Search for Higgs boson pair production in the $bb\tau\tau$ final state in proton-proton collisions at $\sqrt{s}=8$ TeV

A. M. Sirunyan et al.
(CMS Collaboration)
(Received 2 July 2017; published 20 October 2017)

Results are presented from a search for production of Higgs boson pairs ($HH$) where one boson decays to a pair of $b$ quarks and the other to a $\tau$ lepton pair. This work is based on proton-proton collision data collected by the CMS experiment at $\sqrt{s}=8$ TeV, corresponding to an integrated luminosity of 18.3 fb$^{-1}$. Resonant and nonresonant modes of $HH$ production have been probed and no significant excess relative to the background-only hypotheses has been found in either mode. Upper limits on cross sections of the two $HH$ production modes have been set. The results have been combined with previously published searches at $\sqrt{s}=8$ TeV, in decay modes to two photons and two $b$ quarks, as well as to four $b$ quarks, which also show no evidence for a signal. Limits from the combination have been set on resonant $HH$ production by an unknown particle $X$ in the mass range $m_X=300$ GeV to $m_X=1000$ GeV. For resonant production of spin 0 (spin 2) particles, the observed 95% CL upper limit is 1.13 pb (1.09 pb) at $m_X=300$ GeV and to 21 fb (18 fb) at $m_X=1000$ GeV. For nonresonant $HH$ production, a limit of 43 times the rate predicted by the standard model has been set.

DOI: 10.1103/PhysRevD.96.072004

I. INTRODUCTION

The discovery of a standard model (SM)-like Higgs ($H$) boson [1,2] motivates further investigation of the nature of electroweak symmetry breaking. In particular, the measurement of the Higgs self-coupling can provide valuable information about the details of the mechanism by which the electroweak symmetry is broken.

The measurement of the $H$ pair ($HH$) production rate allows us to probe the trilinear $H$ self-coupling. The leading-order (LO) Feynman diagrams for SM $HH$ production are shown in Fig. 1. The amplitude of the triangle diagram depends on the trilinear $H$ self-coupling. Interference of the box diagram with the triangle diagram reduces the SM cross section to a value of about 10 fb at a center-of-mass energy of $\sqrt{s}=8$ TeV [3]. A deviation of the trilinear $H$ self-coupling from the SM value may enhance the $HH$ production rate significantly. The composite Higgs models discussed in Refs. [4,5] predict such an enhancement in which the mass distribution of the $H$ pair is expected to be broad. We refer to this case as nonresonant $HH$ production.

Alternatively, the $HH$ production rate could be enhanced if an unknown heavy particle $X$ decays into a pair of $H$’s. The LO process for this case is shown in Fig. 2. We refer to this case as resonant $HH$ production. Several models beyond the SM give rise to such decays, in particular, two-Higgs-doublet models [6,7], composite Higgs boson models [4,8], Higgs portal models [9,10], and models involving warped extra dimensions (WED) [11]. The present search is performed in the context of the latter models in which the heavy resonance $X$ can either be a radion with spin 0 [12–15] or a Kaluza-Klein (KK) excitation of the graviton with spin 2 [16,17]. The benchmark points for both models can be expressed in terms of the dimensionless quantity $k/M_{Pl}$ and the mass scale $\Lambda_k = \sqrt{6e^{-kl}M_{Pl}}$, where $k$ is the exponential warp factor for the extra dimension, $l$ is the size of the extra dimension, and $M_{Pl}$ is the reduced Planck mass which is defined by $M_{Pl}/\sqrt{8\pi}$, where $M_{Pl}$ is the Planck mass. The mass scale $\Lambda_k$ is interpreted as the ultraviolet cutoff of the model [18,19]. In this paper we assume that the SM particles within such a theory follow the characteristics of the SM gauge group and that the right-handed top quark is localized on the TeV brane, referred to as the elementary top hypothesis [20]. A possible mixing between the radion and the $H$ ($R/H$ mixing) [21] is neglected, since precision electroweak studies show that the mixing is most likely to be small [22].

Searches for $HH$ production have been performed previously by the CMS Collaboration at the CERN LHC [23–27] in multilepton, multilepton + $\gamma\gamma$, $bb\tau\tau$, $\gamma\gamma bb$, and $bbbb$ final states. In this paper we present the results for $HH$ production when one of the $H$’s decays to two bottom quarks, and the other decays to two $\tau$ leptons, where the $\tau$ leptons decay to hadrons and a $\nu_\tau$ ($\bar{\nu}_\tau$). This decay channel is important because of its large branching fraction.

*Full author list given at the end of the article.

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article’s title, journal citation, and DOI.
A previous search in this channel was performed in the mass range of \( m_X = 260-350 \text{ GeV} \) [24]. The present work extends that search to a larger range of resonance mass and to the case of nonresonant \( HH \) production. The sensitivity of the analysis is enhanced by reconstructing the full four-momentum of the \( H \) that decays into \( \tau \) leptons with a likelihood based algorithm and identifying hadronic \( \tau \) decays with a multivariate algorithm. We combine the results of the search in the \( b\tau\tau \) decay channel with those from searches in the \( \gamma\gamma \) and \( bb \) final states in order to increase the sensitivity to potential signals.

The ATLAS Collaboration has searched for resonant as well as nonresonant \( HH \) production in the \( bb\tau\tau, \gamma\gamma WW^*, \gamma\gamma bb, \) and \( bbbb \) decay channels [28–30]. Their observed (expected) limit on nonresonant \( HH \) production, obtained by combining all channels, corresponds to 70 (48) times the SM production rate further to less than 1 kHz.

This search is based on proton-proton (pp) collision data corresponding to an integrated luminosity of \( 18.3 \text{ fb}^{-1} \) recorded at \( \sqrt{s} = 8 \text{ TeV} \) in 2012. On average, 21 inelastic pp interactions per LHC bunch crossing occurred during this period [33]. One of the interactions is selected as the primary interaction and the rest are called “pileup.”
a horizontal template morphing technique [35] in steps of 50 GeV between 300 and 700 GeV mass points and in steps of 100 GeV between 700 and 1000 GeV mass points. The efficiency and the acceptance are interpolated linearly between the mass points.

The background contribution from multijet events is estimated from data, as described in Sec. VI A. Background events arising from $Z/\gamma^* \to \ell\ell$ ($\ell = e$, $\mu$), $W +$ jets, $t\bar{t}$, single top quark, and diboson ($WW$, $WZ$, $ZZ$) production are modeled using MC samples. Among these backgrounds $Z/\gamma^* \to \ell\ell$, $W +$ jets, $t\bar{t}$, and diboson samples are generated with MadGraph 5.1, while the single top quark samples are modeled with POWHEG 1.0[36].

The $Z/\gamma^* \to \ell\ell$ and the $W +$ jets backgrounds are generated in bins of generator-level parton multiplicity in order to enhance the event statistics in regions of high signal purity. These samples are normalized to their respective next-to-next-to-leading order (NNLO) cross sections [37]. The $t\bar{t}$ sample is normalized to the top quark pair production cross section measured by CMS [38] multiplied by a correction factor obtained from a $t\bar{t}$ enriched control region in data. Furthermore, a kinematic reweighting is applied to simulated $t\bar{t}$ events [39,40] to match the top quark $p_T$ distribution observed in data. The single top quark and the diboson events are normalized to their respective next-to-leading order (NLO) cross sections [41].

Production of events with a single $H$ in the SM scenario is simulated with POWHEG 1.0. The production processes considered are gluon-gluon fusion ($ggH$), vector boson fusion ($qgH$), associated production of the $H$ with $W$ and $Z$ bosons ($VH$), $bb$ or $t\bar{t}$ pairs. These samples are produced for a $H$ of mass $m_H = 125$ GeV and are normalized to the corresponding cross section given in Ref. [42]. The $H$ decays that have been taken into account in this analysis are $H \to bb$ for $VH$ production, $H \to \tau\tau$ for $VH$ and $ggH$ production, and both $H \to bb$ and $H \to \tau\tau$ for $qqH$ production.

Parton shower and hadronization processes are modeled using PYTHIA 6.4. Taus are decayed by TAUOLA 27.121.5 [43]. Pileup interactions represented by minimum bias events generated with PYTHIA 6.4 [44] are added to all simulated samples according to the pileup profile observed in data during the 2012 data-taking period. The generated events are passed through a Geant4 [45] based simulation of the CMS detector and are reconstructed using the same version of the CMS software as that for data.

A special technique, referred to as embedding, is used to model the background arising from $Z/\gamma^* \to \tau\tau$ production. Embedded samples are produced by selecting $Z/\gamma^* \to \mu\mu$ events in data and replacing the reconstructed muons by generator-level $\tau$ leptons with the same four-vectors as that of the muons [46]. The $\tau$ lepton decays are simulated using TAUOLA 27.121.5 and their polarization effects are modeled with TauSpinner (Tauola++ 1.1.4) [47]. The visible decay products of the $\tau$ are reconstructed with the particle-flow (PF) algorithm (cf. Sec. III), and then added to the remaining particles of the $Z/\gamma^* \to \mu\mu$ event, after removing the two muons. Finally, the $\tau_b$ candidates, the jets, and the missing transverse momentum vector $p_T^{\text{miss}}$, which is defined as the negative vectorial sum of the $p_T$ of all reconstructed particles, are reconstructed, and the event is analyzed as if it were data.

The sample of $Z/\gamma^* \to \mu\mu$ events that is used as input for the production of $Z/\gamma^* \to \tau\tau$ embedded samples contains contributions from the background $t\bar{t} \to W^+bW^−\bar{b} \to \mu^+\nu_b\mu^−\bar{\nu}_b\bar{b}$. While the overall level of this contribution is small (~0.1% of the $Z/\gamma^* \to \tau\tau$ embedded sample), the contamination of the embedded sample with these events becomes relevant for events selected with one or more jets originating from $b$ quarks. The $t\bar{t}$ contamination is corrected using simulated $t\bar{t}$ events that are fed through the same embedding procedure as described above.

### III. Physics Object Reconstruction and Identification

This section describes the methods employed to identify various particles used in this analysis. The PF algorithm is used to reconstruct and identify individual particles (referred to as candidates), such as electrons, muons, photons, charged and neutral hadrons with an optimized combination of information from various elements of the CMS detector [48]. The resulting candidates are used to reconstruct jets, hadronic $\tau$ decays, and $p_T^{\text{miss}}$. It is required that all candidates in an event originate from a common interaction point, the primary vertex. The sum of $p_T^2$ of all tracks associated with each interaction vertex is computed and the one with the largest value is selected as the primary vertex.

#### A. Jets and $p_T^{\text{miss}}$

Jets with $|\eta| < 4.7$ are built using the anti-$k_T$ algorithm [49] implemented in the FastJet package [50], with distance parameter of 0.5, using PF candidates as input. Misreconstructed jets, mainly arising from calorimeter noise, are rejected by requiring the jets to pass a set of loose identification criteria [51]. Jets originating from pileup interactions are suppressed by an identification discriminant [52] based on multivariate (MVA) techniques. Corrections based on the median energy density per event [53,54] as computed by the FastJet algorithm, are applied to the jet energy in order to correct for other pileup effects.

The energy of reconstructed jets is calibrated as a function of $p_T$ and $\eta$ of the jet [55]. Jets of $|\eta| < 2.4$ and $p_T > 20$ GeV are tagged as $b$ quark jets if they are selected by an MVA based algorithm which uses lifetime information of $b$ quarks (“combined secondary vertex,” CSV, algorithm). The $b$ tagging efficiency and mistag (misidentification of jets without $b$ quarks as $b$ quark jets) rates for this search
are 70% and 1.5% (10%) for light (charm) quarks respectively [56].

The magnitude and direction of the \( \vec{p}_{T}^{\text{miss}} \) vector are reconstructed using an MVA based algorithm [33] which uses the fact that pileup predominantly produces low-\( p_{T} \) jets and “unclustered energy” (hadrons not within jets), while isolated leptons and high-\( p_{T} \) jets are almost exclusively produced by the hard-scatter interaction, even in high-pileup conditions. In addition, the algorithm provides event-by-event estimate of the \( \vec{p}_{T}^{\text{miss}} \) resolution.

**B. Lepton identification**

Electrons and muons are used in this analysis solely for the purpose of vetoing events, as described in Sec. IV. A description of the electron and the muon identification criteria and the computation of their isolation from other particles is given in Refs. [57,58].

The reconstruction of a \( \tau \) lepton starts with a PF jet as the initial seed. This is followed by the reconstruction of the \( \pi^{0} \) components in the jet which are then combined with the charged hadron components to fully reconstruct the decay mode of the \( \tau \) and to calculate its four-momentum [59]. The identification of \( \tau \) is performed by a MVA based discriminant [60]. The main handle to separate hadronic \( \tau \) decays from quark and gluon jets is the isolation of the \( \tau \) candidate from other charged hadrons and photons. Variables that are sensitive to the distance of separation between the production and decay vertices of the \( \tau \) candidate complement the MVA inputs. This algorithm achieves a \( \tau \) identification efficiency of 50% with a misidentification rate for quark and gluon jets below 1%. Additional discriminants are used to separate \( \tau \) candidates from electrons and muons [60]. The discriminant against electrons uses variables sensitive to electron shower shape, electron track, and \( \tau \) decay kinematics. The discriminant against muons uses inputs based on calorimetric information of the \( \tau \) jet and reconstructed hits and track segments in the muon system.

**IV. HH MASS RECONSTRUCTION AND EVENT SELECTION**

This analysis is based on data satisfying a \( \tau \tau \) trigger which requires the presence of two \( \tau \) objects with a \( p_{T} \) threshold of 35 GeV and \( \eta \leq 2.1 \) for each \( \tau \). A further selection of events is made offline. It is first ensured that the data considered in the analysis are of good quality and each event contains a primary vertex with the absolute value of the \( z \) coordinate less than 24 cm, and within the radial distance of 2 cm from the beam axis. The following analysis specific selection criteria are then applied, determined by the need to suppress specific types of backgrounds. These selection criteria depend on the mass of the pair of \( \tau \) candidates and the pair of \( b \) quark jets which are determined as follows.

The \( H \) that decays into a pair of \( \tau \) leptons is reconstructed by a likelihood based algorithm, referred to as SVfit [61]. The algorithm uses the four-momenta of the two \( \tau \) candidates, the magnitude and direction of the \( \vec{p}_{T}^{\text{miss}} \) vector as well as the event-by-event estimate of the \( \vec{p}_{T}^{\text{miss}} \) resolution as input to reconstruct the full four-momentum vector \( (p_{T}, \eta, \phi, \text{mass}) \) of the pair of \( \tau \) candidates without any constraint on its mass. A mass window constraint is later applied as described below. The four-vector of the \( H \) that decays into \( b \) quarks is reconstructed by means of a kinematic fit. The fit varies the energy of the highest quality (according to the CSV algorithm) \( b \) quark jet within the expected resolution, keeping the jet direction fixed, subject to the constraint that the invariant mass of the two \( b \) quark jets equals \( m_{b} = 125 \text{ GeV} \). Further selection is based on a mass window criterion as described below.

In the search for resonant \( HH \) production, the four-momentum vectors of the two \( H \)'s are used to reconstruct the mass of the \( HH \) system, \( m_{HH} \). We assume that the width of the new particle \( X \) is small compared to the experimental resolution on the mass of the \( H \) pair, which, for resonances of true mass \( m_{X} \) in the range 300 to 1000 GeV, typically amounts to 8% times \( m_{X} \). A peak in the \( HH \) mass distribution is expected this case. The search for heavy spin 0 and spin 2 resonances is hence based on finding a peak in the \( HH \) mass spectrum.

In the nonresonant case, the mass distribution of the \( H \) pair is expected to be broader than the experimental resolution. After comparing different observables in terms of their capability to separate a potential signal from the background we have found that the observable \( m_{T2} \) [62] performs the best. Our search for nonresonant \( HH \) production is hence based on the \( m_{T2} \) variable which is an analog of the transverse mass variable used in \( W \rightarrow \ell \nu \) analyses, adapted to the cascade decays of \( \tau \tau \) pairs to pairs of \( b \) quarks, leptons, and neutrinos. It improves the separation of the \( HH \) signal in particular from the \( \tau \tau \) background, due to the fact that values of the \( m_{T2} \) variable extend up to 300–400 GeV for signal events, while for \( \tau \tau \) background events they are concentrated below the top quark mass. The usage of this observable in analyses of nonresonant \( HH \) production in the \( bb\tau\tau \) final state was first proposed in Ref. [63].

The selection of events is based on the following additional requirements:

(i) The event is required to contain two \( \tau \) candidates with \( p_{T} > 45 \text{ GeV} \) and \( |\eta| < 2.1 \), which pass the identification criteria described in Sec. III B. Both \( \tau \) candidates are required to be matched to the \( \tau \) objects that trigger the event within \( \Delta R < 0.5 \). Here \( \Delta R = \sqrt{(\Delta \eta)^{2} + (\Delta \phi)^{2}} \) and \( \Delta \eta \) and \( \Delta \phi \) are the distances in pseudorapidity and azimuthal angle (in radians), respectively, between the reconstructed tau object and the tau object at the trigger level.
V. DEFINITION OF EVENT CATEGORIES

The $HH \rightarrow b\bar{b}\tau\tau$ signal events are expected to contain two $b$ quark jets in the final state. The efficiency to reconstruct a single $b$ jet is higher than reconstructing two $b$ jets in an event. The efficiency of signal selection is therefore enhanced in this analysis by accepting events with one $b$ tagged jet and one jet which is not $b$ tagged. A control region containing events with two or more jets, none of which passes the $b$ tagging criteria, is used to constrain systematic uncertainties. More specifically, the event categories are as follows:

(i) 2 $b$ tags

Events in this category are required to contain at least two jets of $p_T > 20$ GeV and $|\eta| < 2.4$ which are selected by the CSV discriminant described in Sec. III A.

(ii) 1 $b$ tag

Events in this category are required to contain one jet of $p_T > 20$ GeV and $|\eta| < 2.4$, which is selected by the CSV discriminant and one or more additional jets of $p_T > 20$ GeV. These jets are required to either not satisfy $|\eta| < 2.4$ or not to be selected by the CSV discriminant.

(iii) 0 $b$ tags

Events in this category are required to contain at least two jets of $p_T > 20$ GeV, all of which either do not satisfy $|\eta| < 2.4$ or are not selected by the CSV discriminant.

VI. BACKGROUND ESTIMATION

The two important sources of background in the $0 b$ tag and $1 b$ tag categories are events containing $Z/\gamma^* \rightarrow \tau\tau$ decays and multijet production. In the $2 b$ tag category $Z/\gamma^* \rightarrow \tau\tau$ decays and $t\bar{t}$ events are dominant sources of background events.

A. The multijet events

The reconstructed $\tau_h$ candidates in multijet events are typically due to the misidentification of quark or gluon jets. The contribution from this background in the signal region, in terms of event yield and shape of the distributions in $m_{hh}$ and $m_{T2}$ ("shape template"), is determined entirely from data. The normalization and shape is obtained separately in each event category, from events that pass the selection criteria described in Sec. IV and contain two $\tau_h$ candidates of opposite charge. It is required that the leading (higher $p_T$) $\tau_h$ candidate passes relaxed, but fails the nominal $\tau_h$ identification criteria. The probabilities for the leading $\tau_h$ candidate to pass the relaxed and nominal $\tau_h$ identification criteria are measured in events that contain two $\tau_h$ candidates of the same charge, as functions of $p_T$ of the leading $\tau_h$ candidate in three regions of $\eta$, $|\eta| < 1.2$, $1.2 < |\eta| < 1.7$, and $1.7 < |\eta| < 2.1$. A linear function is fitted to the variation of the ratio of these two probabilities with $p_T$ and is applied as an event weight to obtain the estimate for the shape template of the multijet background in the signal region. Contributions from other backgrounds to these events are subtracted based on MC predictions.

B. The $Z/\gamma^* \rightarrow \tau\tau$ events

The dominant irreducible $Z/\gamma^* \rightarrow \tau\tau$ background in the event categories with $2 b$ tags, $1 b$ tag, and $0 b$ tags is modeled by applying embedding to $Z/\gamma^* \rightarrow \mu\mu$ events selected from data as described in Sec. II B. The embedded sample is normalized to the $Z/\gamma^* \rightarrow \tau\tau$ event yield obtained from the MC simulation in the inclusive event category. The correction due to $t\bar{t}$ contamination is performed by subtracting the distribution in $m_{HH}$ or $m_{T2}$ whose shape and normalization are determined using the $t\bar{t}$ embedded sample from that in the $Z/\gamma^* \rightarrow \tau\tau$ embedded sample in each event category. An uncertainty on the number of events in each bin is set to the sum of uncertainties of the $Z/\gamma^* \rightarrow \tau\tau$ and $t\bar{t}$ embedded yields in that bin, added in quadrature.
The embedded samples cover only a part of the $Z/\gamma^* \to \tau\tau$ background, namely events in which both reconstructed $\tau_h$ candidates match generator-level hadronic $\tau$ decays, because of requirements that are applied at the generator level during the production of the embedded samples to enhance the number of events that pass the selection criteria described in Secs. IV. The small additional contribution arising from $Z/\gamma^* \to \tau\tau$ production in which one or both reconstructed $\tau_h$ candidates are due to a misidentified electron, muon, or jet are taken from the $Z/\gamma^* \to \tau\tau$ MC sample.

C. Other backgrounds

The contribution of $t\bar{t}$ background is estimated using an MC sample after reweighting the events as described in Sec. II.B. The background contributions arising from $W +$ jets, $Z/\gamma^* \to e\ell$ ($\ell = e, \mu$), single top quark, and diboson production, as well as from the production of events with a single SM H boson are small and are modeled using MC samples.

VII. SYSTEMATIC UNCERTAINTIES

The systematic uncertainties in this analysis may affect the number of signal or background events selected in a given event category or affect the relative number of signal or background events in individual bins of kinematic distributions. An additional uncertainty arises due to the limited statistics available to model the $m_{HH}$ or $m_{T2}$ distributions of individual backgrounds in some of the event categories. The treatment of such uncertainties is described in Sec. VIII. The systematic uncertainties relevant to this analysis are the following:

(i) $\tau_h$ trigger and identification efficiency

The uncertainty in the $\tau_h$ identification efficiency has been measured as 6% using $Z/\gamma^* \to \tau\tau \to \mu\tau_h$ events. The $\tau_h$ candidates in $Z/\gamma^* \to \tau\tau$ events typically have $p_T$ in the range 20 to 50 GeV. An uncorrelated uncertainty of 20%/$p_T$ (1000 GeV) is added to account for the extrapolation to the high-$p_T$ region, including the uncertainty in the charge misidentification rate of high-$p_T$ $\tau$ leptons.

TABLE I. Observed and expected event yields in different event categories, in the search for nonresonant (top) and resonant (bottom) $HH$ production $[(pp \to X)B(X \to HH)]$. Expected event yields are computed using values of nuisance parameters obtained by the maximum likelihood fit to the data as described in Sec. VIII. Quoted uncertainties represent the combination of statistical and systematic uncertainties. The WED model parameters are $k_l = 35$, $k/M_{Pl} = 0.2$ (assuming an elementary top hypothesis and no radion-Higgs mixing).

<table>
<thead>
<tr>
<th>Process</th>
<th>0 b tags</th>
<th>1 b tag</th>
<th>2 b tags</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonresonant $HH$ production (100 SM)</td>
<td>1.2 ± 0.2</td>
<td>4.6 ± 0.6</td>
<td>4.3 ± 0.5</td>
</tr>
<tr>
<td>$Z \to \tau\tau$</td>
<td>120.3 ± 11.1</td>
<td>17.7 ± 3.0</td>
<td>2.0 ± 0.8</td>
</tr>
<tr>
<td>Multijet</td>
<td>27.9 ± 2.7</td>
<td>5.4 ± 1.0</td>
<td>0.7 ± 0.2</td>
</tr>
<tr>
<td>$W +$ jets</td>
<td>4.3 ± 0.8</td>
<td>0.4 ± 0.1</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>$Z +$ jets ($e, \mu$, or jet misidentified as $\tau_h$)</td>
<td>0.7 ± 0.2</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>1.3 ± 0.2</td>
<td>3.4 ± 0.5</td>
<td>1.2 ± 0.2</td>
</tr>
<tr>
<td>Dibosons + single top quark</td>
<td>5.7 ± 1.0</td>
<td>1.1 ± 0.2</td>
<td>0.5 ± 0.1</td>
</tr>
<tr>
<td>SM Higgs boson</td>
<td>3.7 ± 1.3</td>
<td>0.6 ± 0.2</td>
<td>0.2 ± 0.1</td>
</tr>
<tr>
<td>Total expected</td>
<td>163.9 ± 11.4</td>
<td>28.6 ± 3.2</td>
<td>5.2 ± 1.1</td>
</tr>
<tr>
<td>Observed data</td>
<td>165</td>
<td>26</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Process</th>
<th>0 b tags</th>
<th>1 b tag</th>
<th>2 b tags</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 GeV radion $\to HH$</td>
<td>1.6 ± 0.2</td>
<td>5.7 ± 0.7</td>
<td>6.2 ± 0.8</td>
</tr>
<tr>
<td>500 GeV graviton $\to HH$</td>
<td>2.4 ± 0.3</td>
<td>7.8 ± 0.9</td>
<td>7.6 ± 0.9</td>
</tr>
<tr>
<td>$Z \to \tau\tau$</td>
<td>130.6 ± 13.8</td>
<td>19.8 ± 3.4</td>
<td>2.7 ± 1.0</td>
</tr>
<tr>
<td>Multijet</td>
<td>92.7 ± 8.1</td>
<td>12.6 ± 2.2</td>
<td>1.8 ± 0.6</td>
</tr>
<tr>
<td>$W +$ jets</td>
<td>8.4 ± 1.5</td>
<td>0.8 ± 0.3</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>$Z +$ jets ($e, \mu$, or jet misidentified as $\tau_h$)</td>
<td>1.6 ± 0.5</td>
<td>&lt; 0.1</td>
<td>0.2 ± 0.1</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>2.5 ± 0.4</td>
<td>5.2 ± 0.7</td>
<td>2.7 ± 0.5</td>
</tr>
<tr>
<td>Dibosons + single top</td>
<td>6.1 ± 1.1</td>
<td>1.7 ± 0.4</td>
<td>0.5 ± 0.1</td>
</tr>
<tr>
<td>SM Higgs boson</td>
<td>5.0 ± 1.7</td>
<td>0.7 ± 0.2</td>
<td>0.2 ± 0.1</td>
</tr>
<tr>
<td>Total expected</td>
<td>246.8 ± 13.9</td>
<td>40.6 ± 3.9</td>
<td>8.4 ± 1.3</td>
</tr>
<tr>
<td>Observed data</td>
<td>268</td>
<td>39</td>
<td>4</td>
</tr>
</tbody>
</table>
above uncertainties have been taken from Ref. [60].

The uncertainty in the efficiency of the $\tau_h\tau_h$ trigger amounts to 4.5% per $\tau_h$ candidate [24].

(ii) $\tau_h$ energy scale

The uncertainty in the $\tau_h$ energy scale is taken as 3% [60].

(iii) Background yields

The rate of the $Z/\gamma^* \to \ell \ell$ ($\ell = e, \mu, \tau$) background is attributed an uncertainty of 5%. The normalization of the $Z/\gamma^* \to \tau\tau$ embedded samples, as described in Sec. VI B, is attributed an uncertainty of 5%. An additional uncertainty of 5% is assigned to the fraction of $Z/\gamma^* \to \tau\tau$ events entering the 2 $b$ tag and 1 $b$ tag categories. This uncertainty has been introduced to cover potential small biases of the embedding technique. The rate of the $t\bar{t}$ background is known with an uncertainty of 7%. The uncertainty in the MC yield of single top quark and diboson backgrounds amounts to 15%. An uncertainty of 30% has been applied to the $W$ + jets background yield obtained from MC. The above uncertainties have been taken from Refs. [24,64].

(iv) Integrated luminosity

The uncertainty in the integrated luminosity is taken as 2.6% [65]. This uncertainty is applied to signal and to $Z/\gamma^* \to \ell \ell$ ($\ell = e, \mu, \tau$), $W$ + jets, single top quark and diboson backgrounds. This uncertainty is not applied to the $t\bar{t}$ background, as this background is

FIG. 3. Distributions in $m_{T2}$ observed in the event categories with 0 $b$ tags, 1 $b$ tag, and 2 $b$ tags in the data compared to the background expectation. Hypothetical nonresonant $HH$ signals with a cross section $\sigma(pp \to HH)$ of 1 pb, corresponding to 100 times the SM cross section are overlaid for comparison. The expectation for signal and background processes is shown for values of nuisance parameters obtained from the likelihood fit.
normalized to the top quark pair production cross section measured by CMS with a correction factor obtained from a $t\bar{t}$ dominated control region in data as described in Sec. II B. The normalization of the multijet background is obtained from data and hence is not subject to the luminosity uncertainty.

(v) Jet energy scale

Jet energy scale uncertainties range from 1% to 10% and are parametrized as functions of jet $p_T$ and $\eta$ [55]. They affect the yield of signal and background events in different event categories and the shape of the $m_{HH}$ and $m_{T2}$ distributions.

(vi) $b$ tagging efficiency and the mistag rate

Uncertainties in the $b$ tagging efficiencies and the mistag rates result in event migration between categories. These are evaluated as functions of jet $p_T$ and $\eta$ as determined in Ref. [56] and are applied to MC samples.

(vii) multijet background estimation

The uncertainty in this background contribution is obtained by adding the statistical uncertainty in the yield of events in the sample with two opposite charge $\tau\tau$ candidates in quadrature with the uncertainty in the slope and offset parameters of the $m_{HH}$ and $m_{T2}$ distributions.

FIG. 4. Distributions in $m_{HH}$ observed in the event categories with 0 $b$ tags, 1 $b$ tag, and 2 $b$ tags in the data compared to the background expectation. Hypothetical signal distributions corresponding to the decays of a spin 2 resonance $X$ of mass $m_X = 500$ GeV that is produced with a $\sigma(pp \to X)B(X \to HH)$ of 1 pb are overlaid for comparison. The corresponding WED model parameters are $kl = 35$ and $k/\bar{M}_{Pl} = 0.2$. The expectation for signal and background processes is shown for values of nuisance parameters obtained from the likelihood fit.
function used as event weight to the shape template as described in Sec. VI A.

(viii) $\vec{p}_T^{\text{miss}}$ resolution and response

The uncertainties related to the magnitude and direction of the $\vec{p}_T^{\text{miss}}$ vector, which affect the shape of the $m_{HH}$ and $m_{T2}$ distributions, are covered by uncertainties in the $Z$ boson recoil correction. The $Z$ boson recoil correction is computed by comparing data with simulation in $Z \rightarrow ee$, $Z \rightarrow \mu\mu$, and photon + jets samples, which do not have any genuine missing transverse momentum. All observables related to $\vec{p}_T^{\text{miss}}$ (including $m_{HH}$ and $m_{T2}$) are recomputed by varying $\vec{p}_T^{\text{miss}}$ within its uncertainty [33] and applied to MC samples.

(ix) Top quark $p_T$ reweighting

The reweighting that is applied to simulated $t\bar{t}$ events (Sec. II B) is varied between one (no correction) and twice the reweighting factor (overcorrection by 100%) to account for the uncertainty due to reweighting [39,40].

(x) Other sources

The uncertainties on the SM $HH$ cross section are $+4.1\% / -5.7\%$ due to scale, $\pm5\%$ due to approximations concerning top quark mass effects that are made in the theoretical calculations, $\pm2.6\%$ due to $a_S$ and $\pm3.1\%$ due to the parton density function [3]. The uncertainty due to the $H \rightarrow \tau\tau$ ($H \rightarrow bb$) branching fraction is $\pm3.3\%$ ($\pm3.2\%$) [66]. The effect of the uncertainty on the number of pileup interactions amounts to less than 1% and is neglected.

VIII. SIGNAL EXTRACTION

Signal rates are determined from a binned maximum likelihood fit for signal plus background and background-only hypotheses. In case of resonant (nonresonant) $HH$ production, we fit the distribution of $m_{HH}$ ($m_{T2}$), reconstructed as described in Sec. IV. Constraints on systematic uncertainties that correspond to multiplicative factors on the signal or the background yield (e.g., cross sections, efficiencies, misreconstruction rates, and sideband extrapolation factors) are represented by log-normal probability density functions. Systematic uncertainties in the shape of $m_{HH}$ and $m_{T2}$ distributions for signal as well as background processes are accounted for by the “vertical template morphing” technique [67] and represented by Gaussian

![Graph 1](image1)

**Graph 1.** The 95% CL observed and expected upper limits on the $\sigma(pp \rightarrow X)B(X \rightarrow HH)$ for a spin 0 (upper) and for a spin 2 (lower) resonance $X$ as functions of the resonance mass $m_X$, obtained from the search in the decay channel $b\bar{b}\tau\tau$.

**Graph 2.** The 95% CL observed and expected upper limits on the $\sigma(pp \rightarrow X)B(X \rightarrow HH)$ for a spin 0 (upper) and for a spin 2 (lower) resonance $X$ as functions of the resonance mass $m_X$, obtained from the search in the decay channel $b\bar{b}\tau\tau$.

![Graph 2](image2)

**Graph 2.** The 95% CL observed and expected upper limits on the $\sigma(pp \rightarrow X)B(X \rightarrow HH)$ for a spin 0 (upper) and for a spin 2 (lower) resonance $X$ as functions of the resonance mass $m_X$, obtained from the search in the decay channel $b\bar{b}\tau\tau$.

**Graph 3.** The 95% CL observed and expected upper limits on the $\sigma(pp \rightarrow X)B(X \rightarrow HH)$ for a spin 0 (upper) and for a spin 2 (lower) resonance $X$ as functions of the resonance mass $m_X$, obtained from the search in the decay channel $b\bar{b}\tau\tau$.

**Graph 4.** The 95% CL observed and expected upper limits on the $\sigma(pp \rightarrow X)B(X \rightarrow HH)$ for a spin 0 (upper) and for a spin 2 (lower) resonance $X$ as functions of the resonance mass $m_X$, obtained from the search in the decay channel $b\bar{b}\tau\tau$.
probability density functions. The Barlow–Beeston method [67,68] is employed to account for statistical uncertainties on the $m_{HH}$ and $m_{T_2}$ shape templates.

IX. RESULTS

A. Observed yields

The number of events observed in the event categories with 2 $b$ tags, 1 $b$ tag, and 0 $b$ tags as well as the expected yield of background processes in these categories are given in Table I. The signal rate expected for nonresonant $HH$ production has been computed for a cross section $\sigma(pp \rightarrow HH)$ of 1 pb, corresponding to 100 times the SM cross section, and SM event kinematics [69,70]. In the case of resonant $HH$ production, the signal yield has been computed for a resonance $X$ (radion or graviton) of mass $m_X = 500$ GeV and a $\sigma(pp \rightarrow X)B(X \rightarrow HH)$ of 1 pb. The corresponding WED model parameters are $kl = 35$, $k/\bar{M}_{Pl} = 0.2$, assuming an elementary top hypothesis and no radion-Higgs ($r/H$) mixing [20–22].

For nonresonant $HH$ production the distributions of $m_{T_2}$ are shown in Fig. 3. For the resonant case the distribution of $m_{HH}$ for events selected in the three categories mentioned above are shown in Fig. 4. In both figures, the sum of $W +$ jets, single top quark and diboson events and of $Z +$ jets events in which one or both reconstructed $\tau$s are due to a misidentified $e$, $\mu$, or jet is referred to as “electroweak” background. Bins in which zero events are observed in the data are indicated by the absence of a data point. The vertical bar drawn in these bins indicate the 84% confidence interval, corresponding to a tail probability of 16%. The event yields and the shape of mass distributions observed in data are in agreement with background predictions. No evidence for the presence of a signal is observed.

TABLE III. The 95% CL upper limits on resonant $HH$ production $[\sigma(pp \rightarrow X)B(X \rightarrow HH)]$ in units of fb for spin 0 (radion) and spin 2 (graviton) resonances $X$, at different masses $m_X$, obtained from the combination of $HH$ searches performed in the $b\bar{b}\tau\tau$, $\gamma\gamma bb$, and $bbbb$ decay channels.

<table>
<thead>
<tr>
<th>$m_X$ [GeV]</th>
<th>Radion (spin 0) ($\sigma$)</th>
<th>Graviton (spin 2) ($\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expected (fb)</td>
<td>Observed (fb)</td>
</tr>
<tr>
<td>300</td>
<td>776</td>
<td>1134</td>
</tr>
<tr>
<td>350</td>
<td>544</td>
<td>285</td>
</tr>
<tr>
<td>400</td>
<td>333</td>
<td>244</td>
</tr>
<tr>
<td>450</td>
<td>201</td>
<td>204</td>
</tr>
<tr>
<td>500</td>
<td>145</td>
<td>207</td>
</tr>
<tr>
<td>600</td>
<td>82</td>
<td>121</td>
</tr>
<tr>
<td>700</td>
<td>52</td>
<td>40</td>
</tr>
<tr>
<td>800</td>
<td>34</td>
<td>39</td>
</tr>
<tr>
<td>900</td>
<td>28</td>
<td>22</td>
</tr>
<tr>
<td>1000</td>
<td>31</td>
<td>21</td>
</tr>
</tbody>
</table>

B. Cross section limits

We have set 95% CL upper limits on cross section times branching fraction for $HH$ production using a modified frequentist approach, known as the CL$_s$ method [71–73]. For nonresonant production SM event kinematics have been assumed. Some model dependency is expected in this case, as the signal acceptance times efficiency as well as the shape of the $m_{T_2}$ distribution vary as functions of the $m_{HH}$ spectrum predicted by the model. The observed (expected) limits on $\sigma(pp \rightarrow HH)$ are 0.59...
(0.94^{+0.46}_{-0.24}) pb, corresponding to a factor of about 59 (94) times the cross section predicted by the SM. For the production of resonances decaying to a pair of SM-like H’s of mass $m_H = 125$ GeV the difference between the limits computed for radion $\rightarrow HH$ and graviton $\rightarrow HH$ signals is small, indicating that the limits on resonant $HH$ production cross section do not depend on these particular models. The limits obtained for resonant $HH$ production are given in Table II and are shown in Fig. 5. In this figure, the expected limits are computed for a generic spin 0/2 resonance decaying to two SM H’s. The theoretical curves for the graviton case are based on KK graviton production in the bulk and RS1 models, respectively [18,19]. To obtain the radion theoretical curves, cross section for radion production via gluon fusion are computed (to NLO electroweak and NNLO QCD accuracy) for different values of the fundamental theoretical parameter $\Lambda_R$. These values are then multiplied by a k factor calculated for SM-like H production through gluon-gluon fusion [74–76].

The results of the search for $HH$ production in the $bb\tau\tau$ decay channel are combined with those in the decay channels $\gamma\gamma bb$ and $bb\gamma\gamma$, published in Refs. [25,26] respectively. The combination is performed by adding the three individual log likelihood functions. The correlated systematics are taken into account by using the same nuisance parameters for the fully correlated sources. They are the luminosity uncertainty, the uncertainty on the b tagging efficiency, the uncertainties related to the underlying event and parton showering, the uncertainties on the branching fractions of the three $HH$ decays channels, and the theoretical uncertainties on the SM nonresonant $HH$ cross section, parton density functions and $\alpha_S$. The uncertainty on the branching fraction of $H \rightarrow \gamma\gamma$ is $\pm5\%$ [66].

The signal yield in the three decay channels is determined assuming that the branching fractions for the decays $H \rightarrow bb$, $H \rightarrow \tau\tau$, and $H \rightarrow \gamma\gamma$ are equal to the SM predictions [66] for a H with mass $m_H = 125$ GeV. The data sets analyzed by the $\gamma\gamma bb$ and $bb\gamma\gamma$ decay channels correspond to integrated luminosities of 19.7 and 17.9 fb$^{-1}$, recorded at $\sqrt{s} = 8$ TeV respectively. The search in the $\gamma\gamma bb$ decay channel targets resonant as well as nonresonant $HH$ production, while the search in the $bb\gamma\gamma$ decay channel focuses on resonant $HH$ signals. No evidence for a signal is observed in the combined search.

The limits on resonant $HH$ production obtained from the combination of $bb\tau\tau$, $\gamma\gamma bb$, and $bb\gamma\gamma$ channels are given in Table III and Fig. 6. In the case of nonresonant $HH$ production, an observed (expected) limit on $\sigma(pp \rightarrow HH)$ of $0.43$ pb ($0.47^{+0.20}_{-0.12}$ pb), corresponding to 43 (47) times the SM cross section, is obtained by combining the $bb\tau\tau$ and $\gamma\gamma bb$ decay channels. The low mass sensitivity ($m_{HH} \leq 400$ GeV) is dominated by the $\gamma\gamma bb$ channel while the high mass ($m_{HH} > 700$ GeV) sensitivity is driven by the $bb\gamma\gamma$ channel. The $bb\tau\tau$ channel is competitive with the $\gamma\gamma bb$ channel in the intermediate mass range ($400 \text{ GeV} < m_{HH} \leq 700 \text{ GeV}$).

X. SUMMARY

A search has been performed for events containing a pair of SM-like H’s in resonant and nonresonant production of the pair in the channel where one boson decays to a pair of $b$ quarks and the other to a $\tau$ lepton pair, in $pp$ collisions collected by the CMS experiment at 8 TeV center-of-mass energy, corresponding to an integrated luminosity of 18.3 fb$^{-1}$. Results are expressed as 95% CL upper limits on the production of a signal. The limit on nonresonant $HH$ production corresponds to a factor of 59 times the rate expected in the SM. For resonant $X \rightarrow HH$ production, the limit on $\sigma(pp \rightarrow X)B(X \rightarrow HH)$ for a resonance of spin 0 and spin 2 ranges, respectively, from 5.42 and 3.97 pb at a mass $m_X = 300$ GeV to 0.14 pb and 0.14 pb at $m_X = 1000$ GeV. The results of the search in the $bb\tau\tau$ decay channel are combined with those in the $\gamma\gamma bb$ and $bb\gamma\gamma$ decay channels. For nonresonant $HH$ production, the combination of $bb\tau\tau$ and $\gamma\gamma bb$ decay channels yields a limit that is a factor of 43 times the SM rate. The limit on resonant $HH$ production obtained from the combination ranges from 1.13 and 1.09 pb at $m_X = 300$ GeV, to 21 and 18 fb at $m_X = 1000$ GeV for resonances of spin 0 and spin 2 respectively.

ACKNOWLEDGMENTS

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR and RAEP (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and
FEDER (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA). Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, Contract No. 675440 (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Recherche dans l’Industrie et dans l’Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Clarín-COFUND del Principado de Asturias; the Thalis and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); and the Welch Foundation, Contract No. C-1845.


[29] ATLAS Collaboration, Search for Higgs boson pair production in the $b\bar{b}b\bar{b}$ final state from pp collisions at $\sqrt{s} = 8$ TeV from the ATLAS detector, Eur. Phys. J. C 75, 412 (2015).

[30] ATLAS Collaboration, Searches for Higgs boson pair production in the $hh \rightarrow bb\tau\tau, \gamma\gamma W^*W^*, \gamma\gamma bb, bbb\bar{b}$ channels with the ATLAS detector, Phys. Rev. D 92, 092004 (2015).


SEARCH FOR HIGGS BOSON PAIR PRODUCTION IN THE … PHYSICAL REVIEW D 96, 072004 (2017)
(CMS Collaboration)
<table>
<thead>
<tr>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre de Calcul de l’Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France</td>
</tr>
<tr>
<td>Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France</td>
</tr>
<tr>
<td>Georgian Technical University, Tbilisi, Georgia</td>
</tr>
<tr>
<td>Tbilisi State University, Tbilisi, Georgia</td>
</tr>
<tr>
<td>RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany</td>
</tr>
<tr>
<td>RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany</td>
</tr>
<tr>
<td>RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany</td>
</tr>
<tr>
<td>Deutsches Elektronen-Synchrotron, Hamburg, Germany</td>
</tr>
<tr>
<td>University of Hamburg, Hamburg, Germany</td>
</tr>
<tr>
<td>Institut für Experimentelle Kernphysik, Karlsruhe, Germany</td>
</tr>
<tr>
<td>Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Greece</td>
</tr>
<tr>
<td>National and Kapodistrian University of Athens, Athens, Greece</td>
</tr>
<tr>
<td>University of Ioánnina, Ioánnina, Greece</td>
</tr>
<tr>
<td>MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary</td>
</tr>
<tr>
<td>Wigner Research Centre for Physics, Budapest, Hungary</td>
</tr>
<tr>
<td>Institute of Physics, University of Debrecen, Debrecen, Hungary</td>
</tr>
<tr>
<td>National Institute of Science Education and Research, Bhubaneswar, India</td>
</tr>
<tr>
<td>Panjab University, Chandigarh, India</td>
</tr>
<tr>
<td>University of Delhi, Delhi, India</td>
</tr>
<tr>
<td>Saha Institute of Nuclear Physics, HBNI, Kolkata, India</td>
</tr>
<tr>
<td>Indian Institute of Technology Madras, Madras, India</td>
</tr>
<tr>
<td>Bhabha Atomic Research Centre, Mumbai, India</td>
</tr>
<tr>
<td>Tata Institute of Fundamental Research-A, Mumbai, India</td>
</tr>
<tr>
<td>Tata Institute of Fundamental Research-B, Mumbai, India</td>
</tr>
<tr>
<td>Indian Institute of Science Education and Research (IISER), Pune, India</td>
</tr>
<tr>
<td>Institute for Research in Fundamental Sciences (IPM), Tehran, Iran</td>
</tr>
<tr>
<td>University College Dublin, Dublin, Ireland</td>
</tr>
<tr>
<td>INFN Sezione di Bari, Bari, Italy</td>
</tr>
<tr>
<td>Università di Bari, Bari, Italy</td>
</tr>
<tr>
<td>Politecnico di Bari, Bari, Italy</td>
</tr>
<tr>
<td>INFN Sezione di Bologna, Bologna, Italy</td>
</tr>
<tr>
<td>Università di Bologna, Bologna, Italy</td>
</tr>
<tr>
<td>INFN Sezione di Catania, Catania, Italy</td>
</tr>
<tr>
<td>Università di Catania, Catania, Italy</td>
</tr>
<tr>
<td>INFN Sezione di Firenze, Firenze, Italy</td>
</tr>
<tr>
<td>Università di Firenze, Firenze, Italy</td>
</tr>
<tr>
<td>INFN Laboratori Nazionali di Frascati, Frascati, Italy</td>
</tr>
<tr>
<td>INFN Sezione di Genova, Genova, Italy</td>
</tr>
<tr>
<td>Università di Genova, Genova, Italy</td>
</tr>
<tr>
<td>INFN Sezione di Milano-Bicocca, Milano, Italy</td>
</tr>
<tr>
<td>Università di Milano-Bicocca, Milano, Italy</td>
</tr>
<tr>
<td>INFN Sezione di Napoli, Napoli, Italy</td>
</tr>
<tr>
<td>Università di Napoli ‘Federico II’, Napoli, Italy</td>
</tr>
<tr>
<td>Università della Basilicata, Roma, Italy</td>
</tr>
<tr>
<td>Università G. Marconi, Roma, Italy</td>
</tr>
<tr>
<td>INFN Sezione di Padova, Padova, Italy</td>
</tr>
<tr>
<td>Università di Padova, Padova, Italy</td>
</tr>
<tr>
<td>Università di Trento, Trento, Italy</td>
</tr>
<tr>
<td>INFN Sezione di Pavia, Pavia, Italy</td>
</tr>
<tr>
<td>Università di Pavia, Pavia, Italy</td>
</tr>
<tr>
<td>INFN Sezione di Perugia, Perugia, Italy</td>
</tr>
<tr>
<td>Università di Perugia, Perugia, Italy</td>
</tr>
<tr>
<td>INFN Sezione di Pisa, Pisa, Italy</td>
</tr>
<tr>
<td>Università di Pisa, Pisa, Italy</td>
</tr>
<tr>
<td>Scuola Normale Superiore di Pisa, Pisa, Italy</td>
</tr>
<tr>
<td>INFN Sezione di Roma</td>
</tr>
</tbody>
</table>
Sapienza Università di Roma
INFN Sezione di Torino, Torino, Italy
Università di Torino, Torino, Italy
Università del Piemonte Orientale, Novara, Italy
INFN Sezione di Trieste, Trieste, Italy
Università di Trieste, Trieste, Italy
Kyungpook National University, Daegu, Korea
Chonbuk National University, Jeonju, Korea
Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
Hanyang University, Seoul, Korea
Korea University, Seoul, Korea
Seoul National University, Seoul, Korea
University of Seoul, Seoul, Korea
Sungkyunkwan University, Suwon, Korea
Vilnius University, Vilnius, Lithuania
National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
Universidad Iberoamericana, Mexico City, Mexico
Benemérita Universidad Autónoma de Puebla, Puebla, Mexico
Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
University of Auckland, Auckland, New Zealand
University of Canterbury, Christchurch, New Zealand
National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
National Centre for Nuclear Research, Swierk, Poland
Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
Joint Institute for Nuclear Research, Dubna, Russia
Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
Institute for Nuclear Research, Moscow, Russia
Institute for Theoretical and Experimental Physics, Moscow, Russia
Moscow Institute of Physics and Technology, Moscow, Russia
National Research Nuclear University, Moscow Engineering Physics Institute (MEPhI), Moscow, Russia
P.N. Lebedev Physical Institute, Moscow, Russia
Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
Novosibirsk State University (NSU), Novosibirsk, Russia
State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
Universidad Autónoma de Madrid, Madrid, Spain
Universidad de Oviedo, Oviedo, Spain
Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
CERN, European Organization for Nuclear Research, Geneva, Switzerland
Paul Scherrer Institut, Villigen, Switzerland
Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
Universität Zürich, Zurich, Switzerland
National Central University, Chung-Li, Taiwan
National Taiwan University (NTU), Taipei, Taiwan
Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
Cukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
Middle East Technical University, Physics Department, Ankara, Turkey
Bogazici University, Istanbul, Turkey
Istanbul Technical University, Istanbul, Turkey
Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
University of Bristol, Bristol, United Kingdom
Rutherford Appleton Laboratory, Didcot, United Kingdom
Imperial College, London, United Kingdom
Brunel University, Uxbridge, United Kingdom
Baylor University, Waco, USA
The University of Alabama, Tuscaloosa, USA

Boston University, Boston, USA

Brown University, Providence, USA

University of California, Davis, Davis, USA

University of California, Los Angeles, USA

University of California, Riverside, Riverside, USA

University of California, San Diego, La Jolla, USA

University of California, Santa Barbara—Department of Physics, Santa Barbara, USA

California Institute of Technology, Pasadena, USA

Carnegie Mellon University, Pittsburgh, USA

University of Colorado Boulder, Boulder, USA

Cornell University, Ithaca, USA

Fairfield University, Fairfield, USA

Fermi National Accelerator Laboratory, Batavia, USA

University of Florida, Gainesville, USA

Florida International University, Miami, USA

Florida State University, Tallahassee, USA

Florida Institute of Technology, Melbourne, USA

University of Illinois at Chicago (UIC), Chicago, USA

The University of Iowa, Iowa City, USA

Johns Hopkins University, Baltimore, USA

The University of Kansas, Lawrence, USA

Kansas State University, Manhattan, USA

Lawrence Livermore National Laboratory, Livermore, USA

University of Maryland, College Park, USA

Massachusetts Institute of Technology, Cambridge, USA

University of Minnesota, Minneapolis, USA

University of Mississippi, Oxford, USA

University of Nebraska-Lincoln, Lincoln, USA

State University of New York at Buffalo, Buffalo, USA

Northeastern University, Boston, USA

Northwestern University, Evanston, USA

University of Notre Dame, Notre Dame, USA

The Ohio State University, Columbus, USA

Princeton University, Princeton, USA

University of Puerto Rico, Mayaguez, USA

Purdue University, West Lafayette, USA

Purdue University Northwest, Hammond, USA

Rice University, Houston, USA

University of Rochester, Rochester, USA

Rutgers, The State University of New Jersey, Piscataway, USA

University of Tennessee, Knoxville, USA

Texas A&M University, College Station, USA

Texas Tech University, Lubbock, USA

Vanderbilt University, Nashville, USA

University of Virginia, Charlottesville, USA

Wayne State University, Detroit, USA

University of Wisconsin—Madison, Madison, WI, USA

Deceased.

Also at Vienna University of Technology, Vienna, Austria.

Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.

Also at Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France.

Also at Universidade Estadual de Campinas, Campinas, Brazil.

Also at Universidade Federal de Pelotas, Pelotas, Brazil.

Also at Université Libre de Bruxelles, Bruxelles, Belgium.

Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.

Also at Joint Institute for Nuclear Research, Dubna, Russia.

Also at Suez University, Suez, Egypt.
Also at British University in Egypt, Cairo, Egypt.

Also at Ain Shams University, Cairo, Egypt.

Also at Helwan University, Cairo, Egypt.

Also at Université de Haute Alsace, Mulhouse, France.

Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.

Also at University of Hamburg, Hamburg, Germany.

Also at Brandenburg University of Technology, Cottbus, Germany.

Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.

Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.

Also at Indian Institute of Science Education and Research, Bhopal, India.

Also at Institute of Physics, Bhubaneswar, India.

Also at University of Visva-Bharati, Santiniketan, India.

Also at University of Ruhuna, Matara, Sri Lanka.

Also at Isfahan University of Technology, Isfahan, Iran.

Also at University of Tehran, Department of Engineering Science, Tehran, Iran.

Also at Yazd University, Yazd, Iran.

Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.

Also at Università degli Studi di Siena, Siena, Italy.

Also at Purdue University, West Lafayette, USA.

Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.

Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.

Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.

Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.

Also at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia.

Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.

Also at University of Florida, Gainesville, USA.

Also at P.N. Lebedev Physical Institute, Moscow, Russia.

Also at California Institute of Technology, Pasadena, USA.

Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.

Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.

Also at INFN Sezione di Roma, Sapienza Università di Roma, Rome, Italy.

Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.

Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy.

Also at National and Kapodistrian University of Athens, Athens, Greece.

Also at Riga Technical University, Riga, Latvia.

Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.

Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.

Also at Gaziosmanpasa University, Tokat, Turkey.

Also at Adiyaman University, Adiyaman, Turkey.

Also at Istanbul Aydin University, Istanbul, Turkey.

Also at Mersin University, Mersin, Turkey.

Also at Cag University, Mersin, Turkey.

Also at Piri Reis University, Istanbul, Turkey.

Also at Ozyegin University, Istanbul, Turkey.

Also at Izmir Institute of Technology, Izmir, Turkey.

Also at Marmara University, Istanbul, Turkey.

Also at Kafkas University, Kars, Turkey.

Also at Istanbul Bilgi University, Istanbul, Turkey.

Also at Yildiz Technical University, Istanbul, Turkey.

Also at Hacettepe University, Ankara, Turkey.

Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.

Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.

Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.

Also at Utah Valley University, Orem, USA.

Also at Argonne National Laboratory, Argonne, USA.
Also at Erzincan University, Erzincan, Turkey.
Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
Also at Catholic University of America, Washington, USA.
Also at Texas A&M University at Qatar, Doha, Qatar.
Also at Kyungpook National University, Daegu, Korea.