Search for an exotic decay of the Higgs boson to a pair of light pseudoscalars in the final state with two b quarks and two $\tau$ leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

A search for an exotic decay of the Higgs boson to a pair of light pseudoscalar bosons is performed for the first time in the final state with two b quarks and two $\tau$ leptons. The search is motivated in the context of models of physics beyond the standard model (SM), such as two Higgs doublet models extended with a complex scalar singlet (2HDM+S), which include the next-to-minimal supersymmetric SM (NMSSM). The results are based on a data set of proton-proton collisions corresponding to an integrated luminosity of 35.9 fb$^{-1}$, accumulated by the CMS experiment at the LHC in 2016 at a center-of-mass energy of 13 TeV. Masses of the pseudoscalar boson between 15 and 60 GeV are probed, and no excess of events above the SM expectation is observed. Upper limits between 3 and 12% are set on the branching fraction $B(h \rightarrow aa \rightarrow 2\tau 2b)$ assuming the SM production of the Higgs boson. Upper limits are also set on the branching fraction of the Higgs boson to two light pseudoscalar bosons in different 2HDM+S scenarios. Assuming the SM production cross section for the Higgs boson, the upper limit on this quantity is as low as 20% for a mass of the pseudoscalar of 40 GeV in the NMSSM.

*See Appendix A for the list of collaboration members
1 Introduction

Within the standard model (SM), the Brout–Englert–Higgs mechanism [1–6] is responsible for electroweak symmetry breaking and predicts the existence of a scalar particle—the Higgs boson. A particle compatible with the Higgs boson was discovered by the ATLAS and CMS collaborations at the CERN LHC [7–9]. Measurements of the couplings and properties of this particle leave room for exotic decays to beyond-the-SM particles, with a limit of 34% on this branching fraction at 95% confidence level (CL), using data collected at center-of-mass energies of 7 and 8 TeV [10].

The possible existence of exotic decays of the Higgs boson is well motivated [11–16]. The decay width of the Higgs boson in the SM is so narrow that a small coupling to a light state could lead to branching fractions of the Higgs boson to that light state of the order of several percent. Additionally, the scalar sector can theoretically serve as a portal that allows matter from a hidden sector to interact with SM particles [17]. In general, exotic decays of the Higgs boson are allowed in many models that are consistent with all LHC measurements published so far.

An interesting class of such processes consists of decays to a pair of light pseudoscalar particles, which then decay to pairs of SM particles. The minimal supersymmetric SM (MSSM) cannot accommodate such processes with all the measurements performed at the LHC [18–25]. This type of process is, however, allowed in various other models, including two Higgs doublet models augmented by a scalar singlet (2HDM+S). Seven scalar and pseudoscalar particles are predicted in 2HDM+S. One of them, \( h \), is a scalar that can be compatible with the discovered particle with a mass of 125 GeV, and another, the pseudoscalar \( a \), can be light enough so that \( h \rightarrow aa \) decays are allowed.

Four types of 2HDM, and by extension 2HDM+S, forbid flavor-changing neutral currents at tree level [26]. In type I, all SM particles couple to the first doublet. In type II, up-type quarks couple to the first doublet, whereas leptons and down-type quarks couple to the second doublet. The next-to-minimal supersymmetric SM (NMSSM) is a particular case of 2HDM+S of type II that brings a solution to the \( \mu \) problem [27]. In type III, quarks couple to the first doublet, and leptons to the second one. Finally, in type IV, leptons and up-type quarks couple to the first doublet, while down-type quarks couple to the second doublet [15]. The branching fractions of the light pseudoscalars to pairs of SM particles depend on the type of 2HDM+S, on the pseudoscalar mass \( m_a \), and on \( \tan \beta \), defined as the ratio of the vacuum expectation values of the second and first doublets. The value of the branching fraction \( B(\tau \tau \rightarrow bb\tau \tau) \) is slightly above 10% in the NMSSM—or more generally in 2HDM+S type II—for \( \tan \beta > 1 \), and can reach up to about 50% in 2HDM+S type III with \( \tan \beta \sim 2 \), as shown in Fig. 1.

Several searches for exotic decays of the Higgs boson to a pair of light short-lived pseudoscalar bosons have been performed by the CMS Collaboration with data collected at a center-of-mass energy of 8 TeV in different final states: \( 2\mu 2b \) for \( 25.0 < m_a < 62.5 \) GeV [28], \( 2\mu 2\tau \) for \( 15.0 < m_a < 62.5 \) GeV [28], \( 4\tau \) for \( 4 < m_a < 8 \) GeV [29] and \( 5 < m_a < 15 \) GeV [28], and \( 4\mu \) for \( 0.25 < m_a < 3.50 \) GeV [30]. The CMS Collaboration also studied the \( 2\mu 2\tau \) final state for \( 15.0 < m_a < 62.5 \) GeV at a center-of-mass energy of 13 TeV [31]. The ATLAS Collaboration reported results for the following final states at a center-of-mass energy of 8 TeV: \( 4\mu, 4e, \) and \( 2e2\mu \) for \( 15 < m_a < 60 \) GeV [32]; \( 4\gamma \) for \( 10 < m_a < 62 \) GeV [33]; and \( 2\mu 2\tau \) for \( 3.7 < m_a < 50.0 \) GeV [34]. At a center-of-mass energy of 13 TeV, the ATLAS Collaboration published results for the 4b decay channel for \( 20 < m_a < 60 \) GeV [35], and \( 4\mu, 4e, \) and \( 2e2\mu \) for \( 1 < m_a < 60 \) GeV [36]. The \( 2b2\tau \) final state has never been probed so far. This final state benefits from large branching fractions in most models because of the large mass of \( \tau \) leptons and b quarks with respect to other leptons and quarks. The presence of light leptons originating from the \( \tau \) decays allows
Figure 1: Predicted $B(aa \to bb\tau\tau)$ for $m_a = 40$ GeV in the different models of 2HDM+S, for various values of $\tan \beta$. The picture is essentially the same for all $m_a$ hypotheses considered in this Letter. The branching fractions are computed following the formulas of Ref. [15].

events to be triggered in the dominant gluon fusion production mode.

This Letter reports on the first search with the CMS experiment for exotic decays of the Higgs boson to a pair of light pseudoscalar bosons, in the final state with two $\tau$ leptons and two $b$ quarks. The search focuses on the mass range between 15 and 60 GeV. For low $m_a$ values, between the $b\bar{b}$ threshold and 15 GeV, the decay products of each of the pseudoscalar bosons become collimated, which would necessitate the use of special reconstruction techniques to identify them.

The search is based on proton-proton (pp) collision data collected at a center-of-mass energy of 13 TeV and corresponding to an integrated luminosity of $35.9 \text{ fb}^{-1}$. Throughout this Letter, the term $\tau_h$ denotes $\tau$ leptons decaying hadronically. The $\tau\tau$ final states studied in this search are $e\mu$, $e\tau_h$, and $\mu\tau_h$. Despite its large branching fraction, the $\tau_h\tau_h$ final state is not considered because the signal acceptance after the trigger requirements is negligible. The ee and $\mu\mu$ final states for the $\tau\tau$ pair are not considered either, because they have a low branching fraction and suffer from a large contribution of Drell–Yan background events.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume, there are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. Events of interest are selected using a two-tiered trigger system [37]. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [38].
3 Simulated samples and event reconstruction

The signal and some of the background processes are modeled with samples of simulated events. The MadGraph5_aMC@NLO [39] 2.3.2 generator is used for the $h \rightarrow aa \rightarrow 2\tau 2b$ signal process, in gluon fusion (ggf), vector boson fusion (VBF), or associated vector boson (Wh, Zh) processes. These samples are simulated at leading order (LO) in perturbative quantum chromodynamics (QCD) with the MLM jet matching and merging [40]. The $Z + \text{jets}$ and $W + \text{jets}$ processes are also generated with the MadGraph5_aMC@NLO generator at LO with the MLM jet matching and merging. The FxFx merging scheme [41] is used to generate diboson background with the MadGraph5_aMC@NLO generator at next-to-LO (NLO). The $t\bar{t}$ and single top quark processes are generated at NLO with the POWHEG 2.0 and 1.0 generator [42–47]. Backgrounds from SM Higgs boson production are generated at NLO with the POWHEG generator [48], and the MINLO HVJ [49] extension of POWHEG 2.0 is used for the Wh and Zh simulated samples. The generators are interfaced with PYTHIA 8.212 [50] to model the parton showering and fragmentation, as well as the decay of the $\tau$ leptons. The CUETP8M1 tune [51] is chosen for the PYTHIA parameters that affect the description of the underlying event. The set of parton distribution functions (PDFs) is NLO NNPDF3.0 for NLO samples, and LO NNPDF3.0 for LO samples [52]. The full next-to-NLO (NNLO) plus next-to-next-to-leading logarithmic (NNLL) order calculation [53–58], performed with the Top++ 2.0 program [59], is used to compute a $t\bar{t}$ production cross section equal to $832^{+20}_{-29}^{(-29)}$ pb setting the top quark mass to 172.5 GeV. This cross section is used to normalize the $t\bar{t}$ background simulated with POWHEG.

All simulated samples include additional proton-proton interactions per bunch crossing, referred to as “pileup”, obtained by generating concurrent minimum bias collision events using PYTHIA. The simulated events are reweighted in such a way to have the same pileup distribution as data. Generated events are processed through a simulation of the CMS detector based on GEANT4 [60].

The reconstruction of events relies on the particle-flow (PF) algorithm [61], which combines information from the CMS subdetectors to identify and reconstruct the particles emerging from pp collisions: charged and neutral hadrons, photons, muons, and electrons. Combinations of these PF objects are used to reconstruct higher-level objects such as jets, $\tau_\text{h}$ candidates, and missing transverse momentum.

Electrons are reconstructed by matching ECAL clusters to tracks in the tracker. They are then identified with a multivariate analysis (MVA) discriminant that makes use of variables related to the energy deposits in the ECAL, the quality of the track, and the compatibility between the properties of the ECAL clusters and the track that have been matched [62]. The MVA working point chosen in this search has an efficiency of about 80%. The reconstruction of muon candidates is performed combining the information of the tracker and the muon systems. Muons are then identified on the basis of the track reconstruction quality and on the number of measurements in the tracker and the muon systems [63]. The relative isolation of electrons and muons is defined as:

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

In this formula, $\sum_{\text{charged}} p_T$ is the scalar sum of the transverse momenta of the charged particles, excluding the lepton itself, associated with the primary vertex and in a cone around the lepton direction, with size $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.3$ for electrons, or 0.4 for muons. The sum $\sum_{\text{neutral}} p_T$ represents a similar quantity for neutral particles. The last term corresponds to
the $p_T$ of neutral particles from pileup vertices, which, as estimated from simulation, is equal to approximately half of that of charged hadrons associated with pileup vertices, denoted by $\sum_{\text{charged, PU}} p_T$. The $p_T$ of the lepton is denoted $p_{\ell}^T$. The azimuthal angle, $\phi$, is measured in radians.

Jets are reconstructed from PF objects with the anti-$k_T$ clustering algorithm implemented in the FASTJET library [64, 65], using a distance parameter of 0.4. Corrections to the jet energy are applied as a function of the $p_T$ and $\eta$ of the jet [66]. The jets in this search are required to be separated from the selected electrons, muons, or $\tau_v$ by $\Delta R \geq 0.5$. Jets that originate from b quarks, called b jets, are identified with the combined secondary vertex (CSVv2) algorithm [67]. The CSVv2 algorithm builds a discriminant from variables related to secondary vertices associated with the jet if any, and from track-based lifetime information. The working point chosen in this search provides an efficiency for b quark jets of approximately 70%, and a misidentification rate for light-flavor and c quark jets of approximately 1 and 10%, respectively.

Hadronically decaying $\tau$ leptons are reconstructed with the hadrons-plus-strips (HPS) algorithm [68, 69] as a combination of tracks and energy deposits in strips of the ECAL. The tracks are the signature of the charged hadrons, and the strips that of the neutral pions, which decay to a pair of photons with potential electron-positron conversion. The reconstructed $\tau_v$ decay modes are one track, one track plus at least one strip, and three tracks. The rate for jets to be misidentified as $\tau_v$ is reduced by applying an MVA discriminator that uses isolation as well as lifetime variables. Its working point has been chosen to have an efficiency of approximately 45% for a misidentification rate of light-flavor jets of the order of 0.1%. Additionally, discriminators that reduce the rates with which electrons and muons are misidentified as $\tau_v$ are applied. Loose working points with an efficiency above 90% are chosen because the $Z \rightarrow e\mu/\mu\mu$ background does not contribute much in the region where the signal is expected.

To account for the contribution of undetectable particles, such as the neutrinos, the missing transverse momentum, $\vec{p}_T^{\text{miss}}$, is defined as the negative vectorial sum of the transverse momenta of all PF objects reconstructed in the event. The magnitude of this vector is denoted $p_T^{\text{miss}}$. The reconstructed vertex with the largest value of summed physics-object $p_T^2$ is taken to be the primary pp interaction vertex. The physics objects are the objects constructed by a jet finding algorithm [64, 70] applied to all charged tracks associated with the vertex, and the corresponding associated missing transverse momentum.

## 4 Event selection

Events are selected in three different $\tau\tau$ final states: $e\mu$, $e\tau_v$, and $\mu\tau_v$. They are additionally required to contain at least one b-tagged jet. The dominant backgrounds with these objects in the final state are $t\bar{t}$ and $Z \rightarrow \tau\tau$ production. Another large background consists of events with jets misidentified as $\tau_v$, such as $W +$ jets events, the background from SM events composed uniquely of jets produced through the strong interaction, referred to as QCD multijet events, or semileptonic $t\bar{t}$ events.

All events are required to have at least one b-tagged jet with $p_T > 20\text{GeV}$ and $|\eta| < 2.4$. About 90% of simulated signal events passing this condition have only one such jet, as a result of the typically soft b jet $p_T$ spectrum and of the limited efficiency of the b tagging algorithm. Events in the $e\mu$ final state are selected with a trigger that relies on the presence of both an electron and a muon, where the leading lepton has $p_T > 23\text{GeV}$ and the subleading one $p_T > 12\text{GeV}$ if it is an electron or 8 GeV if it is a muon. In the $e\tau_v$ final state, the trigger is based on the presence of an isolated electron with $p_T > 25\text{GeV}$, whereas in the $\mu\tau_v$ final state events are selected with a
Table 1: Baseline selection criteria for objects required in various final states. The numbers given for the $p_T$ thresholds of the electron and muon in the $e\mu$ final state correspond to the leading and subleading particles. The $p_T$ threshold for the $\tau_h$ candidates is the result of an optimization of the expected exclusion limits of the signal.

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To increase the sensitivity of the analysis, events in each final state are separated into four categories with different signal-to-background ratios. The categories are defined on the basis of the invariant mass of the visible decay products of the $\tau$ leptons and the b-tagged jet with the highest $p_T$, denoted by $m_{\tau\tau}^{\text{vis}}$. This variable is typically low for signal events because the three objects originate from a 125 GeV Higgs boson, but it is on average much larger for background events, where the three objects do not originate from a decay of a resonance, as shown in Fig. 2 for the $\mu\tau_h$ final state. The thresholds that define the categories depend on the $\tau\tau$ final state: they are lower in the $e\mu$ final state because there are more neutrinos not included in the mass calculation, and they are higher in the $e\tau_h$ final state to keep enough events despite the lower signal acceptance related to the electron $p_T$ thresholds. Signal events with $m_\Delta \gtrsim 25$ GeV contribute mostly to the first two categories, whereas those with $m_\Delta \lesssim 25$ GeV are concentrated in the second and third categories. This can be explained by the fact that the missing b jet in the mass calculation would be closer to the reconstructed b jet for a signal with lower $m_\Delta$ because of the boost of the pseudoscalar bosons, leading to a larger reconstructed mass. The last category has large background yields; it is useful to constrain the various backgrounds and provides some additional sensitivity for low-$m_\Delta$ signal samples. The results of the search are extracted from a fit of the visible $\tau\tau$ mass ($m_{\tau\tau}^{\text{vis}}$) distributions in each of the categories, because this is a resonant distribution for signal events.

Selection criteria are applied to optimize the expected limits on the product of the signal cross section and branching fraction. The same thresholds would be obtained with an optimization based on the discovery potential. One such criterion is based on the transverse mass of $p_T^{\text{miss}}$ and each of the leptons. The transverse mass $m_T$ between a lepton $\ell$ and $p_T^{\text{miss}}$ is defined as

$$m_T(\ell, p_T^{\text{miss}}) \equiv \sqrt{2p_T^\ell p_T^{\text{miss}}[1 - \cos(\Delta\phi)]},$$

where $p_T^\ell$ is the transverse momentum of the lepton $\ell$, and $\Delta\phi$ is the azimuthal angle between
Figure 2: Visible invariant mass of the leptons and the leading b jet, \( m_{\text{vis}}^{bTX} \), after the baseline selection, in the \( \mu \tau_h \) final state, for the signal with different mass hypotheses (left). Distribution of \( m_{\text{vis}}^{bTX} \) in the \( \mu \tau_h \) final state (right). The "jet \( \rightarrow \tau_h \)" contribution includes all events with a jet misidentified as a \( \tau_h \) candidate, whereas the rest of background contributions only include events where the reconstructed \( \tau_h \) corresponds to a \( \tau_h \), a muon, or an electron, at the generator level. The "Other" contribution includes events from single top quark, diboson, and SM Higgs boson processes. The signal histogram corresponds to 10 times the SM production cross section for ggh, VBF, and Vh processes, and assumes \( B(h \rightarrow aa \rightarrow 2\tau 2b) = 100\% \).

The lepton momentum and \( \vec{p}_{\text{T,miss}} \). Selecting events with low \( m_T \) strongly reduces the backgrounds from \( W + \) jets and \( t\bar{t} \) events, which are characterized by a larger \( \vec{p}_{\text{T,miss}} \). In addition, for \( W + \) jets events in which the selected lepton comes from the W boson decay, \( m_T \) has a Jacobian peak near the W boson mass. The distributions of \( m_{\text{T,miss}}(\mu, \vec{p}_{\text{T,miss}}) \) and \( m_{\text{T,miss}}(\tau_h, \vec{p}_{\text{T,miss}}) \) in the \( \mu \tau_h \) final state before the \( m_{\text{vis}}^{bTX} \)-based categorization are shown in Fig. 3 (top left and top right).

Another selection criterion is based on the variable \( D_\tau \), which is defined as

\[
D_\tau \equiv p_\tau - 0.85 p_{\text{vis}}^\tau,
\]

where \( p_\tau \) is the component of \( \vec{p}_{\text{T,miss}} \) along the bisector of the transverse momenta of the two \( \tau \) candidates and \( p_{\text{vis}}^\tau \) is the sum of the components of the lepton \( p_T \) along the same direction [19]. As shown in Fig. 3 (bottom), the \( Z \rightarrow \tau \tau \) background typically has \( D_\tau \) values close to zero because \( \vec{p}_{\text{T,miss}} \) is approximately collinear to the \( \tau \tau \) system, whereas the \( t\bar{t} \) background is concentrated at lower \( D_\tau \) values because of typically large \( \vec{p}_{\text{T,miss}} \) not aligned with the \( \tau \tau \) system. The signal lies in an intermediate region because \( \vec{p}_{\text{T,miss}} \) is approximately aligned with the \( \tau \tau \) system, but \( p_{\text{T,miss}} \) is usually small. The precise criteria for each final state and category are indicated in Table 2.

5 Background estimation

The \( Z \rightarrow \ell \ell \) background is estimated from simulation. The distributions of the \( p_T \) of the dilepton system and the visible invariant mass between the leptons and the leading b jet are reweighed with corrections derived using data from a region enriched in \( Z \rightarrow \mu \mu + \geq 1 \) b events. The simulation is separated between \( Z \rightarrow \tau \tau \), where the reconstructed \( \tau \) candidates
Figure 3: Distributions of $m_T(\mu, p_T^{\text{miss}})$ (top left), $m_T(\tau, p_T^{\text{miss}})$ (top right), and $D_\zeta$ (bottom) in the $\mu\tau_\nu$ final state before the $m_{\text{Vvis}}$-based categorization. The “jet $\to$ $\tau_\nu$” contribution includes all events with a jet misidentified as a $\tau_\nu$ candidate, whereas the rest of background contributions only include events where the reconstructed $\tau_\nu$ corresponds to a $\tau_\nu$, a muon, or an electron, at the generator level. The “Other” contribution includes events from single top quark, diboson, and SM Higgs boson processes. The signal histogram corresponds to 10 times the SM production cross section for ggh, VBF, and Vh processes, and assumes $B(h \to \tau\tau \to 2\tau 2b) = 100\%$. 
Table 2: Optimized selection and categorization in the various final states. The selection criterion $D_\tau > -30 \text{ GeV}$ in the $e\mu$ final state reduces the large $t\bar{t}$ background. In the the other final states the $t\bar{t}$ background is less important, and only events with $D_\tau > 0 \text{ GeV}$ are discarded in one of the categories of the $\mu\tau_h$ final state to reduce the $Z \rightarrow \tau\tau$ background. This selection criterion does not improve the sensitivity in the $e\tau_h$ final state because of the lower expected signal and background yields, and is therefore not applied.

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correspond to $\tau$ leptons at generator level, and $Z \rightarrow ee/\mu\mu$ decays, where at least one electron or muon is misidentified as a $\tau_h$ candidate.

Backgrounds with a jet misidentified as a $\tau_h$ candidate are estimated from data. They consist mostly of $W +$ jets and QCD multijet events, as well as the fraction of $t\bar{t}$, diboson, and single top quark production where the reconstructed $\tau_h$ candidate comes from a jet. The probabilities for jets to be misidentified as $\tau_h$ candidates, denoted $f$, are estimated from $Z \rightarrow \mu\mu +$ jets events in data. They are parameterized with Landau distributions as a function of the $p_T$ of the $\tau_h$ candidate, separately for every reconstructed $\tau_h$ decay mode. Events that pass all the selection criteria, except that the $\tau_h$ candidate fails the isolation condition, are reweighted with a weight $f/(1-f)$ to estimate the contribution of events with jets in the signal region. The contribution of events with genuine electrons, muons, or $\tau_h$ candidates in the control region is estimated from simulation and subtracted from data.

In the $e\mu$ final state, the small $W +$ jets background is estimated from simulation [71]. Such events typically have a genuine lepton coming from the $W$ boson decay and a jet misidentified as the other lepton. The QCD multijet background, which also contains jets misidentified as leptons, is estimated from data. Its normalization corresponds to the difference between the data and the sum of all the other backgrounds in a so-called same-sign region where the $\tau$ candidates have the same sign. A smooth distribution is obtained by additionally relaxing the isolation conditions of both leptons. A correction that is extracted from data is applied to extrapolate the normalization obtained in the same-sign region to the signal region.

Other processes, including diboson, $t\bar{t}$, and single top quark production without jet misidentified as a $\tau_h$ candidate, as well as SM Higgs boson processes in various production and decay modes, are estimated from simulation. The $t\bar{t}$ production is a major background, especially in the $e\mu$ final state. The $t\bar{t}$ simulation models the variables used in this analysis well, as it has
been verified in a control region in the $e\mu$ final state where no selection criterion is applied on $m_T(e, \vec{p}_T^{\text{miss}})$ or $m_T(\mu, \vec{p}_T^{\text{miss}})$, and where the $D_\tau$ selection criterion is inverted.

In the $e\tau_h$ and $\mu\tau_h$ final states, where all backgrounds with a jet misidentified as a $\tau_h$ candidate are estimated from data, simulated events with a reconstructed $\tau_h$ that is not matched to an electron, a muon, or a $\tau_h$ at the generator level are discarded to avoid double counting. Approximately 30% of simulated $t\bar{t}$ events after the selection have a reconstructed $\tau_h$ that is not matched to an electron, a muon, or a $\tau_h$ at the generator level.

6 Fit method and systematic uncertainties

The search for an excess of signal events over the expected background involves a global binned maximum likelihood fit based on the $m_{\text{vis}}^{\tau\tau}$ distributions in the different channels and categories. The statistical uncertainty largely dominates over systematic uncertainties in this search. The systematic uncertainties are represented by nuisance parameters that are varied in the fit according to their probability density functions. A log-normal probability density function is assumed for the nuisance parameters that affect the event yields of the various background and signal contributions, whereas systematic uncertainties that affect the distributions are represented by nuisance parameters whose variation results in a continuous perturbation of the spectrum [72] and which are assumed to have a Gaussian probability density function.

To take into account the limited size of simulated samples and of data in the control regions used to estimate some of the background processes, statistical uncertainties in individual bins of the $m_{\text{vis}}^{\tau\tau}$ distributions are considered as Poissonian nuisance parameters. The uncertainty can be as large as 40% for some bins in the low-$m_{\text{vis}}^{\tau\tau}$ categories. The combined effect of all these uncertainties is the dominant systematic uncertainty in this search.

The uncertainties in the jet energy scale [66] affect the overall yields of processes estimated from simulation, as well as their relative contribution to the different categories because the categorization is based on the value of $m_{\text{vis}}^{\tau\tau}$ for each event. They are functions of the jet $p_T$ and $\eta$. The $\vec{p}_T^{\text{miss}}$ is recomputed for each variation of the jet energy scale. The uncertainty in $\vec{p}_T^{\text{miss}}$ related to the measurement of the energy that is not clustered in jets [73] is evaluated event-by-event, and is also considered as a shape uncertainty.

Corrections for the efficiency of the identification of electrons, muons, and $\tau_h$ candidates are derived from data using tag-and-probe methods [74], and are applied to simulated events as a function of the lepton $p_T$ and $\eta$. Uncertainties related to these corrections amount to 2% for electrons, 2% for muons, and 5% for $\tau_h$ candidates. Additionally, events with an electron or muon misidentified as a $\tau_h$ candidate have a yield uncertainty of 5%. Trigger scale factors are also estimated with tag-and-probe methods and their corresponding uncertainties in the yields of simulated processes are 1%.

The energy scale of $\tau_h$ candidates is corrected for each reconstructed decay mode, and the uncertainty of 1.2% for each single decay mode is considered as a shape uncertainty. Uncertainties in the energy scales of electrons and muons are also included as shape uncertainties.

Corrections to the efficiency for identifying a $b$ quark jet as a $b$ jet, as well as for mistagging a jet originating from a different flavor, are applied to simulated events on the basis of the generated flavor of the jets. The uncertainties in the scale factors depend on the $p_T$ of the jet and are therefore considered as shape uncertainties. They amount to 1.5% for a jet originating from a $b$ quark, 5% from a $c$ quark, and 10% from a light-flavor parton.
The uncertainty in the yield of the backgrounds with jets misidentified as $\tau_h$ candidates accounts for possibly different misidentification rates in $Z +$ jets events (where the misidentification rates are measured), and in $W +$ jets and QCD multijet events (which dominate the constitution of the reducible background in the signal region), and for differences between data and predicted backgrounds observed in a region enriched in reducible background events by inverting the charge requirement on the $\tau$ candidates and removing the $m_T$ and $D_\tau$ selection criteria. This uncertainty amounts to 20%, and is constrained to about 7% after the maximum likelihood fit because of the large number of events contributing to the last $m_{\text{vis}}^{\text{b}} \tau \tau$ category. Shape uncertainties are also considered for the backgrounds with jets misidentified as $\tau_h$ candidates; they are related to the fit uncertainties of the misidentification probabilities.

The uncertainty in the yield of the QCD multijet background in the $e\mu$ final state is 20%; the value comes from the uncertainty in the extrapolation factor from the same-sign region to the opposite-sign region. The uncertainty in the $W +$ jets background in this channel also amounts to 20%, and accounts for a potential mismodeling in simulation of the misidentification rate of jets as electrons or muons.

The theoretical yield uncertainty of the $t\bar{t}$ background is related to the PDF uncertainty and to the uncertainty associated to the strong coupling constant $\alpha_S$ in the full NNLO plus NNLL order calculation of the cross section; it amounts to about 4%. The yield uncertainties for other backgrounds estimated from simulation are taken from recent CMS measurements: 6% for di-boson processes [75], 13% for single top quark processes [76], and 7% for $Z +$ jets events with at least one b-tagged jet in the final state [77]. The uncertainty in the correction of the dilepton $p_T$ distribution for Drell–Yan events is equal to 10% of the size of the correction itself. The uncertainty in the correction of the $m_{\text{vis}}^{\text{b}} \tau \tau$ distribution is equal to the correction itself, and considered as a shape uncertainty. Uncertainties in the production cross sections and branching fractions for SM Higgs boson processes are taken from Ref. [78]. The uncertainty in the integrated luminosity amounts to 2.5% [79].

7 Results

The $m_{\text{vis}}^{\text{b}}$ distributions in the different channels and categories are shown in Figs. 4–6. The binning corresponds to the bins used in the likelihood fit.

No excess is observed relatively to the SM background prediction. Upper limits at 95% CL are set on $(\sigma(h)/\sigma_{\text{SM}})B(h \rightarrow aa \rightarrow 2\tau 2b)$ using the modified frequentist construction $\text{CL}_s$ in the asymptotic approximation [80–84], for pseudoscalar masses between 15 and 60 GeV. In this expression, $\sigma_{\text{SM}}$ denotes the SM production cross section of the Higgs boson, whereas $\sigma(h)$ is the $h$ production cross section. The limits per channel and for the combination of the three channels are shown in Fig. 7. The most sensitive final state is $\mu \tau_h$. The sensitivity of the $e\tau_h$ and $e\mu$ channels is approximately equivalent; the first channel suffers from higher trigger thresholds and lower object identification efficiency than $\mu \tau_h$, and the second one suffers from a lower branching fraction than $\mu \tau_h$. At low $m_a$, the $e\mu$ final state has a higher signal acceptance than the other final states, especially $e\tau_h$. The limits are more stringent in the intermediate mass range. The low-$m_a$ signals have a lower acceptance because of the overlap of the leptons related to the boost of the pseudoscalar bosons, and of the typically softer lepton and b jet $p_T$ spectra. The high $m_a$ signals lie in a region where more backgrounds contribute, leading also to lower sensitivity than in the intermediate mass region. The categories are complementary over the probed mass range, with the low-$m_{\text{vis}}^{\text{b}}$ signal regions more sensitive for heavy resonances, and the high-$m_{\text{vis}}^{\text{b}}$ signal regions for light resonances.
Figure 4: Distributions of $m_{\text{vis}}$ in the four categories of the $e\mu$ channel. The "Other" contribution includes events from single top quark, diboson, SM Higgs boson, and $W + \text{jets}$ productions. The signal histogram corresponds to the SM production cross section for $ggH$, VBF, and $Vh$ processes, and assumes $\mathcal{B}(h \rightarrow aa \rightarrow 2\tau 2b) = 10\%$. The normalization of the predicted background distributions corresponds to the result of the global fit.
Figure 5: Distributions of $m_{\ell\ell}$ in the four categories of the $e\tau_b$ channel. The "jet → $\tau_b$" contribution includes all events with a jet misidentified as a $\tau_b$ candidate, whereas the rest of background contributions only include events where the reconstructed $\tau_b$ corresponds to a $\tau_b$, a muon, or an electron, at the generator level. The "Other" contribution includes events from single top quark, diboson, and SM Higgs boson processes. The signal histogram corresponds to the SM production cross section for ggh, VBF, and Vh processes, and assumes $B(h \rightarrow aa \rightarrow 2\tau 2b) = 10\%$. The normalization of the predicted background distributions corresponds to the result of the global fit.
Figure 6: Distributions of \( m_{\text{VH}} \) in the four categories of the \( \mu\tau \) channel. The “jet \( \rightarrow \tau \nu \)” contribution includes all events with a jet misidentified as a \( \tau \) candidate, whereas the rest of background contributions only include events where the reconstructed \( \tau \) corresponds to a \( \tau_h \), a muon, or an electron, at the generator level. The “Other” contribution includes events from single top quark, diboson, and SM Higgs boson processes. The signal histogram corresponds to the SM production cross section for ggh, VBF, and Vh processes, and assumes \( \mathcal{B}(h \rightarrow aa \rightarrow 2\tau2b) = 10\% \). The normalization of the predicted background distributions corresponds to the result of the global fit.
Figure 7: Expected and observed 95% CL limits on $(\sigma(h)/\sigma_{SM})\mathcal{B}(h \rightarrow aa \rightarrow 2\tau 2b)$ in %. The $e\mu$ results are shown in the top left panel, $e\tau_h$ in the top right, $\mu \tau_h$ in the bottom left, and the combination in the bottom right. The inner (green) band and the outer (yellow) band indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis.
The combined limit at intermediate mass is as low as 3% on $\mathcal{B}(h \to aa \to 2\tau 2b)$, assuming the SM production cross section and mechanisms for the Higgs boson, and is up to 12% for the lowest mass point $m_a = 15$ GeV. Computing the branching fractions of the light pseudoscalar to SM particles [15, 85], this translates to limits on $(\sigma(h)/\sigma_{SM})\mathcal{B}(h \to aa)$ of about 20% in 2HDM+S type II—including the NMSSM—with tan $\beta > 1$ for $m_a = 40$ GeV. This improves by more than one order of magnitude previous limits on $\mathcal{B}(h \to aa)$ obtained in the $2\mu 2\tau$ final state by CMS for $15 < m_a < 25$ GeV [28, 31], and by up to a factor five those obtained in the $2\mu 2b$ final state by CMS for $25 < m_a < 60$ GeV [28]. In the scenario with the highest branching fraction, 2HDM+S type III with tan $\beta = 2$, the expected limit is as low as 6% at intermediate $m_a$. Figure 8 shows the observed limits at 95% CL on $(\sigma(h)/\sigma_{SM})\mathcal{B}(h \to aa)$ as a function of $m_a$ and tan $\beta$ for type III and type IV 2HDM+S, for which there is a strong dependence with tan $\beta$. Figure 9 shows the observed limits at 95% CL on $(\sigma(h)/\sigma_{SM})\mathcal{B}(h \to aa)$ for a few scenarios of 2HDM+S, assuming the branching fractions of the light pseudoscalar to SM particles computed using Refs. [15, 85]. The limit shown for type II 2HDM+S is approximately valid for any value of tan $\beta > 1$, and that for type I 2HDM+S does not depend on tan $\beta$.

Figure 8: Observed 95% CL limits on $(\sigma(h)/\sigma_{SM})\mathcal{B}(h \to aa)$ in 2HDM+S of type III (left), and type IV (right). The contours corresponding to a 95% CL exclusion of $(\sigma(h)/\sigma_{SM})\mathcal{B}(h \to aa) = 1.00$ and 0.34 are drawn with dashed lines. The number 34% corresponds to the limit on the branching fraction of the Higgs boson to beyond-the-SM particles at the 95% CL obtained with data collected at center-of-mass energies of 7 and 8 TeV by the ATLAS and CMS experiments [10].

8 Summary

The first search for exotic decays of the Higgs boson to pairs of light bosons with two b quark jets and two $\tau$ leptons in the final state has been performed with 35.9 fb$^{-1}$ of data collected at 13 TeV center-of-mass energy in 2016. This decay channel has a large branching fraction in many models where the couplings to fermions are proportional to the fermion mass, and can be triggered in the dominant gluon fusion production mode because of the presence of light leptons from leptonic $\tau$ decays. No excess of events is found on top of the expected standard model background for masses of the light boson, $m_a$, between 15 and 60 GeV. Upper limits between 3 and 12% are set on the branching fraction $\mathcal{B}(h \to aa \to 2\tau 2b)$ assuming the SM
production of the Higgs boson. This translates to upper limits on \( B(h \rightarrow aa) \) as low as 20\% for \( m_a = 40 \text{ GeV} \) in the NMSSM. These results improve by more than one order of magnitude the sensitivity to exotic Higgs boson decays to pairs of light pseudoscalars in the NMSSM from previous CMS results in other final states for 15 < \( m_a < 25 \text{ GeV} \), and by a factor up to five for 25 < \( m_a < 60 \text{ GeV} \) [28, 31].

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References


References


A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria

Institute for Nuclear Problems, Minsk, Belarus
V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

Universität Antwerpen, Antwerpen, Belgium

Vrije Universiteit Brussel, Brussel, Belgium

Université Libre de Bruxelles, Bruxelles, Belgium

Ghent University, Ghent, Belgium

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

Universidade Estadual Paulista a, Universidade Federal do ABC b, São Paulo, Brazil
S. Ahuja a, C.A. Bernardes a, L. Calligaris a, T.R. Fernandez Perez Tomei a, E.M. Gregores b, P.G. Mercadante b, S.F. Novaes a, SandraS. Padula a, D. Romero Abad b

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, A. Marinov, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov
University of Sofia, Sofia, Bulgaria
A. Dimitrov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China
W. Fang, X. Gao, L. Yuan

Institute of High Energy Physics, Beijing, China
Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, E. Yazgan, H. Zhang,
J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang, Z. Xu

Tsinghua University, Beijing, China
Y. Wang

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez,
C.F. Gonzalez Hernandez, M.A. Segura Delgado

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval
Architecture, Split, Croatia
B. Courbon, N. Godinovic, D. Lesal, I. Puljak, T. Sculac

University of Split, Faculty of Science, Split, Croatia
Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov, T. Susa

University of Cyprus, Nicosia, Cyprus
M.W. Ather, A. Attikis, M. Kolosova, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos,
P.A. Razis, H. Rykaczewski, D. Tsiakkouri

Charles University, Prague, Czech Republic
M. Finger, M. Finger Jr.

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian
Network of High Energy Physics, Cairo, Egypt
H. Abdalla, A.A. Abdelalim, A. Mohamed

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik,
M. Raidal, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen
Helsinki Institute of Physics, Helsinki, Finland

Lappeenranta University of Technology, Lappeenranta, Finland
T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France

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

Centre de Calcul de l’Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

Georgian Technical University, Tbilisi, Georgia
A. Khvedelidze7

Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze7

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

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

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
Deutsches Elektronen-Synchrotron, Hamburg, Germany

University of Hamburg, Hamburg, Germany

Karlsruher Institut fuer Technology

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

National and Kapodistrian University of Athens, Athens, Greece
G. Karathanasis, S. Kesisoglou, P. Kontaxakis, A. Panagiotou, N. Saoulidou, E. Tziaferi, K. Vellidis

National Technical University of Athens, Athens, Greece
K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

University of Ioάnnina, Ioάnnina, Greece

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

Wigner Research Centre for Physics, Budapest, Hungary

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi, A. Makovec, J. Molnar, Z. Szillasi
Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, Z.L. Trocsanyi, B. Ujvari

Indian Institute of Science (IISc), Bangalore, India
S. Choudhury, J.R. Komaragiri, P.C. Tiwari

National Institute of Science Education and Research, HBNI, Bhubaneswar, India

Panjab University, Chandigarh, India

University of Delhi, Delhi, India
A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, Ashok Kumar, S. Malhotra, M. Naimuddin, P. Priyanka, K. Ranjan, Aashaq Shah, R. Sharma

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

Indian Institute of Technology Madras, Madras, India
P.K. Behera

Bhabha Atomic Research Centre, Mumbai, India
R. Chudasama, D. Dutta, V. Jha, V. Kumar, P.K. Netrakanti, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, B. Sutar, Ravindra Kumar Verma

Tata Institute of Fundamental Research-B, Mumbai, India

Indian Institute of Science Education and Research (IISER), Pune, India
S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani, E. Eskandari Tadavani, S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi, M. Nasiri, F. Rezaei Hosseinabadi, B. Safarzadeh, M. Zeinali

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy

INFN Sezione di Bologna, Università di Bologna, Bologna, Italy
G. Abbiendi, C. Battilana, D. Bonacorsi, L. Borgonovi, S. Braibant-Giacomelli, R. Campanini, P. Capiluppi, A. Castro, F.R. Cavallo, S.S. Chhibra, C. Ciocca,

INFN Sezione di Catania, Università di Catania, Catania, Italy
S. Albergo, A. Di Mattia, R. Potenza, A. Tricomi, C. Tuve

INFN Sezione di Firenze, Università di Firenze, Firenze, Italy

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, F. Fabbri, D. Piccolo

INFN Sezione di Genova, Università di Genova, Genova, Italy
F. Ferro, F. Ravera, E. Robutti, S. Tosi

INFN Sezione di Milano-Bicocca, Università di Milano-Bicocca, Milano, Italy

INFN Sezione di Napoli, Università di Napoli ‘Federico II’, Napoli, Italy, Università della Basilicata, Potenza, Italy, Università G. Marconi, Roma, Italy

INFN Sezione di Padova, Università di Padova, Padova, Italy, Università di Trento, Trento, Italy

INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
A. Braghieri, A. Magnani, P. Montagna, S.P. Ratti, V. Re, M. Ressegotti, C. Riccardi, P. Salvini, I. Vai, P. Vitullo

INFN Sezione di Perugia, Università di Perugia, Perugia, Italy
L. Alunni Solestizzi, M. Biasini, G.M. Bilei, C. Cecchi, D. Ciangottini, L. Fanò, P. Lariccia, R. Leonardì, E. Manoni, G. Mantovani, V. Mariani, M. Menichelli, A. Rossi, A. Santocchia, D. Spiga

INFN Sezione di Pisa, Università di Pisa, Scuola Normale Superiore di Pisa, Pisa, Italy
INFN Sezione di Roma $^a$, Sapienza Università di Roma $^b$, Rome, Italy  
L. Barone$^{a,b}$, F. Cavallari$^a$, M. Cipriani$^{a,b}$, N. Daci$^a$, D. Del Re$^{a,b}$, E. Di Marco$^{a,b}$, M. Diemoz$^a$, S. Gelli$^{a,b}$, E. Longo$^{a,b}$, B. Marzocchi$^{a,b}$, P. Meridiani$^{a,b}$, G. Organtini$^{a,b}$, F. Pandolfi$^a$, R. Paramatti$^{a,b}$, F. Preiato$^{a,b}$, S. Rahatlou$^{a,b}$, C. Rovelli$^a$, F. Santanastasio$^{a,b}$

INFN Sezione di Torino $^a$, Università di Torino $^b$, Torino, Italy, Università del Piemonte Orientale $^c$, Novara, Italy  
N. Amapane$^{a,b}$, R. Arcidiacono$^{a,c}$, S. Argiro$^{a,b}$, M. Arneodo$^{a,c}$, N. Bartosik$^a$, R. Bellan$^{a,b}$, C. Biino$^a$, N. Cartiglia$^a$, F. Cenna$^{a,b}$, S. Cometti, M. Costa$^{a,b}$, R. Covarelli$^{a,b}$, N. Demaria$^a$, B. Kiani$^{a,b}$, C. Mariotti$^a$, S. Maselli$^a$, E. Migliore$^{a,b}$, V. Monaco$^{a,b}$, E. Monteil$^{a,b}$, M. Monteno$^a$, M.M. Obertino$^{a,b}$, L. Pacher$^{a,b}$, N. Pastrone$^a$, M. Pelliccioni$^a$, G.L. Pinna Angioni$^{a,b}$, A. Romero$^{a,b}$, M. Ruspa$^{a,c}$, R. Sacchi$^{a,b}$, K. Shchelina$^{a,b}$, V. Sola$^a$, A. Solano$^{a,b}$, D. Soldi, A. Staiano$^a$

INFN Sezione di Trieste $^a$, Università di Trieste $^b$, Trieste, Italy  
S. Belforte$^a$, V. Candelise$^{a,b}$, M. Casarsa$^a$, F. Cossutti$^a$, G. Della Ricca$^{a,b}$, F. Vazzoler$^{a,b}$, A. Zanetti$^a$

Kyungpook National University  

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea  
H. Kim, D.H. Moon, G. Oh

Hanyang University, Seoul, Korea  
J. Goh, T.J. Kim

Korea University, Seoul, Korea  

Sejong University, Seoul, Korea  
H.S. Kim

Seoul National University, Seoul, Korea  

University of Seoul, Seoul, Korea  

Sungkyunkwan University, Suwon, Korea  
Y. Choi, C. Hwang, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania  
V. Dudenas, A. Juodagalvis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia  

Universidad de Sonora (UNISON), Hermosillo, Mexico  
A. Castaneda Hernandez, J.A. Murillo Quijada
Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, C. Orosea Barrera, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
A. Morelos Pineda

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
S. Bheesette, P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. Ahmad, M.I. Asghar, Q. Hassan, H.R. Hoorani, A. Saddique, M.A. Shah, M. Shoab, M. Waqas

National Centre for Nuclear Research, Swierk, Poland

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

Laboratório de Instrumentação e Física Experimentál de Partículas, Lisboa, Portugal

Joint Institute for Nuclear Research, Dubna, Russia

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
V. Golovtsov, Y. Ivanov, V. Kim, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lyakhovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepennov, V. Stolin, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia
T. Aushev
National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
R. Chistov, M. Danilov, P. Parygin, D. Philippov, S. Polikarpov, E. Tarkovskii

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, S.V. Rusakov, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin

Novosibirsk State University (NSU), Novosibirsk, Russia
V. Blinov, T. Dimova, L. Kardapoltsev, D. Shtol, Y. Skovpen

State Research Center of Russian Federation, Institute for High Energy Physics of NRC ‘Kurchatov Institute’, Protvino, Russia

National Research Tomsk Polytechnic University, Tomsk, Russia
A. Babaev, S. Baidali

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J.F. de Trocóniz

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
National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom

Rutherford Appleton Laboratory, Didcot, United Kingdom

Imperial College, London, United Kingdom

Brunel University, Uxbridge, United Kingdom
J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, A. Morton, I.D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, USA
K. Call, J. Dittmann, K. Hatakeyama, H. Liu, C. Madrid, B. McMaster, N. Pastika, C. Smith

Catholic University of America, Washington DC, USA
R. Bartek, A. Dominguez

The University of Alabama, Tuscaloosa, USA
A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

Boston University, Boston, USA
D. Arca, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Brown University, Providence, USA

University of California, Davis, Davis, USA

University of California, Los Angeles, USA

University of California, Riverside, Riverside, USA
E. Bouvier, K. Burt, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli,

University of California, San Diego, La Jolla, USA
J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

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
J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, S. Leontsinis, E. MacDonald, T. Mulholland, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, USA

Fermi National Accelerator Laboratory, Batavia, USA

University of Florida, Gainesville, USA

Florida International University, Miami, USA
Y.R. Joshi, S. Linn

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
F. Rebassoo, D. Wright

University of Maryland, College Park, USA

Massachusetts Institute of Technology, Cambridge, USA

University of Minnesota, Minneapolis, USA

University of Mississippi, Oxford, USA
J.G. Acosta, S. Oliveros

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
S. Malik, S. Norberg

Purdue University, West Lafayette, USA

Purdue University Northwest, Hammond, USA
T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, USA

University of Rochester, Rochester, USA

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

University of Tennessee, Knoxville, USA
A.G. Delannoy, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

Texas A&M University, College Station, USA
Texas Tech University, Lubbock, USA

Vanderbilt University, Nashville, USA

University of Virginia, Charlottesville, USA
M.W. Arenton, P. Barria, B. Cox, R. Hirosky, M. Joyce, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, USA

University of Wisconsin - Madison, Madison, WI, USA

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
3: Also at Universidade Estadual de Campinas, Campinas, Brazil
4: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
5: Also at Université Libre de Bruxelles, Bruxelles, Belgium
6: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
7: Also at Joint Institute for Nuclear Research, Dubna, Russia
8: Also at Cairo University, Cairo, Egypt
9: Also at Helwan University, Cairo, Egypt
10: Now at Zewail City of Science and Technology, Zewail, Egypt
11: Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia
12: Also at Université de Haute Alsace, Mulhouse, France
13: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
14: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
15: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
16: Also at University of Hamburg, Hamburg, Germany
17: Also at Brandenburg University of Technology, Cottbus, Germany
18: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
19: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
20: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
21: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
22: Also at Institute of Physics, Bhubaneswar, India
23: Also at Shoolini University, Solan, India
24: Also at University of Visva-Bharati, Santiniketan, India
25: Also at Isfahan University of Technology, Isfahan, Iran
26: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
27: Also at Università degli Studi di Siena, Siena, Italy
28: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
29: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
30: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
31: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
32: Also at Institute for Nuclear Research, Moscow, Russia
33: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
34: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
35: Also at University of Florida, Gainesville, USA
36: Also at P.N. Lebedev Physical Institute, Moscow, Russia
37: Also at California Institute of Technology, Pasadena, USA
38: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
39: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
40: Also at INFN Sezione di Pavia 
41: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
42: Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy
43: Also at National and Kapodistrian University of Athens, Athens, Greece
44: Also at Riga Technical University, Riga, Latvia
45: Also at Universität Zürich, Zurich, Switzerland
46: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
47: Also at Adiyaman University, Adiyaman, Turkey
48: Also at Istanbul Aydin University, Istanbul, Turkey
49: Also at Mersin University, Mersin, Turkey
50: Also at Piri Reis University, Istanbul, Turkey
51: Also at Gaziosmanpasa University, Tokat, Turkey
52: Also at Ozyegin University, Istanbul, Turkey
53: Also at Izmir Institute of Technology, Izmir, Turkey
54: Also at Marmara University, Istanbul, Turkey
55: Also at Kafkas University, Kars, Turkey
56: Also at Istanbul Bilgi University, Istanbul, Turkey
57: Also at Hacettepe University, Ankara, Turkey
58: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
59: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
60: Also at Monash University, Faculty of Science, Clayton, Australia
61: Also at Bethel University, St. Paul, USA
62: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
63: Also at Utah Valley University, Orem, USA
64: Also at Purdue University, West Lafayette, USA
65: Also at Beykent University, Istanbul, Turkey
66: Also at Bingol University, Bingol, Turkey
67: Also at Sinop University, Sinop, Turkey
68: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
69: Also at Texas A&M University at Qatar, Doha, Qatar
70: Also at Kyungpook National University, Daegu, Korea