measurements of  $Z \rightarrow \tau\tau$  events and, for the high  $p_T$  regime, an additional uncertainty is assigned from the validation of the  $\tau_{\text{had-vis}}$  properties in high- $p_T$  dijet events. The uncertainty in the  $\tau_{\text{had-vis}}$  energy scale is derived from  $Z \rightarrow \tau\tau$  events as well, and from single hadron test-beam data, and it is validated for high- $p_T$   $\tau_{\text{had-vis}}$  with top-quark events and  $Z(\rightarrow \tau\tau)$  events with large transverse momentum. Uncertainties in the determination of backgrounds with misidentified  $\tau_{\text{had-vis}}$  include the uncertainty from the subtraction of other backgrounds in the control regions, the uncertainty from the limited number of events in the control regions and the uncertainty from

differences in the jet composition between control regions and signal regions. For  $Z$  + jets production, cross-section and modeling uncertainties are taken from Refs. [108,109].

A simultaneous fit of the  $m_T^{\text{tot}}$  distributions of the top-quark control region and of the  $b$ -veto and  $b$ -tag categories of the  $\tau_{\text{lep}}\tau_{\text{had}}$  and  $\tau_{\text{had}}\tau_{\text{had}}$  channels is performed in the statistical analysis. The numbers of observed events in the  $b$ -veto and  $b$ -tag categories of the  $\tau_{\text{lep}}\tau_{\text{had}}$  channel are 728 174 and 19 542, while event yields of  $728\,200 \pm 2900$  and  $19\,600 \pm 400$  for the background-only hypothesis are obtained from the statistical analysis, which includes the fit of the nuisance parameters associated with the systematic uncertainties.

For the  $\tau_{\text{had}}\tau_{\text{had}}$  channel, the numbers of observed events in the  $b$ -veto and  $b$ -tag categories are 8420 and 381, and the fitted event yields from background processes are  $8430 \pm 150$  and  $368 \pm 27$ . The  $m_T^{\text{tot}}$  distributions obtained from the fit performed simultaneously in the  $b$ -veto and  $b$ -tag categories of the two channels are shown in Fig. 1.

The data are found to be in good agreement with the obtained background yields, and the results are given in terms of exclusion limits. Upper limits on the cross section times branching fraction for a scalar boson (generically called  $\phi$ ) decaying into  $\tau$ -lepton pairs are set at the 95% confidence level (C.L.) as a function of the boson mass. They are computed using a modified frequentist CLs method [110] with the profile likelihood ratio as the test statistic. The asymptotic approximation is used [111]. The upper limits cover the mass range 0.2–2.5 TeV and are shown for a production entirely via ggF in Fig. 2(a) and entirely via  $b$ -quark associated production in Fig. 2(b). The observed (expected) upper limits are 1.8 fb (3.8 fb) for ggF and 1.1 fb (2.2 fb) for  $bbH$  production at  $m_\phi = 1$  TeV. For

ggF, the lowest local  $p_0$ , the probability that the background can produce a fluctuation greater than the excess observed in data, is 0.014 ( $2.2\sigma$ ) at  $m_\phi = 400$  GeV, while for  $bbH$  production it is 0.003 ( $2.7\sigma$ ) at  $m_\phi = 400$  GeV. The natural width of the scalar boson is assumed to be negligible compared to the experimental resolution. Results are interpreted in terms of the MSSM in Fig. 2(c), which shows the regions in the  $m_A$ – $\tan\beta$  plane excluded at the 95% C.L. in the  $M_h^{125}$  scenario. The observed (expected) upper limits exclude  $\tan\beta > 21$  (24) for  $m_A = 1.5$  TeV.

In conclusion, a search for heavy neutral Higgs bosons decaying into a pair of  $\tau$  leptons is performed in the mass range 0.2–2.5 TeV using a data sample corresponding to an integrated luminosity of  $139\text{ fb}^{-1}$  from proton-proton collisions at  $\sqrt{s} = 13$  TeV recorded by the ATLAS detector at the LHC. No significant excess over the expected SM backgrounds is found. Upper limits on the cross section for the production of a scalar boson times the branching fraction to  $\tau\tau$  final states are set at the 95% C.L., significantly increasing the sensitivity and explored mass range compared to previous searches. They are in the range 240–1.2 fb (230–1.0 fb) for gluon-gluon fusion ( $b$ -associated) production of scalar bosons with masses of 0.2–2.5 TeV. In the  $M_h^{125}$  scenario, the data exclude  $\tan\beta > 8$  for  $m_A = 1.0$  TeV and  $\tan\beta > 21$  for  $m_A = 1.5$  TeV at the 95% C.L.

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 W. Dabrowski,<sup>84a</sup> F. Dachs,<sup>36</sup> T. Dado,<sup>28a</sup> S. Dahbi,<sup>33e</sup> T. Dai,<sup>106</sup> C. Dallapiccola,<sup>103</sup> M. Dam,<sup>40</sup> G. D'amen,<sup>29</sup>  
 V. D'Amico,<sup>75a,75b</sup> J. Damp,<sup>100</sup> J. R. Dandoy,<sup>136</sup> M. F. Daneri,<sup>30</sup> N. S. Dann,<sup>101</sup> M. Danninger,<sup>151</sup> V. Dao,<sup>36</sup> G. Darbo,<sup>55b</sup>  
 O. Dartsis,<sup>5</sup> A. Dattagupta,<sup>131</sup> T. Daubney,<sup>46</sup> S. D'Auria,<sup>69a,69b</sup> C. David,<sup>167b</sup> T. Davidek,<sup>142</sup> D. R. Davis,<sup>49</sup> I. Dawson,<sup>148</sup>  
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 H. De la Torre,<sup>107</sup> A. De Maria,<sup>15c</sup> D. De Pedis,<sup>73a</sup> A. De Salvo,<sup>73a</sup> U. De Sanctis,<sup>74a,74b</sup> M. De Santis,<sup>74a,74b</sup> A. De Santo,<sup>155</sup>  
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 Y. Delabat Diaz,<sup>46</sup> D. Delgove,<sup>65</sup> F. Deliot,<sup>144,m</sup> C. M. Delitzsch,<sup>7</sup> M. Della Pietra,<sup>70a,70b</sup> D. Della Volpe,<sup>54</sup> A. Dell'Acqua,<sup>36</sup>  
 L. Dell'Asta,<sup>74a,74b</sup> M. Delmastro,<sup>5</sup> C. Delporte,<sup>65</sup> P. A. Delsart,<sup>58</sup> D. A. DeMarco,<sup>166</sup> S. Demers,<sup>182</sup> M. Demichev,<sup>80</sup>  
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 C. Deterre,<sup>46</sup> K. Dette,<sup>166</sup> C. Deutsch,<sup>24</sup> M. R. Devesa,<sup>30</sup> P. O. Deviveiros,<sup>36</sup> F. A. Di Bello,<sup>73a,73b</sup> A. Di Ciaccio,<sup>74a,74b</sup>  
 L. Di Ciaccio,<sup>5</sup> W. K. Di Clemente,<sup>136</sup> C. Di Donato,<sup>70a,70b</sup> A. Di Girolamo,<sup>36</sup> G. Di Gregorio,<sup>72a,72b</sup> B. Di Micco,<sup>75a,75b</sup>  
 R. Di Nardo,<sup>75a,75b</sup> K. F. Di Petrillo,<sup>59</sup> R. Di Sipio,<sup>166</sup> C. Diaconu,<sup>102</sup> F. A. Dias,<sup>40</sup> T. Dias Do Vale,<sup>139a</sup> M. A. Diaz,<sup>146a</sup>  
 F. G. Diaz Capriles,<sup>24</sup> J. Dickinson,<sup>18</sup> E. B. Diehl,<sup>106</sup> J. Dietrich,<sup>19</sup> S. Díez Cornell,<sup>46</sup> A. Dimitrievska,<sup>18</sup> W. Ding,<sup>15b</sup>  
 J. Dingfelder,<sup>24</sup> F. Dittus,<sup>36</sup> F. Djama,<sup>102</sup> T. Djobava,<sup>158b</sup> J. I. Djuvsland,<sup>17</sup> M. A. B. Do Vale,<sup>81c</sup> M. Dobre,<sup>27b</sup>  
 D. Dodsworth,<sup>26</sup> C. Doglioni,<sup>97</sup> J. Dolejsi,<sup>142</sup> Z. Dolezal,<sup>142</sup> M. Donadelli,<sup>81d</sup> B. Dong,<sup>60c</sup> J. Donini,<sup>38</sup> A. D'onofrio,<sup>15c</sup>  
 M. D'Onofrio,<sup>91</sup> J. Dopke,<sup>143</sup> A. Doria,<sup>70a</sup> M. T. Dova,<sup>89</sup> A. T. Doyle,<sup>57</sup> E. Drechsler,<sup>151</sup> E. Dreyer,<sup>151</sup> T. Dreyer,<sup>53</sup>  
 A. S. Drobac,<sup>169</sup> D. Du,<sup>60b</sup> T. A. du Pree,<sup>120</sup> Y. Duan,<sup>60b</sup> F. Dubinin,<sup>111</sup> M. Dubovsky,<sup>28a</sup> A. Dubreuil,<sup>54</sup> E. Duchovni,<sup>179</sup>  
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 M. Düren,<sup>56</sup> A. Durglishvili,<sup>158b</sup> D. Duschinger,<sup>48</sup> B. Dutta,<sup>46</sup> D. Duvnjak,<sup>1</sup> G. I. Dyckes,<sup>136</sup> M. Dyndal,<sup>36</sup> S. Dysch,<sup>101</sup>  
 B. S. Dziedzic,<sup>85</sup> K. M. Ecker,<sup>115</sup> M. G. Eggleston,<sup>49</sup> T. Eifert,<sup>8</sup> G. Eigen,<sup>17</sup> K. Einsweiler,<sup>18</sup> T. Ekelof,<sup>171</sup> H. El Jarrari,<sup>35e</sup>  
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- C. Ferretti,<sup>106</sup> F. Fiedler,<sup>100</sup> A. Filipčič,<sup>92</sup> F. Filthaut,<sup>119</sup> K. D. Finelli,<sup>25</sup> M. C. N. Fiolhais,<sup>139a,139c,p</sup> L. Fiorini,<sup>173</sup> F. Fischer,<sup>114</sup>  
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 D. Francis,<sup>36</sup> L. Franco,<sup>5</sup> L. Franconi,<sup>20</sup> M. Franklin,<sup>59</sup> A. N. Fray,<sup>93</sup> P. M. Freeman,<sup>21</sup> B. Freund,<sup>110</sup> W. S. Freund,<sup>81b</sup>  
 E. M. Freundlich,<sup>47</sup> D. C. Frizzell,<sup>128</sup> D. Froidevaux,<sup>36</sup> J. A. Frost,<sup>134</sup> M. Fujimoto,<sup>126</sup> C. Fukunaga,<sup>163</sup>  
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 R. Gamboa Goni,<sup>93</sup> K. K. Gan,<sup>127</sup> S. Ganguly,<sup>179</sup> J. Gao,<sup>60a</sup> Y. Gao,<sup>50</sup> Y. S. Gao,<sup>31,q</sup> C. García,<sup>173</sup> J. E. García Navarro,<sup>173</sup>  
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 A. Gavriluk,<sup>124</sup> C. Gay,<sup>174</sup> G. Gaycken,<sup>46</sup> E. N. Gazis,<sup>10</sup> A. A. Geanta,<sup>27b</sup> C. M. Gee,<sup>145</sup> C. N. P. Gee,<sup>143</sup> J. Geisen,<sup>97</sup>  
 M. Geisen,<sup>100</sup> C. Gemme,<sup>55b</sup> M. H. Genest,<sup>58</sup> C. Geng,<sup>106</sup> S. Gentile,<sup>73a,73b</sup> S. George,<sup>94</sup> T. Gerasis,<sup>44</sup> L. O. Gerlach,<sup>53</sup>  
 P. Gessinger-Befurt,<sup>100</sup> G. Gessner,<sup>47</sup> S. Ghasemi,<sup>150</sup> M. Ghasemi Bostanabad,<sup>175</sup> M. Ghneimat,<sup>150</sup> A. Ghosh,<sup>65</sup> A. Ghosh,<sup>78</sup>  
 B. Giacobbe,<sup>23b</sup> S. Giagu,<sup>73a,73b</sup> N. Giangiacomi,<sup>23b,23a</sup> P. Giannetti,<sup>72a</sup> A. Giannini,<sup>70a,70b</sup> G. Giannini,<sup>14</sup> S. M. Gibson,<sup>94</sup>  
 M. Gignac,<sup>145</sup> D. Gillberg,<sup>34</sup> G. Gilles,<sup>181</sup> D. M. Gingrich,<sup>3,d</sup> M. P. Giordani,<sup>67a,67c</sup> P. F. Giraud,<sup>144</sup> G. Giudliarelli,<sup>67a,67c</sup>  
 D. Giugni,<sup>69a</sup> F. Giuli,<sup>74a,74b</sup> S. Gkaitatzis,<sup>161</sup> I. Gkialas,<sup>9r</sup> E. L. Gkougkousis,<sup>14</sup> P. Gkoutoumis,<sup>10</sup> L. K. Gladilin,<sup>113</sup>  
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 S. Goldfarb,<sup>105</sup> T. Golling,<sup>54</sup> D. Golubkov,<sup>123</sup> A. Gomes,<sup>139a,139b</sup> R. Goncalves Gama,<sup>53</sup> R. Gonçalves,<sup>139a</sup> G. Gonella,<sup>131</sup>  
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 M. I. Gostkin,<sup>80</sup> C. A. Gottardo,<sup>119</sup> M. Goughri,<sup>35b</sup> A. G. Goussiou,<sup>147</sup> N. Govender,<sup>33c</sup> C. Goy,<sup>5</sup> E. Gozani,<sup>159</sup>  
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 K. Grevtsov,<sup>46</sup> C. Grieco,<sup>14</sup> N. A. Grieser,<sup>128</sup> A. A. Grillo,<sup>145</sup> K. Grimm,<sup>31,s</sup> S. Grinstein,<sup>14,t</sup> J.-F. Grivaz,<sup>65</sup> S. Groh,<sup>100</sup>  
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 T. Guillemain,<sup>5</sup> S. Guindon,<sup>36</sup> U. Gul,<sup>57</sup> J. Guo,<sup>60c</sup> W. Guo,<sup>106</sup> Y. Guo,<sup>60a</sup> Z. Guo,<sup>102</sup> R. Gupta,<sup>46</sup> S. Gurbuz,<sup>12c</sup>  
 G. Gustavino,<sup>128</sup> M. Guth,<sup>52</sup> P. Gutierrez,<sup>128</sup> C. Gutschow,<sup>95</sup> C. Guyot,<sup>144</sup> C. Gwenlan,<sup>134</sup> C. B. Gwilliam,<sup>91</sup> A. Haas,<sup>125</sup>  
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 S. Han,<sup>15a</sup> Y. F. Han,<sup>166</sup> K. Hanagaki,<sup>82,v</sup> M. Hance,<sup>145</sup> D. M. Handl,<sup>114</sup> B. Haney,<sup>136</sup> M. D. Hank,<sup>37</sup> R. Hankache,<sup>135</sup>  
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 A. M. Henriques Correia,<sup>36</sup> H. Herde,<sup>26</sup> Y. Hernández Jiménez,<sup>33e</sup> H. Herr,<sup>100</sup> M. G. Herrmann,<sup>114</sup> T. Herrmann,<sup>48</sup>  
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 Y. Sano,<sup>117</sup> A. Sansoni,<sup>51</sup> C. Santoni,<sup>38</sup> H. Santos,<sup>139a,139b</sup> S. N. Santpur,<sup>18</sup> A. Santra,<sup>173</sup> A. Sapronov,<sup>80</sup> J. G. Saraiva,<sup>139a,139d</sup>  
 O. Sasaki,<sup>82</sup> K. Sato,<sup>168</sup> F. Sauerburger,<sup>52</sup> E. Sauvan,<sup>5</sup> P. Savard,<sup>166,d</sup> R. Sawada,<sup>162</sup> C. Sawyer,<sup>143</sup> L. Sawyer,<sup>96,ff</sup> C. Sbarra,<sup>23b</sup>  
 A. Sbrizzi,<sup>23a</sup> T. Scanlon,<sup>95</sup> J. Schaarschmidt,<sup>147</sup> P. Schacht,<sup>115</sup> B. M. Schachtner,<sup>114</sup> D. Schaefer,<sup>37</sup> L. Schaefer,<sup>136</sup>  
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 Z. M. Schillaci,<sup>26</sup> E. J. Schioppa,<sup>68a,68b</sup> M. Schioppa,<sup>41b,41a</sup> K. E. Schleicher,<sup>52</sup> S. Schlenker,<sup>36</sup> K. R. Schmidt-Sommerfeld,<sup>115</sup>  
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 M. Scornajenghi,<sup>41b,41a</sup> F. Scuri,<sup>72a</sup> F. Scutti,<sup>105</sup> L. M. Scyboz,<sup>115</sup> C. D. Sebastiani,<sup>73a,73b</sup> P. Seema,<sup>19</sup> S. C. Seidel,<sup>118</sup>  
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 N. Semprini-Cesari,<sup>23b,23a</sup> S. Sen,<sup>49</sup> C. Serfon,<sup>29</sup> L. Serin,<sup>65</sup> L. Serkin,<sup>67a,67b</sup> M. Sessa,<sup>60a</sup> H. Severini,<sup>128</sup> S. Sevova,<sup>152</sup>  
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 O. Sidiropoulou,<sup>36</sup> A. Sidoti,<sup>23b,23a</sup> F. Siegert,<sup>48</sup> Dj. Sijacki,<sup>16</sup> M. Silva Jr.,<sup>180</sup> M. V. Silva Oliveira,<sup>81a</sup> S. B. Silverstein,<sup>45a</sup>  
 S. Simion,<sup>65</sup> R. Simoniello,<sup>100</sup> C. J. Simpson-allsoy,<sup>21</sup> S. Simsek,<sup>12b</sup> P. Sinervo,<sup>166</sup> V. Sinetckii,<sup>113</sup> S. Singh,<sup>151</sup> M. Sioli,<sup>23b,23a</sup>  
 I. Siral,<sup>131</sup> S. Yu. Sivoklov,<sup>113</sup> J. Sjölin,<sup>45a,45b</sup> A. Skaf,<sup>53</sup> E. Skorda,<sup>97</sup> P. Skubic,<sup>128</sup> M. Slawinska,<sup>85</sup> K. Sliwa,<sup>169</sup>  
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 S. Sottocornola,<sup>71a,71b</sup> R. Soualah,<sup>67a,67c,ii</sup> A. M. Soukharev,<sup>122b,122a</sup> D. South,<sup>46</sup> S. Spagnolo,<sup>68a,68b</sup> M. Spalla,<sup>115</sup>  
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Turgeman,<sup>179</sup> I. Turk Cakir,<sup>4b,nn</sup> R. J. Turner,<sup>21</sup> R. Turra,<sup>69a</sup> P. M. Tuts,<sup>39</sup> S. Tzamarias,<sup>161</sup> E. Tzovara,<sup>100</sup> G. Ucchielli,<sup>47</sup> K. Uchida,<sup>162</sup> F. Ukegawa,<sup>168</sup> G. Unal,<sup>36</sup> A. Undrus,<sup>29</sup> G. Unel,<sup>170</sup> F. C. Ungaro,<sup>105</sup> Y. Unno,<sup>82</sup> K. Uno,<sup>162</sup> J. Urban,<sup>28b</sup> P. Urquijo,<sup>105</sup> G. Usai,<sup>8</sup> Z. Uysal,<sup>12d</sup> V. Vacek,<sup>141</sup> B. Vachon,<sup>104</sup> K. O. H. Vadla,<sup>133</sup> A. Vaidya,<sup>95</sup> C. Valderanis,<sup>114</sup> E. Valdes Santurio,<sup>45a,45b</sup> M. Valente,<sup>54</sup> S. Valentinetti,<sup>23b,23a</sup> A. Valero,<sup>173</sup> L. Valéry,<sup>46</sup> R. A. Vallance,<sup>21</sup> A. Vallier,<sup>36</sup> J. A. Valls Ferrer,<sup>173</sup> T. R. Van Daalen,<sup>14</sup> P. Van Gemmeren,<sup>6</sup> I. Van Vulpen,<sup>120</sup> M. Vanadia,<sup>74a,74b</sup> W. 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