Search for Higgs boson pair production in events with two bottom quarks and two tau leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Abstract

A search for the production of Higgs boson pairs in proton-proton collisions at a centre-of-mass energy of 13 TeV is presented, using a data sample corresponding to an integrated luminosity of 35.9 fb$^{-1}$ collected with the CMS detector at the LHC. Events with one Higgs boson decaying into two bottom quarks and the other decaying into two $\tau$ leptons are explored to investigate both resonant and nonresonant production mechanisms. The data are found to be consistent, within uncertainties, with the standard model background predictions. For resonant production, upper limits at the 95% confidence level are set on the production cross section for Higgs boson pairs as a function of the hypothesized resonance mass and are interpreted in the context of the minimal supersymmetric standard model. For nonresonant production, upper limits on the production cross section constrain the parameter space for anomalous Higgs boson couplings. The observed (expected) upper limit at 95% confidence level corresponds to about 30 (25) times the prediction of the standard model.

Submitted to Physics Letters B
1 Introduction

The discovery of the Higgs boson (H) by the ATLAS and CMS Collaborations [1–3] was a major step towards improving the understanding of the mechanism of electroweak symmetry breaking (EWSB). With the mass of the Higgs boson now precisely determined [4], the structure of the Higgs scalar field potential and the Higgs boson self-couplings are precisely predicted in the standard model (SM). While the measured properties of the Higgs boson are thus far consistent with the expectations from the SM [3], the measurement of the Higgs boson self-coupling provides an independent test of the SM and verification that the Higgs mechanism is truly responsible for the EWSB by giving access to the shape of the Higgs scalar field potential [6].

The trilinear self-coupling of the Higgs boson (λ_{HHH}) can be extracted from the measurement of the Higgs boson pair (HH) production cross section. In the SM, for proton-proton (pp) collisions at the CERN LHC, this process occurs mainly via gluon-gluon fusion and involves either couplings of the Higgs boson to virtual fermions in a quantum loop, or the λ_{HHH} coupling itself, with the two processes interfering destructively as illustrated in Fig. [1].

The SM prediction for the cross section is σ_{HH} = 33.49\pm 4.3\% (scale) \pm 5.9\% (theo) fb [7]. This value was computed at the next-to-next-to-leading order (NNLO) of the theoretical perturbative quantum chromodynamics (QCD) calculation, including next-to-next-to-leading-logarithm (NNLL) corrections and finite top quark mass effects at next-to-leading order (NLO). The theoretical uncertainties in σ_{HH} include uncertainties in the QCD factorization and renormalization scales, the strong coupling parameter α_s, parton distribution functions (PDF), and unknown effects from the finite top quark mass at NNLO.

Beyond the standard model (BSM) physics effects can appear either via anomalous couplings of the Higgs boson or via new particles that can be directly produced or contribute to the quantum loops responsible for HH production. The experimental signature would be an enhancement of the HH production cross section for a specific value of the invariant mass of the pair (resonant production) or over the whole invariant mass spectrum (nonresonant production).

Resonant double Higgs boson production is predicted by many extensions of the SM such as the singlet model [8–10], the two-Higgs-doublet model [11], the minimal supersymmetric standard model (MSSM) [12, 13], and models with warped extra dimensions (WED) [14, 15]. Although the physics motivation and the phenomenology of these theoretical models are very different, the signal is represented by a CP-even scalar particle (S) decaying into a Higgs boson pair, with an intrinsic width that is often negligible with respect to the detector resolution.

In the nonresonant case, the BSM physics is modelled through an effective Lagrangian that extends the SM Lagrangian with dimension-6 operators [16]. Five Higgs boson couplings result from this parametrization: the Higgs boson coupling to the top quark, γ_t, the trilinear coupling λ_{HHH}, and three additional couplings, denoted as c_2, c_3, and c_4 using the notation in Ref. [7], that represent, respectively, the interactions of a top quark pair with a Higgs boson pair, of a gluon pair with a Higgs boson pair, and of a gluon pair with a single Higgs boson. For simplicity, we investigate only anomalous γ_t and λ_{HHH} couplings, while the other anomalous couplings are assumed to be zero. Extension of these results to any combination of the cou-
plings can be obtained by following the procedure detailed in Ref. [17]. These two couplings are currently largely unconstrained by experimental results, and deviations from the SM can be accommodated by the combined measurements of Higgs boson properties [5] depending on the particular assumptions made about the BSM physics contributions.

Previous searches for the production of Higgs boson pairs were performed by both the ATLAS [18, 19] and CMS [20, 21] Collaborations using the LHC data collected at \( \sqrt{s} = 8 \) and 13 TeV. The most sensitive upper limit at 95% confidence level (CL) on HH production corresponds to 43 times the rate predicted by the SM and is obtained from the combination of the HH \( \to \text{b}\overline{\text{b}}\gamma\gamma \) and HH \( \to \text{b}\overline{\text{b}}\tau^+\tau^- \) decay channels using data collected at \( \sqrt{s} = 8 \) TeV [22].

In this Letter we present a search for Higgs boson pair production in the final state where one Higgs boson decays to \( \text{b}\overline{\text{b}} \) and the other decays to \( \tau^+\tau^- \). For simplicity, we refer to this process as HH \( \to \text{b}\overline{\text{b}}\tau\tau \) in the following, omitting the quark and lepton charges. This process has a combined branching fraction of 7.3% for a Higgs boson mass of 125 GeV. Its sizeable branching fraction, together with the relatively small background contribution from other SM processes, makes this final state one of the most sensitive to HH production. Three final states of the \( \tau \) lepton pair are considered: one of the two \( \tau \) leptons is required to decay into hadrons and a neutrino (\( \tau_h \)), while the other can decay either to the same final state, or into an electron (\( \tau_e \)) or a muon (\( \tau_\mu \)) and neutrinos. Together, these three final states include about 88% of the decays of the \( \tau\tau \) system and are the most sensitive ones for this search. The data sample analyzed corresponds to an integrated luminosity of 35.9 fb\(^{-1} \) collected in pp collisions at \( \sqrt{s} = 13 \) TeV.

### 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 are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), 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 [23]. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than 4 \( \mu s \). The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to less than 1 kHz before data storage. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, including pseudorapidity \( \eta \) and azimuthal angle \( \phi \), can be found in Ref. [24].

### 3 Modelling of physics processes

Simulated samples of resonant and nonresonant HH production via gluon-gluon fusion are generated at leading order (LO) precision with MADGRAPH\textregistered\textsubscript{aMC@NLO} 2.3.2 [25]. In the case of resonant production, separate samples are generated for mass values of the resonance ranging from 250 to 900 GeV. In the case of nonresonant production, separate samples are generated for different values of the effective Lagrangian couplings, including the couplings predicted by the SM [17,26]. In the latter case, an event weight determined as a function of the generated HH pair kinematics is applied to these samples to model signals corresponding to additional points in the effective Lagrangian parametrization.
Backgrounds arising from $Z/\gamma^* \rightarrow \ell\ell$ and $W \rightarrow \ell\nu_{\ell}$ in association with jets (with $\ell = e, \mu, \tau$), diboson (WW, ZZ, and WZ), and SM single Higgs boson production are simulated with MADGRAPH5_AMC@NLO 2.3.2 at LO with MLM merging \cite{27}, while the single top and $t\bar{t}$ backgrounds are simulated at NLO precision with POWHEG 2.0 \cite{28, 29}. The NNPDF3.0 \cite{30} PDF set is used. In order to increase the number of simulated events that satisfy the requirements detailed in Section 4, the inclusive simulation of the $Z/\gamma^*$ and $W$ processes is complemented by samples simulated in selected regions of multiplicity, flavour, and the transverse momentum scalar sum of the partons emitted at the matrix element level. Signal and background generators are interfaced with PYTHIA 8.212 \cite{31} with the tune CUETP8M1 \cite{32} to simulate the multiparton, parton shower, and hadronization effects. The simulated events include multiple overlapping hadron interactions as observed in the data.

The $t\bar{t}$, $Z/\gamma^* \rightarrow \ell\ell$, $W \rightarrow \ell\nu_{\ell}$ and single top quark samples are normalized to their theoretical cross sections at NNLO precision \cite{33, 34}, and the diboson samples are normalized to their cross section at NLO precision \cite{36}. The single Higgs boson production cross section is computed at the NNLO precision of the QCD corrections and at the NLO precision of electroweak corrections \cite{7}.

4 Object reconstruction and event selection

In order to reconstruct an $HH \rightarrow bb\tau\tau$ event, it is necessary to identify the $e, \mu,$ and $\tau$ leptons, the jets originating from the two $b$ quarks, and the missing transverse momentum vector $p_T^{\text{miss}}$, defined as the projection onto the plane perpendicular to the beam axis of the negative vector sum of the momenta of all reconstructed particle-flow objects in an event. Its magnitude is referred to as $p_T^{\text{miss}}$.

The particle-flow (PF) event algorithm \cite{37} reconstructs and identifies each individual particle (PF candidate) with an optimized combination of information from the various elements of the CMS detector. The momentum of the muons is obtained from the curvature of the corresponding track. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex, as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies. Complex objects, such as $\tau$ jets, jets, and the $p_T^{\text{miss}}$ vector are reconstructed from PF candidates. For each event, hadronic jets are clustered from PF candidates with the infrared and collinear safe anti-$k_T$ algorithm \cite{38, 39}, operated with a distance parameter of 0.4 and 0.8. These jets are denoted as “AK4” and “AK8” in the following. The jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found in the simulation to be within 5 to 10% of the true momentum over the whole $p_T$ spectrum and detector acceptance. The invariant mass of AK8 jets is obtained by applying the soft drop jet grooming algorithm \cite{40, 41}, that iteratively decomposes the jet into subjets to remove the soft wide-angle radiation and mitigates the contribution from initial state radiation, underlying event, and multiple hadron scattering. Jet energy corrections are derived from the simulation, and are confirmed with in situ measurements using the energy balance of dijet, multijet, $\gamma$+jet, and leptonic $Z$+jet events \cite{42, 43}. The PF components of the jets are used to reconstruct $\tau$ candidates using the hadrons plus strips algorithm \cite{44, 45}, that combines charged tracks with clusters of photons and electrons to identify the decay mode of
the $\tau$ lepton.

Events in the $bb\tau_{h}$ ($bb\tau_{h}$) final state have been recorded using a set of triggers that require the presence of a single muon (electron) in the event. The selected events are required to contain a reconstructed muon (electron) \([46, 47]\) of $p_T > 23\, (27)\, \text{GeV}$ and $|\eta| < 2.1$ and a reconstructed $\tau_h$ candidate \([44]\) of $p_T > 20\, \text{GeV}$ and $|\eta| < 2.3$. The muon (electron) candidate must satisfy the relative isolation requirement $I_{\text{rel}} < 0.15\, (0.1)$ \([46, 47]\), while the $\tau_h$ candidate must satisfy the “medium” working point of a multivariate isolation discriminant \([44]\), that corresponds to a signal efficiency of about 60% and a jet misidentification rate ranging between 0.1% and 1% depending on the jet $p_T$. The reconstructed tracks associated to the selected electron, muon, and $\tau_h$ candidates must be compatible with the primary pp interaction vertex of the event. Electrons and muons erroneously reconstructed as a $\tau_h$ candidate are rejected using discriminants based on the information from the calorimeters and muon detectors and on the properties of the PF candidates that form the $\tau_h$ candidate, as is detailed in \([44]\).

A trigger requiring the presence of two $\tau_h$ candidates is used to record events in the $bb\tau_h\tau_h$ final state. The selected events must contain two reconstructed $\tau_h$ candidates with $p_T > 45\, \text{GeV}$ and $|\eta| < 2.1$, that are required to pass the “medium” working point of the multivariate isolation discriminant and whose associated tracks must be compatible with the primary pp interaction vertex of the event. The discriminants that suppress the contribution from prompt electrons and muons are applied to both $\tau_h$ candidates as in the $bb\tau_{\mu}\tau_h$, $bb\tau_{e}\tau_h$ final states.

For all three final states, the two selected leptons are required to have opposite electric charge. Events containing additional isolated muons or electrons are rejected to reduce the $Z/\gamma^* \rightarrow \ell\ell$ background contribution.

Events selected with the criteria described above ($\tau_{\mu}\tau_{\mu}$, $\tau_{e}\tau_{\mu}$, $\tau_h\tau_h$) are required to have two additional AK4 jets with $p_T > 20\, \text{GeV}$ and $|\eta| < 2.4$. In the case of HH production via a resonance of mass 700 GeV or higher, the two jets originating from the $H \rightarrow bb$ decay partially overlap due to the high Lorentz boost of the Higgs boson, and are reconstructed at the same time as two separate AK4 jets and as a single AK8 jet. To profit from this information, the event is classified as “boosted” if it contains at least one AK8 jet of invariant mass larger than 30 GeV that is composed of two subjets, each geometrically matched to one of the selected AK4 jets ($\Delta R(\text{AK4, subjet}) < 0.4$, where $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$ denotes the spatial separation of the jet candidates). The event is classified as “resolved” if any of these requirements is not satisfied. This classification provides a clear separation of the signal topology against the $t\bar{t}$ background, where the two jets are typically more spatially separated and not reconstructed as a single AK8 jet. The AK8 jet mass requirement is applied to reject candidates resulting from a single quark or gluon hadronization or poorly reconstructed by the soft drop algorithm.

The combined secondary vertex \([48]\) algorithm is applied to the selected jets to identify those originating from a bottom quark and reduce the contribution from the multijet background where jets are initiated by light quarks or gluon radiation. Both the “medium” and the “loose” working points of the b tagging discriminant \([49]\) are used in this search as described below. The efficiency and rate of erroneous b jet identification are about 60% (80%) and 1% (10%) respectively for the “medium” (“loose”) working point.

Jets reconstructed in events classified as “resolved” are defined as b-tagged if they satisfy the “medium” working point of the b tagging algorithm. These events are classified into two groups according to the number of b-tagged jets: the group with at least two b-tagged jets (2b) has the best sensitivity, and the group with exactly one b-tagged jet (1b1j) increases the signal acceptance. Both AK4 jets previously selected in the events classified as “boosted” are
required to satisfy the “loose” working point of the b tagging discriminant.

5 Signal regions and discriminating observables

After the object selection and event classification, the kinematic information of the event is exploited to reduce the contribution from background processes. The invariant mass of the two $\tau$ lepton candidates, $m_{\tau\tau}$, is reconstructed using a dynamic likelihood technique \cite{50} that combines the kinematics of the two visible lepton candidates and the missing transverse momentum in the event. The $bb$ invariant mass, $m_{bb}$, is estimated from the two selected jet candidates for “resolved” topologies and from the invariant mass of the AK8 jet for “boosted” topologies. In the “resolved” case, the events are required to satisfy the condition:

$$\left(\frac{m_{\tau\tau} - 116\,\text{GeV}}{35\,\text{GeV}}\right)^2 + \left(\frac{m_{bb} - 111\,\text{GeV}}{45\,\text{GeV}}\right)^2 < 1,$$

where the values of 35 and 45 GeV are related to the mass resolution of the $\tau\tau$ and $bb$ systems and 116 and 111 GeV correspond to the position of the expected reconstructed 125 GeV Higgs boson peak in the $m_{\tau\tau}$ and $m_{bb}$ distributions, respectively. The selection has been optimized for a signal efficiency of approximately 80% and a background reduction of about 85% in the most sensitive event categories. The shift with respect to the nominal Higgs boson mass is due to the momentum carried by the neutrinos in the $b$ hadron and tau lepton decays. In the “boosted” case the events are required to satisfy:

$$80 < m_{\tau\tau} < 160\,\text{GeV},$$
$$90 < m_{bb} < 160\,\text{GeV}.$$  

In addition to the previous requirements, a multivariate discriminant is applied to the $\tau_\mu\tau_h$ and $\tau_e\tau_h$ selected events to identify and reject the $t\bar{t}$ process, which is the most important source of background in these two final states. The discriminant is built using the boosted decision tree (BDT) \cite{51,52} algorithm that is trained on a set of simulated signal and background events to identify the kinematic differences between the two processes and assigns to every selected event a number that defines its compatibility with a signal or background topology. Two separate BDT trainings are performed to achieve an optimal performance for all the signal processes studied.

One training is performed using resonant signals with masses $m_S \leq 350$ GeV as input. Eight variables are used in the discriminant training because of their good separation between signal and background: $\Delta\phi(H_{bb}, H_{\tau\tau})$, $\Delta\phi(H_{\tau\tau}, p_T^{\text{miss}})$, $\Delta\phi(H_{bb}, p_T^{\text{miss}})$, $\Delta R(b, b)$, $p_T(H_{bb})$, $\Delta R(\ell, \tau_h) p_T(H_{\tau\tau})$, $m_T(\ell)$, and $m_T(\tau_h)$. Here $\ell$ refers to the selected muon or electron, $H_{bb}$ and $H_{\tau\tau}$ denote the H boson candidates reconstructed from the two jets and the two leptons, respectively, and $m_T(\ell) = \sqrt{(p_T^\ell + p_T^{\text{miss}})^2 - (p_T^\ell - p_T^{\text{miss}})^2}$ denotes the transverse mass of the selected lepton candidate, with a similar definition for $m_T(\tau_h)$. The $\Delta R$ separations of the two $b$ quarks and of the two tau leptons are multiplied by the $H_{bb}$ and $H_{\tau\tau}$ candidate $p_T$ respectively to reduce their dependence on the $m_S$ hypothesis. The same training is used both for the search for resonant HH production up to $m_S = 350$ GeV and for the search for nonresonant HH production. No loss of performance is observed by using this training in comparison to a dedicated training on nonresonant signals. Different selections on the BDT discriminant output are applied in the two searches to maximize the sensitivity: these selections correspond to a rejection of the $t\bar{t}$ background of approximately 90 and 70% for the resonant and nonresonant searches, respectively, for a signal efficiency ranging between 65 and 95% depending on the signal hypothesis considered.
A second training is performed on the resonant signals of mass $m_S > 350$ GeV. The variables used as inputs to this training are the same as in the previous case, but replacing $\Delta R(b, b) \ p_T(H_{bb})$ and $\Delta R(\ell, \tau) \ p_T(H_{\tau\tau})$ with $\Delta R(b, b)$ and $\Delta R(\ell, \tau)$. The selection on the BDT output is chosen to maximize the sensitivity and corresponds to a rejection of the $t \bar{t}$ background of approximately 90% for a signal efficiency ranging between 70 and 95% depending on the value of $m_S$. In the case of the resonant search, the selections applied to the two BDT discriminants define low-mass (LM) and high-mass (HM) signal regions.

In the resonant search, the invariant mass of the two visible $\tau$ lepton decay products and the two selected $b$ jets is used to search for a possible signal above the expected background event distribution. In order to improve the resolution and to enhance the sensitivity of the analysis, the invariant mass is reconstructed using a kinematic fit ($m_{TH}^{\text{KinFit}}$) that is detailed in Ref. [53]. The fit is based on the four-momenta of the $\tau$ and $b$ candidates and on the $p_T^{\text{miss}}$ vector in the event, and is performed under the hypothesis of two 125 GeV Higgs bosons decaying into a bottom quark pair and a $\tau$ lepton pair. The use of the kinematic fit improves the resolution on $m_{TH}$ by about a factor of two compared to the four-body invariant mass of the reconstructed leptons and jets.

The transverse mass or $m_{T^2}$ variable is used in the search for a nonresonant signal. This variable, originally introduced for supersymmetry searches involving invisible particles in the final state [54, 55] and later proposed for HH searches in $bbWW$ events [56], is used to reconstruct events where two equal mass particles are produced and each undergoes a two-body decay into a visible and an invisible particle. The $m_{T^2}$ variable is defined as the largest mass of the parent particle that is compatible with the kinematic constraints of the event. In the case of the $bbWW$ decay, where the dominant background is $t \bar{t}$ production, the parent particle is interpreted as the top quark that decays into a bottom quark and a $W$ boson. Following the description in Ref. [56], we denote with $\vec{b}, \vec{b}'$ the momenta of the two selected $b$ jets and with $m_b, m_{b'}$ their invariant masses, and we introduce the $\vec{c}, \vec{c}'$ symbols to denote the momenta of the other particles produced in the top quark decay corresponding to the measured leptons and the neutrinos. We also set $m_c = m^{\text{vis}}(\tau_1)$ and $m_{c'} = m^{\text{vis}}(\tau_2)$, where $m^{\text{vis}}$ denotes the invariant mass of the measured leptons or $\tau_3$. Under this notation, $m_{T^2}$ is defined as:

$$m_{T^2}(m_b, m_{b'}, \vec{b}_T, \vec{b}'_T, \vec{p}_T^{\Sigma}, m_c, m_{c'}) = \min_{\vec{c}_T, \vec{c}'_T = \vec{p}_T^{\Sigma}} \left\{ \max (m_T, m'_T) \right\},$$

where the constraint in the minimization is over the measured lepton momenta and the missing transverse momentum, i.e. $\vec{p}_T^{\Sigma} = \vec{p}_T^{\text{vis}}(\tau_1) + \vec{p}_T^{\text{vis}}(\tau_2) + \vec{p}_T^{\text{miss}}$. In Eq. (3), the transverse mass $m_T$ is defined as

$$m_T(\vec{b}_T, \vec{c}_T, m_b, m_c) = \sqrt{m_b^2 + m_c^2 + 2 \left( e_b e_c - \vec{b}_T \cdot \vec{c}_T \right)},$$

and the “transverse energy” $e$ of a particle of transverse momentum $p_T$ and mass $m$ is defined as

$$e = \sqrt{m^2 + p_T^2}.$$  

We use the implementation in Ref. [57] to perform the minimization of Eq. (3).

The $m_{T^2}$ variable has a large discriminating power between the HH signal and the $t \bar{t}$ background, as it is bounded above by the top quark mass $m_t$ for the irreducible background process $t \bar{t} \rightarrow bbWW \rightarrow bb \tau_1 \nu_1 \tau_2 \nu_2$, while it can assume larger values for the HH signal where the tau and the b jet do not originate from the same parent particle. Detector resolution effects and other decay modes of the $t \bar{t}$ system (e.g. jets from the $W$ boson misidentified as $\tau_3$) result in an extension of the tail of the $m_{T^2}$ distribution in $t \bar{t}$ events beyond the $m_t$ value.
6 Background estimation

The main background sources that contaminate the signal region are $t\bar{t}$ production, $Z/\gamma^* \to \ell\ell$ production and QCD multijet events.

The backgrounds from $t\bar{t}$, single top, single Higgs boson, $W$ boson in association with jets, and diboson processes are estimated from simulation, as described in Section 3.

The $Z/\gamma^* \to \ell\ell$ background contribution is estimated using the simulation, where the LO modeling of jet emission in the $Z/\gamma^*$ process is known to be imperfect [58]. Therefore, correction factors are calculated using events containing two isolated, opposite-sign muons compatible with the $Z \to \mu\mu$ decay in association with two jets that satisfy similar invariant mass criteria as in the signal region. This Z+2 jets sample is divided into three control regions according to the number of $b$-tagged jets (0, 1, and 2) and three correction factors are derived for the $Z/\gamma^*$ production in association with 0, 1, or $\geq 2$ generator level jets initiated by $b$ quarks, and applied in the signal regions.

The multijet background is determined from data in a jet-enriched region defined by requiring that the two selected lepton candidates have the same electric charge. The yield is obtained from this same-sign (SS) region, where all the other selections are applied as in the signal region. The events in this region are scaled by the ratio of opposite-sign (OS) to SS event yields obtained in a multijet-enriched region with inverted $\tau$ lepton isolation. The contributions of other backgrounds, based on predictions from simulated samples, are subtracted in the OS and SS regions. The shape of the multijet background is estimated using the events in an SS region with relaxed $\tau$ lepton isolation, after subtracting the other background contributions.

7 Systematic uncertainties

The effects of an imperfect knowledge of the detector response, discrepancies between simulation and data, and limited knowledge of the background and signal processes are accounted for in the analysis as systematic uncertainties. They are separately treated as “normalization” uncertainties or “shape” uncertainties; the first affect the number of expected events in the signal region, while the second affect their distributions.

7.1 Normalization uncertainties

The following normalization uncertainties are considered:

- The integrated luminosity is known with an uncertainty of 2.5% [59]. This value is obtained from dedicated Van der Meer scans and the stability of detector response during the data taking. The uncertainty is applied to the signal and to $t\bar{t}$, $W$+jets, single top quark, single Higgs boson, and diboson backgrounds, but it is not applied to the multijet and $Z$+jets backgrounds because they are estimated or corrected from data.

- Electron, muon, and $\tau$ lepton trigger, reconstruction and identification efficiencies are measured using $Z \to e\epsilon$, $Z \to \mu\mu$, and $Z \to \tau\tau \to \tau_h \nu\bar{\nu}_\ell \nu\bar{\nu}_\ell \nu\bar{\nu}_\tau$ events collected at $\sqrt{s} = 13$ TeV. The corresponding uncertainties are considered as uncorrelated among the final states and are about 3% for electrons, 2% for muons, and 6% for $\tau$ leptons.

- The uncertainty in the knowledge of the $\tau_h$ energy scale is about 3% for each $\tau_h$ candidate [45], and its impact on the overall normalization ranges from 3 to 10%
7 Systematic uncertainties

Table 1: Systematic uncertainties affecting the normalization of the different processes.

| Systematic uncertainty                  | Value       | Processes                        |
|----------------------------------------|-------------|----------------------------------|
| Luminosity                            | 2.5%        | all but multijet, $Z/\gamma^* \rightarrow \ell\ell$ |
| Lepton trigger and reconstruction      | 2–6%        | all but multijet                 |
| $\tau$ energy scale                   | 3–10%       | all but multijet                 |
| Jet energy scale                       | 2–4%        | all but multijet                 |
| $b$ tag efficiency                     | 2–6%        | all but multijet                 |
| Background cross section               | 1–10%       | all but multijet, $Z/\gamma^* \rightarrow \ell\ell$ |
| $Z/\gamma^* \rightarrow \ell\ell$ SF uncertainty | 0.1–2.5%    | $Z/\gamma^* \rightarrow \ell\ell$ |
| Multijet normalization                 | 5–30%       | multijet                         |
| Scale unc.                             | +4.3%/-6.0% | signals                          |
| Theory unc.                            | 5.9%        | signals                          |

depending on the process being considered. This effect is fully correlated with a corresponding shape uncertainty in the distribution of $m_{T2}$ and $m_{\text{KinFit}}$.

- Uncertainties arising from the imperfect knowledge of the jet and $b$ jet measured energy [42] have an impact of about 2% for the signal processes and 4% for the backgrounds.

- Uncertainties in the $b$ tagging efficiency in the simulation are evaluated as functions of jet $p_T$ and $\eta$ [49] and result in an average value of 2 to 6% for the samples with genuine $b$ jets in the final state.

- For the $t\bar{t}$, $W$+jets, single top quark, single Higgs boson, and diboson backgrounds, uncertainties in the cross sections of the processes considered range from 1 to 10%.

- The uncertainties in the three correction factors derived in the control regions with 0, 1, and 2 $b$-tagged jets for the $Z/\gamma^* \rightarrow \ell\ell$ background are propagated from the control regions to the signal region, taking into account the correlation between them, and amount to an uncertainty in the range 0.1–2.5%.

- The uncertainty in the multijet background normalization is estimated by propagating the statistical uncertainties in the number of events used for its determination in the region with the sign requirement inverted, as described in Section 6, and ranges between 5 and 30% depending on the final state and category.

- The uncertainties in the signal cross section arising from scale variations result in an uncertainty in its normalization of $+4.3%/-6.0%$ while effects from other theoretical uncertainties such as uncertainties on $\alpha_s$, PDFs and finite top quark mass effects at NNLO amount to a further 5.9% uncertainty [7].

The systematic uncertainties are summarized in Table 1.

7.2 Shape uncertainties

The following shape uncertainties are considered:

- The shape uncertainty affecting the kinematic distribution in the simulation of the $t\bar{t}$ background is estimated by varying the top quark $p_T$ distribution according to the uncertainties in differential $p_T$ measurements described in Ref. [60].

- Uncertainties due to the limited number of simulated events or due to the statistical fluctuations of events in the multijet control region are taken into account. These uncertainties are uncorrelated across bins in the individual template shapes.
• Uncertainties due to the $\tau_h$ and jet energy scales are taken into account and are fully correlated with the associated normalization uncertainties. Uncertainties in the energy scales for other objects have negligible impacts on the simulated event distributions and are not taken into account.

8 Results

Figures 2, 3, and 4 show the distributions of the $m_{\text{KinFit}}^{HH}$ and $m_{T2}$ variables in the $\tau\mu\tau\nu$, $\tau\tau\tau\nu$, and $\tau\nu\tau\nu$ final states, respectively. The expected signature of resonant HH production is a localized excess in the $m_{\text{KinFit}}^{HH}$ distribution, while an enhancement in the tails of the $m_{T2}$ distribution would reveal the presence of nonresonant HH production. A binned maximum likelihood fit is performed simultaneously in the signal regions defined in this search for the three final states considered. The systematic uncertainties discussed previously in Section 7 are introduced as nuisance parameters in the maximum likelihood fit. In the absence of evidence for a signal, we set 95% CL upper limits on the cross section for Higgs boson pair production using the asymptotic modified frequentist method (asymptotic CL$_s$) [61, 62].

For the resonant production mode, limits are set as a function of the mass of the resonance $m_S$ under the hypothesis that its intrinsic width is negligible compared to the experimental resolution. The observed and expected 95% CL limits are shown in Fig. 5, upper panel. The figure also shows the expectation for radion production, a spin-0 state predicted in WED models, for the parameters $\Lambda_R = 3$ TeV (mass scale) and $k_L = 35$ (size of the extra dimension), and assuming the absence of mixing with the Higgs boson. The corresponding cross section and branching fractions are taken from [63]. These model-independent limits are also interpreted in the hMSSM scenario [64, 65], that is a parametrization of the MSSM that considers the observed 125 GeV Higgs boson as the lighter scalar predicted from the model (usually denoted as h in the context of the model), while the resonance of mass $m_S$ represents the heavier CP-even scalar (usually denoted as H in the context of the model). Excluded regions as a function of the $m_A$ and $\tan\beta$ parameters, representing respectively the mass of the CP-odd scalar and the ratio of the vacuum expectation values of the two Higgs doublets of the model, are shown in Fig. 5, lower panel. The minimum of the sensitivity around $m_S = 270$ GeV results in the presence of two separate expected excluded regions in this interpretation.

For the nonresonant production mode, including the theoretical uncertainties, the observed 95% CL upper limit on the HH production cross section times branching fraction amounts to 75.4 fb while the expected 95% CL upper limit amounts to 61.0 fb. These values correspond to about 30 and 25 times the SM prediction, respectively. Limits are set for different hypotheses of anomalous self-coupling and top quark coupling of the Higgs boson. The deviations from the SM couplings are parametrized using the coefficients $k_\lambda = \lambda_{HHH}/\lambda_{HHH}^{\text{SM}}$ and $k_t = y_t/y_t^{\text{SM}}$. The signal kinematics depend on the ratio of the two couplings and 95% CL upper limits are set as a function of $k_\lambda/k_t$, assuming the other BSM couplings to be zero. The result is shown in Fig. 6, upper panel, and the exclusion is compared with the theoretical prediction for the cross section for $k_t = 1$ and $k_t = 2$. The sensitivity varies as a function of $k_\lambda$ and $k_t$ because of the corresponding changes in the signal $m_{T2}$ distribution. These upper limits are used to set constraints on anomalous $k_\lambda$ and $k_t$ couplings as shown in Fig. 6, lower panel, where the $c_2$, $c_2g$, and $c_g$ couplings are assumed to be equal to zero. The branching fractions for the decays of the Higgs boson into a $b\bar{b}$ and $\tau\tau$ pair are assumed to be those predicted by the SM for all the values of $k_\lambda$ and $k_t$ tested.
Figure 2: Distributions of the events observed in the signal regions of the $\tau\mu\tau$ final state. The first, second, and third rows show the resolved 1b1j, 2b, and boosted regions, respectively. Panels in the right column show the distribution of the $mT_2$ variable, while the other panels show the distribution of the $m^{\text{KinFit}}_H$ variable, separated in the low-mass (LM, left panels) and high-mass (HM, central panels) regions for the resolved event categories. Data are represented by points with error bars and expected signal contributions are represented by the solid (BSM HH signals) and dashed (SM nonresonant HH signal) lines. Expected background contributions (shaded histograms) and associated systematic uncertainties (dashed areas) are shown as obtained after the maximum likelihood fit to the data under the background-only hypothesis. The background histograms are stacked while the signal histograms are not stacked.
Figure 3: Distributions of the events observed in the signal regions of the $\tau_+\tau_-$ final state. The first, second, and third rows show the resolved 1b1j, 2b, and boosted regions, respectively. Panels in the right column show the distribution of the $m_{T2}$ variable, while the other panels show the distribution of the $m^\text{KinFit}_{HH}$ variable, separated in the low-mass (LM, left panels) and high-mass (HM, central panels) regions for the resolved event categories. Data are represented by points with error bars and expected signal contributions are represented by the solid (BSM HH signals) and dashed (SM nonresonant HH signal) lines. Data are represented by points with error bars and expected signal contributions are represented by the solid (BSM HH signals) and dashed (SM nonresonant HH signal) lines. Expected background contributions (shaded histograms) and associated systematic uncertainties (dashed areas) are shown as obtained after the maximum likelihood fit to the data under the background-only hypothesis. The background histograms are stacked while the signal histograms are not stacked.
Figure 4: Distributions of the events observed in the signal regions of the $\tau_1 \tau_2$ final state. The first, second, and third rows show the resolved 1b1j, 2b, and boosted regions, respectively. Panels in the left column show the distribution of the $m_{T2}^{\text{KinFit}}$ variable and panels in the right column show the distribution of the $m_{T2}$ variable. Data are represented by points with error bars and expected signal contributions are represented by the solid (BSM HH signals) and dashed (SM nonresonant HH signal) lines. Expected background contributions (shaded histograms) and associated systematic uncertainties (dashed areas) are shown as obtained after the maximum likelihood fit to the data under the background-only hypothesis. The background histograms are stacked while the signal histograms are not stacked.
Figure 5: (upper) Observed and expected 95% CL upper limits on cross section times branching fraction as a function of the mass of the resonance $m_S$ under the hypothesis that its intrinsic width is negligible with respect to the experimental resolution. 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 red line denotes the expectation for the production of a radion, a spin-0 state predicted in WED models, for the parameters $\Lambda_R = 3$ TeV (mass scale) and $kL = 35$ (size of the extra dimension), assuming the absence of mixing with the Higgs boson. (lower) Interpretation of the exclusion limit in the context of the hMSSM model, parametrized as a function of the $\tan\beta$ and $m_A$ parameters. In this model, the CP-even lighter scalar is assumed to be the observed 125 GeV Higgs boson and is denoted as $h$, while the CP-even heavier scalar is denoted as $H$ and the CP-odd scalar is denoted as $A$. The dotted lines indicate trajectories in the plane corresponding to equal values of the mass of the CP-even heavier scalar of the model, $m_H$. 
Figure 6: (upper) Observed and expected 95% CL upper limits on cross section times branching fraction as a function of $k_{\lambda} / k_t$. 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 two red bands show the theoretical cross section expectations and the corresponding uncertainties for $k_t = 1$ and $k_t = 2$. (lower) Test of $k_{\lambda}$ and $k_t$ anomalous couplings. The blue region denotes the parameters excluded by the data at 95% CL, while the dashed black line and the grey regions denote the expected exclusions and the $1\sigma$ and $2\sigma$ bands. The dotted lines indicate trajectories in the plane with equal values of cross section times branching fraction that are displayed in the associated labels. The diamond-shaped symbol denotes the couplings predicted by the SM. The theory predictions and the expected and observed limits are symmetric through a $(k_{\lambda}, k_t) \leftrightarrow (-k_{\lambda}, -k_t)$ transformation. In both figures, the couplings that are not explicitly tested are assumed to correspond to the SM prediction.
9 Summary

A search for resonant and nonresonant Higgs boson pair (HH) production in the $b\tau\bar{\tau}$ final state is presented. This search uses a data sample collected in proton-proton collisions at $\sqrt{s} = 13$ TeV that corresponds to an integrated luminosity of 35.9 fb$^{-1}$. The three most sensitive decay channels of the $\tau$ lepton pair, requiring the decay of one or both $\tau$ leptons into final-state hadrons and a neutrino, are used. The results are found to be statistically compatible with the expected standard model (SM) background contribution, and upper limits at the 95% confidence level are set on the HH production cross sections.

For the resonant production mechanism, upper exclusion limits at 95% confidence level (CL) are obtained for the production of a narrow resonance of mass $m_S$ ranging from 250 to 900 GeV. These model-independent results are interpreted in the context of the hMSSM scenario, where a region in the parameter space corresponding to values of $m_A$ between 230 and 360 GeV and $\tan\beta \lesssim 2$ is excluded at 95% CL.

For the nonresonant production mechanism, the theoretical framework of an effective Lagrangian is used to parametrize the cross section as a function of anomalous couplings of the Higgs boson. Upper limits at 95% CL on the HH cross section are obtained as a function of $k_3 = \lambda_{HHH}/\lambda_{HHH}^{SM}$ and $k_1 = y_t/y_t^{SM}$. The observed 95% CL upper limit corresponds to approximately 30 times the theoretical prediction for the SM cross section, and the expected limit is about 25 times the SM prediction. This is the highest sensitivity achieved so far for SM HH production at the LHC.

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 centres 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 programme 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 Formation à la Recherche dans l’Industrie et dans l’Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Tech-
nologie (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 programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus programme 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 programmes 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 C-1845.

References

[1] ATLAS Collaboration, “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC”, *Phys. Lett. B* 716 (2012) 1, doi:10.1016/j.physletb.2012.08.020 [arXiv:1207.7214].

[2] CMS Collaboration, “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC”, *Phys. Lett. B* 716 (2012) 30, doi:10.1016/j.physletb.2012.08.021 [arXiv:1207.7235].

[3] CMS Collaboration, “Observation of a new boson with mass near 125 GeV in pp collisions at $\sqrt{s} = 7$ and 8 TeV”, *JHEP* 06 (2013) 081, doi:10.1007/JHEP06(2013)081 [arXiv:1303.4571].

[4] ATLAS and CMS Collaborations, “Combined measurement of the Higgs boson mass in pp collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS experiments”, *Phys. Rev. Lett.* 114 (2015) 191803, doi:10.1103/PhysRevLett.114.191803 [arXiv:1503.07589].

[5] ATLAS and CMS Collaborations, “Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s} = 7$ and 8 TeV”, *JHEP* 08 (2016) 045, doi:10.1007/JHEP08(2016)045 [arXiv:1606.02266].

[6] J. Baglio et al., “The measurement of the Higgs self-coupling at the LHC: theoretical status”, *JHEP* 04 (2013) 151, doi:10.1007/JHEP04(2013)151 [arXiv:1212.5581].

[7] D. de Florian et al., “Handbook of LHC Higgs cross sections: 4. deciphering the nature of the Higgs sector”, CERN Report CERN-2017-002-M, 2016. doi:10.23731/CYRM-2017-002 [arXiv:1610.07922].

[8] T. Binoth and J. J. van der Bij, “Influence of strongly coupled, hidden scalars on Higgs signals”, *Z. Phys. C* 75 (1997) 17, doi:10.1007/s002880050442 [arXiv:hep-ph/9608245].

[9] R. M. Schabinger and J. D. Wells, “Minimal spontaneously broken hidden sector and its impact on Higgs boson physics at the CERN Large Hadron Collider”, *Phys. Rev. D* 72 (2005) 093007, doi:10.1103/PhysRevD.72.093007 [arXiv:hep-ph/0509209].

[10] B. Patt and F. Wilczek, “Higgs-field portal into hidden sectors”, (2006). [arXiv:hep-ph/0605188].
[11] G. C. Branco et al., “Theory and phenomenology of two-Higgs-doublet models”, Phys. Rept. 516 (2012) 1, doi:10.1016/j.physrep.2012.02.002, arXiv:1106.0034.

[12] P. Fayet, “Supergauge invariant extension of the Higgs mechanism and a model for the electron and its neutrino”, Nucl. Phys. B 90 (1975) 104, doi:10.1016/0550-3213(75)90636-7.

[13] P. Fayet, “Spontaneously broken supersymmetric theories of weak, electromagnetic and strong interactions”, Phys. Lett. B 69 (1977) 489, doi:10.1016/0370-2693(77)90852-8.

[14] K. Agashe, H. Davoudiasl, G. Perez, and A. Soni, “Warped gravitons at the CERN LHC and beyond”, Phys. Rev. D 76 (2007) 036006, doi:10.1103/PhysRevD.76.036006, arXiv:hep-ph/0701186.

[15] A. L. Fitzpatrick, J. Kaplan, L. Randall, and L.-T. Wang, “Searching for the Kaluza-Klein graviton in bulk RS models”, JHEP 09 (2007) 013, doi:10.1088/1126-6708/2007/09/013, arXiv:hep-ph/0701150.

[16] F. Goertz, A. Papaefstathiou, L. L. Yang, and J. Zurita, “Higgs boson pair production in the D=6 extension of the SM”, JHEP 04 (2015) 167, doi:10.1007/JHEP04(2015)167, arXiv:1410.3471.

[17] A. Carvalho et al., “Higgs pair production: choosing benchmarks with cluster analysis”, JHEP 04 (2016) 126, doi:10.1007/JHEP04(2016)126, arXiv:1507.02245.

[18] ATLAS Collaboration, “Searches for Higgs boson pair production in the $lh \rightarrow b\bar{b}\tau\tau$, $\gamma\gamma WW$, $\gamma\gamma bb$, $bbbb$ channels with the ATLAS detector”, Phys. Rev. D 92 (2015) 092004, doi:10.1103/PhysRevD.92.092004, arXiv:1509.04670.

[19] ATLAS Collaboration, “Search for pair production of Higgs bosons in the $b\bar{b}b\bar{b}$ final state using proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, Phys. Rev. D 94 (2016) 052002, doi:10.1103/PhysRevD.94.052002, arXiv:1606.04782.

[20] CMS Collaboration, “Search for two Higgs bosons in final states containing two photons and two bottom quarks in proton-proton collisions at 8 TeV”, Phys. Rev. D 94 (2016) 052012, doi:10.1103/PhysRevD.94.052012, arXiv:1603.06896.

[21] CMS Collaboration, “Search for resonant pair production of Higgs bosons decaying to two bottom quark-antiquark pairs in proton-proton collisions at 8 TeV”, Phys. Lett. B 749 (2015) 560, doi:10.1016/j.physletb.2015.08.047, arXiv:1503.04114.

[22] CMS Collaboration, “A search for Higgs boson pair production in the $b\tau\tau$ final state in proton-proton collisions at $\sqrt{s} = 8$ TeV”, (2017), arXiv:1707.00350. Submitted to Phys. Rev. D.

[23] CMS Collaboration, “The CMS trigger system”, JINST 12 (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.

[24] CMS Collaboration, “The CMS experiment at the CERN LHC”, JINST 3 (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[25] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, JHEP 07 (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.
[26] A. Carvalho et al., “Analytical parametrization and shape classification of anomalous HH production in the EFT approach”, (2016). arXiv:1608.06578.

[27] J. Alwall et al., “Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions”, Eur. Phys. J. C 53 (2008) 473, doi:10.1140/epjc/s10052-007-0490-5 arXiv:0706.2569.

[28] E. Re, “Single-top $Wt$-channel production matched with parton showers using the POWHEG method”, Eur. Phys. J. C 71 (2011) 1547, doi:10.1140/epjc/s10052-011-1547-z arXiv:1009.2450.

[29] J. M. Campbell, R. K. Ellis, P. Nason, and E. Re, “Top-pair production and decay at NLO matched with parton showers”, JHEP 04 (2015) 114, doi:10.1007/JHEP04(2015)114 arXiv:1412.1828.

[30] NNPDF Collaboration, “Parton distributions for the LHC Run II”, JHEP 04 (2015) 040, doi:10.1007/JHEP04(2015)040 arXiv:1410.8849.

[31] T. Sjöstrand et al., “An introduction to PYTHIA 8.2”, Comput. Phys. Commun. 191 (2015) 159, doi:10.1016/j.cpc.2015.01.024 arXiv:1410.3012.

[32] CMS Collaboration, “Event generator tunes obtained from underlying event and multiparton scattering measurements”, Eur. Phys. J. C 76 (2016) 155, doi:10.1140/epjc/s10052-016-3988-x arXiv:1512.00815.

[33] M. Czakon and A. Mitov, “Top++: A Program for the Calculation of the Top-Pair Cross-Section at Hadron Colliders”, Comput. Phys. Commun. 185 (2014) 2930, doi:10.1016/j.cpc.2014.06.021 arXiv:1112.5675.

[34] Y. Li and F. Petriello, “Combining QCD and electroweak corrections to dilepton production in FEWZ”, Phys. Rev. D 86 (2012) 094034, doi:10.1103/PhysRevD.86.094034 arXiv:1208.5967.

[35] N. Kidonakis, “Top quark production”, in Proceedings, Helmholtz International Summer School on Physics of Heavy Quarks and Hadrons (HQ 2013), p. 139. JINR, Dubna, Russia, July, 2014. arXiv:1311.0283 doi:10.3204/DESY-PROC-2013-03/Kidonakis.

[36] J. M. Campbell, R. K. Ellis, and C. Williams, “Vector boson pair production at the LHC”, JHEP 07 (2011) 018, doi:10.1007/JHEP07(2011)018 arXiv:1105.0020.

[37] CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, (2017). arXiv:1706.04965 Submitted to JINST.

[38] M. Cacciari, G. P. Salam, and G. Soyez, “The anti-$k_t$ jet clustering algorithm”, JHEP 04 (2008) 063, doi:10.1088/1126-6708/2008/04/063 arXiv:0802.1189.

[39] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet user manual”, Eur. Phys. J. C 72 (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2 arXiv:1111.6097.

[40] J. M. Butterworth, A. R. Davison, M. Rubin, and G. P. Salam, “Jet substructure as a new Higgs-search channel at the Large Hadron Collider”, Phys. Rev. Lett. 100 (2008) 242001, doi:10.1103/PhysRevLett.100.242001 arXiv:0802.2470.

[41] A. J. Larkoski, S. Marzani, G. Soyez, and J. Thaler, “Soft drop”, JHEP 05 (2014) 146, doi:10.1007/JHEP05(2014)146 arXiv:1402.2657.
References

[42] CMS Collaboration, “Determination of jet energy calibration and transverse momentum resolution in CMS”, JINST 6 (2011) P11002, doi:10.1088/1748-0221/6/11/P11002, arXiv:1107.4277.

[43] CMS Collaboration, “Performance of missing energy reconstruction in 13 TeV pp collision data using the CMS detector”, CMS Physics Analysis Summary CMS-PAS-JME-16-004, CERN, 2016.

[44] CMS Collaboration, “Reconstruction and identification of $\tau$ lepton decays to hadrons and $\nu_{\tau}$ at CMS”, JINST 11 (2016) P01019, doi:10.1088/1748-0221/11/01/P01019, arXiv:1510.07488.

[45] CMS Collaboration, “Performance of reconstruction and identification of tau leptons in their decays to hadrons and tau neutrino in LHC Run-2”, CMS Physics Analysis Summary CMS-PAS-TAU-16-002, CERN, 2016.

[46] CMS Collaboration, “Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV”, JINST 10 (2015) P06005, doi:10.1088/1748-0221/10/06/P06005, arXiv:1502.02701.

[47] CMS Collaboration, “Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV”, JINST 7 (2012) P10002, doi:10.1088/1748-0221/7/10/P10002, arXiv:1206.4071.

[48] CMS Collaboration, “Identification of b-quark jets with the CMS experiment”, JINST 8 (2013) P04013, doi:10.1088/1748-0221/8/04/P04013, arXiv:1211.4462.

[49] CMS Collaboration, “Identification of b quark jets at the CMS Experiment in the LHC Run 2”, CMS Physics Analysis Summary CMS-PAS-BTV-15-001, CERN, 2016.

[50] L. Bianchini, J. Conway, E. K. Friis, and C. Veelken, “Reconstruction of the Higgs mass in $H \to \tau\tau$ events by dynamical likelihood techniques”, in Proceedings, 20th International Conference on Computing in High Energy and Nuclear Physics (CHEP 2013), p. 022035. Amsterdam, the Netherlands, October, 2014. J. Phys. Conf. Ser. 513 (2014) 022035. doi:10.1088/1742-6596/513/2/022035.

[51] H. Voss, A. Hocker, J. Stelzer, and F. Tegenfeldt, “TMVA, the toolkit for multivariate data analysis with ROOT”, in XIth International Workshop on Advanced Computing and Analysis Techniques in Physics Research (ACAT), p. 40. 2007. arXiv:physics/0703039.

[52] J. H. Friedman, “Greedy function approximation: A gradient boosting machine”, Ann. Statist. 29 (2001) 1189, doi:10.1214/aos/1013203451.

[53] CMS Collaboration, “Searches for a heavy scalar boson H decaying to a pair of 125 GeV Higgs bosons hh or for a heavy pseudoscalar boson A decaying to ZH, in the final states with $h \to \tau\tau$”, Phys. Lett. B 755 (2016) 217, doi:10.1016/j.physletb.2016.01.056, arXiv:1510.01181.

[54] C. G. Lester and D. J. Summers, “Measuring masses of semi invisibly decaying particles pair produced at hadron colliders”, Phys. Lett. B 463 (1999) 99, doi:10.1016/S0370-2693(99)00945-4, arXiv:hep-ph/9906349.

[55] A. Barr, C. Lester, and P. Stephens, “A variable for measuring masses at hadron colliders when missing energy is expected; $m_{\text{PD}}$: the truth behind the glamour”, J. Phys. G 29 (2003) 2343, doi:10.1088/0954-3899/29/10/304, arXiv:hep-ph/0304226.
References

[56] A. J. Barr, M. J. Dolan, C. Englert, and M. Spannowsky, “Di-Higgs final states augMT2ed – selecting \(lh\) events at the high luminosity LHC”, *Phys. Lett. B* 728 (2014) 308, doi:10.1016/j.physletb.2013.12.011, arXiv:1309.6318.

[57] C. G. Lester and B. Nachman, “Bisection-based asymmetric MT2 computation: a higher precision calculator than existing symmetric methods”, *JHEP* 03 (2015) 100, doi:10.1007/JHEP03(2015)100, arXiv:1411.4312.

[58] CMS Collaboration, “Measurements of differential production cross sections for a Z boson in association with jets in pp collisions at \(\sqrt{s} = 8\) TeV”, *JHEP* 04 (2017) 022, doi:10.1007/JHEP04(2017)022, arXiv:1611.03844.

[59] CMS Collaboration, “CMS luminosity measurements for the 2016 data taking period”, CMS Physics Analysis Summary CMS-PAS-LUM-17-001, CERN, 2017.

[60] CMS Collaboration, “Measurement of differential cross sections for top quark pair production using the lepton+jets final state in proton-proton collisions at 13 TeV”, *Phys. Rev. D* 95 (2017) 092001, doi:10.1103/PhysRevD.95.092001, arXiv:1610.04191.

[61] T. Junk, “Confidence level computation for combining searches with small statistics”, *Nucl. Instrum. Meth. A* 434 (1999) 435, doi:10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.

[62] A. L. Read, “Presentation of search results: the \(CL_s\) technique”, *J. Phys. G* 28 (2002) 2693, doi:10.1088/0954-3899/28/10/313.

[63] A. Oliveira, “Gravity particles from Warped Extra Dimensions, predictions for LHC”, (2014), arXiv:1404.0102.

[64] A. Djouadi et al., “The post-Higgs MSSM scenario: habemus MSSM?”, *Eur. Phys. J. C* 73 (2013) 2650, doi:10.1140/epjc/s10052-013-2650-0, arXiv:1307.5205.

[65] A. Djouadi et al., “Fully covering the MSSM Higgs sector at the LHC”, *JHEP* 06 (2015) 168, doi:10.1007/JHEP06(2015)168, arXiv:1502.05653.
A The CMS Collaboration

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

Institut für Hochenergiephysik, Wien, Austria
W. Adam, F. Ambrogi, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth, V.M. Ghete, J. Grossmann, J. Hrubec, M. Jeitler, A. König, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, E. Pree, D. Rabady, N. Rad, H. Rohringer, J. Schieck, R. Schöfbeck, M. Spanring, D. Spitzbart, J. Strauss, W. Waltenberger, J. Wittmann, C.-E. Wulz, M. Zarucki

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

Universiteit Antwerpen, Antwerpen, Belgium
E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium
S. Abu Zeid, F. Blekman, J. D’Hondt, I. De Bruyn, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskyi, S. Lovette, S. Moortgat, L. Moreels, A. Olbrechts, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Université Libre de Bruxelles, Bruxelles, Belgium
H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, J. Luetic, T. Maerschalk, A. Marinov, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, D. Vannerom, R. Yonamine, F. Zenoni, F. Zhang

Ghent University, Gent, Belgium
A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov, D. Poyraz, C. Roskas, S. Salva, M. Tytgat, W. Verbeke, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, A. Caudron, S. De Visscher, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, A. Jafari, M. Komm, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, K. Piotrzkowski, L. Quertenmont, M. Vidal Marono, S. Wertz

Université de Mons, Mons, Belgium
N. Beliy

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
W.L. Aldá Júnior, F.L. Alves, G.A. Alves, L. Brito, M. Correa Martins Junior, C. Hensel, A. Moraes, M.E. Pol, P. Rebelo Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato, A. Custódio, E.M. Da Costa, G.G. Da Silveira, D. De Jesus Damiao, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, A. Santoro, A. Sznajder, E.J. Tonelli Manganote, F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista a, Universidade Federal do ABC b, São Paulo, Brazil
S. Ahuja, C.A. Bernardes, T.R. Fernandez Perez Tomei, E.M. Gregores, P.G. Mercadante, S.F. Novaes, Sandra S. Padula, D. Romero Abad, J.C. Ruiz Vargas
Institute for Nuclear Research and Nuclear Energy of Bulgaria Academy of Sciences
A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, S. Stoykova, G. Sultanov

University of Sofia, Sofia, Bulgaria
A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

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

Institute of High Energy Physics, Beijing, China
M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, 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, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, J.D. Ruiz Alvarez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
B. Courbon, N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano, 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, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

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

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
E. El-khateeb, S. Elgammal, A. Mohamed

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
R.K. Dewanjee, M. Kadastik, L. Ferrini, M. Raidal, A. Tikoo, C. Veelken

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

Helsinki Institute of Physics, Helsinki, Finland
J. Härkönen, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, E. Tuominen, J. Tuominen, E. Tuovinen
Lappeenranta University of Technology, Lappeenranta, Finland
J. Talvitie, T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, S. Ghosh, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, I. Kucher, E. Locci, M. Machet, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M.Ö. Sahin, M. Titov

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France
A. Abdulsalam, C. Amendola, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, C. Charlot, R. Granier de Cassagnac, M. Jo, S. Lisniak, A. Lobanov, J. Martin Blanco, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, T. Strebeler, Y. Yilmaz, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
J.-L. Agram, J. Andrea, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte, X. Coubez, J.-C. Fontaine, D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

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
S. Beauceron, C. Bernet, G. Boudoul, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov, V. Sordini, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia
T. Toriashvili

Tbilisi State University, Tbilisi, Georgia
Z. Tsamaladze

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, S. Beranek, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, C. Schomakers, J. Schulz, T. Verlage

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
A. Albert, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, M. Hamer, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, M. Olschewski, K. Padeken, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, D. Teyssier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
G. Flügge, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Eckerlin, D. Eckstein, T. Eichhorn
E. Eren, E. Gallo, J. Garay Garcia, A. Geiser, A. Gizhko, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, A. Harb, J. Hauk, M. Hempel, H. Jung, A. Kalogeropoulos, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, T. Lenz, J. Leonard, K. Lipka, W. Lohmann, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M. Savitskyi, P. Saxena, R. Shevchenko, S. Spannagel, N. Stefaniuk, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

University of Hamburg, Hamburg, Germany
S. Bein, V. Blobel, M. Centis Vignali, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, A. Hinzmann, M. Hoffmann, A. Karavdina, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, T. Lapsien, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo, T. Peiffer, A. Perieanu, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

Institut für Experimentelle Kernphysik, Karlsruhe, Germany
M. Akbiyik, C. Barth, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, B. Freund, R. Friese, M. Giffels, A. Gilbert, D. Haitz, F. Hartmann, S.M. Heinidl, U. Husemann, F. Kassel, S. Kudella, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, T. Geralis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, I. Topsis-Giotis

National and Kapodistrian University of Athens, Athens, Greece
S. Kesisoglou, A. Panagiotou, N. Saoulidou

University of Ioánnina, Ioánnina, Greece
I. Evangelou, C. Foudas, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F.A. Triantis

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanad, N. Filipovic, G. Pasztor

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, D. Horváth, Á. Hunyadi, F. Sikler, V. Veszpremi, G. Vesztergombi, A.J. Zsigmond

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
M. Bartók, P. Raics, Z.L. Trocsanyi, B. Ujvari

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

National Institute of Science Education and Research, Bhubaneswar, India
S. Bahinipati, S. Bhowmik, P. Mal, K. Mandal, A. Nayak, D.K. Sahoo, N. Sahoo, S.K. Swain
Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, U. Bhawandeep, R. Chawla, N. Dhingra, A.K. Kalsi, A. Kaur, M. Kaur, R. Kumar, P. Kumari, A. Mehta, J.B. Singh, G. Walia

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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
R. Bhardwaj, R. Bhattacharya, S. Bhattacharya, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

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

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

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, S. Dugad, B. Mahakud, S. Mitra, G.B. Mohanty, N. Sur, B. Sutar

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Kumar, M. Maity, G. Majumder, K. Mazumdar, T. Sarkar, N. Wickramage

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. Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, 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
M. Abbrescia, C. Calabria, C. Caputo, A. Colaleo, D. Creanza, L. Cristella, N. De Filippines, M. De Palma, F. Errico, L. Fiore, G. Iaselli, S. Lezki, G. Maggi, M. Maggì, G. Miniello, S. My, S. Nuzzo, A. Pompili, G. Pugliese, R. Radogna, A. Ranieri, G. Selvaggi, A. Sharma, L. Silvestris, R. Venditti, P. Verwilligen

INFN Sezione di Catania, Università di Catania, Catania, Italy
S. Albergo, C. Battilana, D. Bonacorsi, S. Braibant-Giacomelli, R. Campanini, P. Capiluppi, A. Castro, F.R. Cavallo, S.S. Chhibra, G. Codispoti, M. Cuffiani, G.M. Dallavalle, F. Fabbri, A. Fanfani, D. Fasanella, P. Giacomelli, C. Grandi, L. Guiducci, S. Marcellini, G. Masetti, A. Montanari, F.L. Navarria, A. Perrotta, A.M. Rossi, T. Rovelli, G.P. Siroli, N. Tosi

INFN Sezione di Bologna, Università di Bologna, Bologna, Italy
G. Abbiendi, C. Battilana, D. Bonacorsi, S. Braibant-Giacomelli, R. Campanini, P. Capiluppi, A. Castro, F.R. Cavallo, S.S. Chhibra, G. Codispoti, M. Cuffiani, G.M. Dallavalle, F. Fabbri, A. Fanfani, D. Fasanella, P. Giacomelli, C. Grandi, L. Guiducci, S. Marcellini, G. Masetti, A. Montanari, F.L. Navarria, A. Perrotta, A.M. Rossi, T. Rovelli, G.P. Siroli, N. Tosi
INFN Sezione di Firenze, Università di Firenze, Firenze, Italy
G. Barbaglio\textsuperscript{a,b}, K. Chatterjee\textsuperscript{a,b}, V. Ciulli\textsuperscript{a,b}, C. Civinini\textsuperscript{a}, R. D’Alessandro\textsuperscript{a,b}, E. Focardi\textsuperscript{a,b}, P. Lenzi\textsuperscript{a,b}, M. Meschini\textsuperscript{a}, S. Paoletti\textsuperscript{a}, L. Russo\textsuperscript{a,28}, G. Sguazzoni\textsuperscript{a}, D. Strom\textsuperscript{a}, L. Viliani\textsuperscript{a,b,14}

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera\textsuperscript{14}

INFN Sezione di Genova, Università di Genova, Genova, Italy
V. Calvelli\textsuperscript{a,b}, F. Ferro\textsuperscript{a}, E. Robutti\textsuperscript{a}, S. Tosi\textsuperscript{a,b}

INFN Sezione di Milano-Bicocca, Università di Milano-Bicocca, Milano, Italy
L. Brianza\textsuperscript{a,b}, F. Brivio\textsuperscript{a,b}, V. Ciriolo\textsuperscript{a,b}, M.E. Dinardo\textsuperscript{a,b}, S. Fiorenti\textsuperscript{a,b}, S. Gennai\textsuperscript{a}, A. Ghezzi\textsuperscript{a,b}, P. Govoni\textsuperscript{a,b}, M. Malberti\textsuperscript{a,b}, S. Malvezzi\textsuperscript{a}, R.A. Manzoni\textsuperscript{a,b}, D. Menasce\textsuperscript{a}, L. Moroni\textsuperscript{a}, M. Paganoni\textsuperscript{a}, K. Pauwels\textsuperscript{a,b}, D. Pedrini\textsuperscript{a}, S. Pigazzini\textsuperscript{a,b,29}, S. Ragazzi\textsuperscript{a,b}, T. Tabarelli de Fatis\textsuperscript{a,b}

INFN Sezione di Napoli, Università di Napoli ‘Federico II’, Napoli, Italy, Università della Basilicata, Potenza, Italy, Università G. Marconi, Roma, Italy
S. Buontempo\textsuperscript{a}, N. Cavallo\textsuperscript{a,c}, S. Di Guida\textsuperscript{a,d,14}, F. Fabozzi\textsuperscript{a,c}, F. Fienga\textsuperscript{a,b}, A.O.M. Iorio\textsuperscript{a,b}, W.A. Khan\textsuperscript{a}, L. Lista\textsuperscript{a}, S. Meola\textsuperscript{a,d,14}, P. Paolucci\textsuperscript{a,14}, C. Sciacca\textsuperscript{a,b}, F. Thyssen\textsuperscript{a}

INFN Sezione di Padova, Università di Padova, Padova, Italy, Università di Trento, Trento, Italy
P. Azzi\textsuperscript{a,14}, N. Bacchetta\textsuperscript{a}, L. Benato\textsuperscript{a,b}, D. Bisello\textsuperscript{a,b}, A. Boletti\textsuperscript{a,b}, R. Carlin\textsuperscript{a,b}, A. Carvalho Antunes De Oliveira\textsuperscript{a,b}, M. Dall’Osso\textsuperscript{a,b}, P. De Castro Manzano\textsuperscript{a}, T. Dorigo\textsuperscript{a}, U. Dosselli\textsuperscript{a}, S. Fantinel\textsuperscript{a}, F. Fanzago\textsuperscript{a}, A. Gozzelino\textsuperscript{a}, S. Laprara\textsuperscript{a}, P. Lujan, M. Margoni\textsuperscript{a,b}, A.T. Meneguzzo\textsuperscript{a,b}, N. Pozzobon\textsuperscript{a,b}, P. Ronchese\textsuperscript{a,b}, R. Rossin\textsuperscript{a,b}, F. Simonetto\textsuperscript{a,b}, E. Torassa\textsuperscript{a}, M. Zanetti\textsuperscript{a,b}, P. Zotto\textsuperscript{a,b}, G. Zumerle\textsuperscript{a,b}

INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
A. Braghieri\textsuperscript{a}, F. Fallavollita\textsuperscript{a,b}, A. Magnani\textsuperscript{a,b}, P. Montagna\textsuperscript{a,b}, S.P. Ratti\textsuperscript{a,b}, V. Re\textsuperscript{a}, M. Ressegotti, C. Riccardi\textsuperscript{a,b}, P. Salvini\textsuperscript{a}, I. Vai\textsuperscript{a,b}, P. Vitullo\textsuperscript{a,b}

INFN Sezione di Perugia, Università di Perugia, Perugia, Italy
L. Alunni Solestiz\textsuperscript{a,b}, M. Biasini\textsuperscript{a,b}, G.M. Bilei\textsuperscript{a}, C. Cecchi\textsuperscript{a,b}, D. Ciangottini\textsuperscript{a,b}, L. Fanò\textsuperscript{a,b}, P. Lariccia\textsuperscript{a,b}, R. Leonardi\textsuperscript{a,b}, E. Manoni\textsuperscript{a}, M. Mantovani\textsuperscript{a,b}, V. Marian\textsuperscript{a,b}, M. Menichelli\textsuperscript{a}, A. Rossi\textsuperscript{a,b}, A. Santocchia\textsuperscript{a,b}, D. Spiga\textsuperscript{a}

INFN Sezione di Pisa, Università di Pisa, Scuola Normale Superiore di Pisa, Pisa, Italy
K. Androsov\textsuperscript{a}, P. Azzurri\textsuperscript{a,14}, G. Bagliesi\textsuperscript{a}, J. Bernardini\textsuperscript{a}, T. Boccali\textsuperscript{a}, L. Borrello, R. Castaldi\textsuperscript{a}, M.A. Ciocci\textsuperscript{a,b}, R. Dell’Orso\textsuperscript{a}, G. Fedi\textsuperscript{a}, L. Giannini\textsuperscript{a,c}, A. Giassi\textsuperscript{a}, M.T. Grippo\textsuperscript{a,28}, F. Ligabue\textsuperscript{a,c}, T. Lomtadze\textsuperscript{a}, E. Manca\textsuperscript{a,c}, G. Mandoni\textsuperscript{a,c}, L. Martini\textsuperscript{a,b}, A. Messineo\textsuperscript{a,b}, F. Palla\textsuperscript{a}, A. Rizzi\textsuperscript{a,b}, A. Savoy-Navarro\textsuperscript{a,30}, P. Spagnolo\textsuperscript{a}, R. Tencini\textsuperscript{a}, G. Tonelli\textsuperscript{a,b}, A. Venturi\textsuperscript{a}, P.G. Verdini\textsuperscript{a}

INFN Sezione di Roma, Sapienza Università di Roma, Rome, Italy
L. Barone\textsuperscript{a,b}, F. Cavallari\textsuperscript{a}, M. Cipriani\textsuperscript{a,b}, D. Del Re\textsuperscript{a,b,14}, M. Diemoz\textsuperscript{a}, S. Gelli\textsuperscript{a,b}, E. Longo\textsuperscript{a,b}, F. Margaroli\textsuperscript{a,b}, B. Marzocchi\textsuperscript{a,b}, P. Meridianti\textsuperscript{a}, G. Organtini\textsuperscript{a,b}, R. Paramatti\textsuperscript{a,b}, E. Preiato\textsuperscript{a,b}, S. Rahatlou\textsuperscript{a,b}, C. Rovelli\textsuperscript{a,b}, F. Santanastasio\textsuperscript{a,b}

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

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

**Kyungpook National University, Daegu, Korea**
D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S. Sekmen, D.C. Son, Y.C. Yang

**Chonbuk National University, Jeonju, Korea**
A. Lee

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

**Hanyang University, Seoul, Korea**
J.A. Brochero Cifuentes, J. Goh, T.J. Kim

**Korea University, Seoul, Korea**
S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, Y. Kim, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park, Y. Roh

**Seoul National University, Seoul, Korea**
J. Almond, J. Kim, J.S. Kim, H. Lee, K. Lee, K. Nam, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

**University of Seoul, Seoul, Korea**
M. Choi, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park, G. Ryu

**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**
I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali$^{31}$, F. Mohamad Idris$^{32}$, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

**Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico**
Duran-Osuna, M. C., H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz$^{33}$, R. Lopez-Fernandez, J. Mejia Guisao, R.I. Rabadán-Trejo, G. Ramirez-Sanchez, R. Reyes-Almanza, A. Sanchez-Hernandez

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

**Benemerita Universidad Autonoma de Puebla, Puebla, Mexico**
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
P.H. Butler

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

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, A. Byszuk, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
P. Bargassa, C. Beirão Da Cruz E Silva, B. Calpas, A. Di Francesco, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Seixas, O. Toldaiev, D. Vadruccio, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiyev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

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

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

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

Moscow Institute of Physics and Technology, Moscow, Russia
T. Aushev, A. Bylinkin

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, 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. Kokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin

Novosibirsk State University (NSU), Novosibirsk, Russia
V. Blinov, Y. Skovpen, D. Shtol
State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

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

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
J. Alcaraz Maestre, M. Barrio Luna, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. García-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares, A. Alvarez Fernández

Universidad Autónoma de Madrid, Madrid, Spain
J.F. de Trocóniz, M. Missiroli, D. Moran

Universidad de Oviedo, Oviedo, Spain
J. Cuevas, C. Erice, J. Fernandez Menendez, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, S. Sanchez Cruz, I. Suárez Andrés, P. Vischia, J.M. Vizan García

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
J.I. Cabrillo, A. Calderon, A. Chazin Quero, E. Chapon, Y. Chen, D. d’Enterria, M. Dobson, B. Dorney, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, G. Franzoni, J. Fulcher, W. Funk, D. Giller, A. Gill, F. Glege, D. Gulhan, S. Gundacker, M. Guthoff, P. Harris, J. Hegeman, V. Innocente, P. Janot, O. Karacheban, J. Kieseler, H. Kirschenmann, V. Knünz, A. Kormayer, M.J. Kortelainen, C. Lange, P. Lecoq, C. Langeo, P. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijsers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic, F. Moortgat, M. Mulders, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, A. Racz, T. Reis, G. Rolandi, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Spilcas, J. Steggemann, M. Stoye, M. Tosi, D. Treille, A. Triossi, A. Tsirou, V. Veckalns, G.I. Veres, M. Verweij, N. Wardle, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
W. Bertl, L. Caminada, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
F. Bachmair, L. Bäni, P. Berger, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, T. Klijnsma, W. Listermann, B. Mangano, M. Marionneau, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi,
A. Rose, E. Scott, C. Seez, A. Shtipliyski, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta, T. Virdee, D. Winterbottom, J. Wright, S.C. Zenz

Brunel University, Uxbridge, United Kingdom
J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, USA
A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika, C. Smith

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

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

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

Brown University, Providence, USA
G. Benelli, D. Cutts, A. Garabedian, J. Hakala, U. Heintz, J.M. Hogan, K.H.M. Kwok, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Piperov, S. Sagir, R. Syarif, D. Yu

University of California, Davis, Davis, USA
R. Band, C. Brainerd, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, M. Gardner, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, J. Smith, M. Squires, D. Stolp, K. Tos, M. Tripathi, Z. Wang

University of California, Los Angeles, USA
M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. McColl, D. Saltzberg, C. Schnaible, V. Valuev

University of California, Riverside, Riverside, USA
E. Bouvier, K. Burt, R. Clare, J. Ellison, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, J. Heilman, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I.Paneva, A. Shrinivas, W. Si, L. Wang, H. Wei, S. Wimpenny, B. R. Yates

University of California, San Diego, La Jolla, USA
J.G. Branson, S. Cittolin, M. Derdzinski, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, I. Macneill, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara - Department of Physics, Santa Barbara, USA
N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, M. Franco Sevilla, C. George, F. Golf, L. Gouskos, J. Gran, R. Heller, J. Incandela, S.D. Mullin, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, J. Yoo

California Institute of Technology, Pasadena, USA
D. Anderson, J. Bendavid, A. Bornheim, J.M. Lawhorn, H.B. Newman, T. Nguyen, C. Pena, M. Spiropulu, J.R. Vlimant, S. Xie, Z. Zhang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev, M. Weinberg
University of Colorado Boulder, Boulder, USA
J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, S. Leontsinis, T. Mulholland, K. Stenson, S.R. Wagner

Cornell University, Ithaca, USA
J. Alexander, J. Chaves, J. Chu, S. Dittmer, K. Mcdermott, N. Mirman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O’Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, B. Schneider, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck

University of Florida, Gainesville, USA
D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, S. Das, R.D. Field, I.K. Furic, J. Königsberg, A. Korytov, K. Kotov, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, D. Rank, D. Sperka, N. Terentyev, L. Thomas, J. Wang, S. Wang, J. Yelton

Florida International University, Miami, USA
Y.R. Joshi, S. Linn, P. Markowitz, J.L. Rodriguez

Florida State University, Tallahassee, USA
A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, G. Martinez, T. Ferry, H. Prosper, A. Saha, A. Santra, R. Yohay

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, I.D. Sandoval Gonzalez, M.B. Tonjes, H. Trauger, N. Varelas, H. Wang, Z. Wu, J. Zhang

The University of Iowa, Iowa City, USA
B. Bilki, W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogu, Y. Onel, F. Ozok, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, USA
B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

The University of Kansas, Lawrence, USA
A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, J. Castle, S. Khalil, A. Kropivnitskaya,
D. Majumder, W. Mcbrayer, M. Murray, C. Royon, S. Sanders, E. Schmitz, R. Stringer, J.D. Tapia
Takaki, Q. Wang

Kansas State University, Manhattan, USA
A. Ivanov, K. Kaadze, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

Lawrence Livermore National Laboratory, Livermore, USA
F. Rebassoo, D. Wright

University of Maryland, College Park, USA
C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, N.J. Hadley,
S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja,
S.C. Tonwar

Massachusetts Institute of Technology, Cambridge, USA
D. Abercrombie, B. Allen, V. Azzolini, R. Barbieri, A. Baty, R. Bi, S. Brandt, W. Busza,
I.A. Cali, M. D’Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, D. Hsu, Y. Iiyama,
G.M. Innocenti, M. Klute, D. Kovalskyi, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, B. Maier,
A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland,
J. Salfeld-Nebgen, G.S.F. Stephens, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

University of Minnesota, Minneapolis, USA
A.C. Benvenuti, R.M. Chatterjee, A. Evans, P. Hansen, S. Kalafut, Y. Kubota, Z. Lesko, J. Mans,
S. Nourbakhsh, N. Ruckstuhl, R. Rusack, J. Turkewitz

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

University of Nebraska-Lincoln, Lincoln, USA
E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin,
I. Kravchenko, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

State University of New York at Buffalo, Buffalo, USA
M. Alyari, J. Dolen, A. Godshalk, C. Harrington, I. Iashvili, D. Nguyen, A. Parker, S. Rappoccio,
B. Roozbahani

Northeastern University, Boston, USA
G. Alverson, E. Barberis, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Orimoto,
R. Teixeira De Lima, D. Trocino, D. Wood

Northwestern University, Evanston, USA
S. Bhattacharya, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, B. Pollack, M.H. Schmitt, K. Sung,
M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA
N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon,
N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko 35, M. Planer, A. Reinsvold, R. Ruchti,
G. Smith, S. Taroni, M. Wayne, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA
J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji,
B. Liu, W. Luo, D. Puigh, B.L. Winer, H.W. Wulsin

Princeton University, Princeton, USA
A. Benaglia, S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S. Higginbotham,
D. Lange, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, USA
S. Malik, S. Norberg

Purdue University, West Lafayette, USA
A. Barker, V.E. Barnes, S. Folgueras, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, A. Khatiwada, D.H. Miller, N. Neumeister, C.C. Peng, J.F. Schulte, J. Sun, F. Wang, W. Xie

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

Rice University, Houston, USA
A. Adair, B. Akgun, Z. Chen, K.M. Ecklund, F.J.M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B.P. Padley, J. Roberts, J. Rorie, Z. Tu, J. Zabel

University of Rochester, Rochester, USA
A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, M. Verzetti

The Rockefeller University, New York, USA
R. Ciesielski, K. Goulianos, C. Mesropian

Rutgers, The State University of New Jersey, Piscataway, USA
A. Agapitos, J.P. Chou, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

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

Texas A&M University, College Station, USA
O. Bouhali, A. Castaneda Hernandez, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov, K.A. Ulmer

Texas Tech University, Lubbock, USA
N. Akchurin, J. Damgov, F. De Guio, P.R. Dudero, J. Faulkner, E. Gurpinar, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Vanderbilt University, Nashville, USA
S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

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

Wayne State University, Detroit, USA
R. Harr, P.E. Karchin, J. Sturdy, S. Zaleski

University of Wisconsin - Madison, Madison, WI, USA
M. Brodski, J. Buchanan, C. Caillol, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe,
M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, G.A. Pierro, G. Polese, T. Ruggles, A. Savin, N. Smith, W.H. Smith, D. Taylor, N. Woods

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
3: Also at Universidade Estadual de Campinas, Campinas, Brazil
4: Also at Universidade Federal de Pelotas, Pelotas, 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: Now at Ain Shams University, Cairo, Egypt
9: Now at British University in Egypt, Cairo, Egypt
10: Also at Zewail City of Science and Technology, Zewail, Egypt
11: Also at Université de Haute Alsace, Mulhouse, France
12: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
13: Also at Tbilisi State University, Tbilisi, Georgia
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 Institute of Nuclear Research ATOMKI, Debrecen, Hungary
19: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, 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 University of Visva-Bharati, Santiniketan, India
24: Also at University of Ruhuna, Matara, Sri Lanka
25: Also at Isfahan University of Technology, Isfahan, Iran
26: Also at Yazd University, Yazd, Iran
27: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
28: Also at Università degli Studi di Siena, Siena, Italy
29: Also at INFN Sezione di Milano-Bicocca; Università di Milano-Bicocca, Milano, Italy
30: Also at Purdue University, West Lafayette, USA
31: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
32: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
33: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
34: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
35: Also at Institute for Nuclear Research, Moscow, Russia
36: Now at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
37: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
38: Also at University of Florida, Gainesville, USA
39: Also at P.N. Lebedev Physical Institute, Moscow, Russia
40: Also at California Institute of Technology, Pasadena, USA
41: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
42: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
43: Also at INFN Sezione di Roma; Sapienza Università di Roma, Rome, Italy
44: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
45: Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy
46: Also at National and Kapodistrian University of Athens, Athens, Greece
47: Also at Riga Technical University, Riga, Latvia
48: Also at Universität Zürich, Zurich, Switzerland
49: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
50: Also at Istanbul University, Faculty of Science, Istanbul, Turkey
51: Also at Adiyaman University, Adiyaman, Turkey
52: Also at Istanbul Aydin University, Istanbul, Turkey
53: Also at Mersin University, Mersin, Turkey
54: Also at Cag University, Mersin, Turkey
55: Also at Piri Reis University, Istanbul, Turkey
56: Also at Izmir Institute of Technology, Izmir, Turkey
57: Also at Necmettin Erbakan University, Konya, Turkey
58: Also at Marmara University, Istanbul, Turkey
59: Also at Kafkas University, Kars, Turkey
60: Also at Istanbul Bilgi University, Istanbul, Turkey
61: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
62: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
63: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
64: Also at Utah Valley University, Orem, USA
65: Also at Beykent University, Istanbul, Turkey
66: Also at Bingol University, Bingol, Turkey
67: Also at Erzincan University, Erzincan, Turkey
68: Also at Sinop University, Sinop, Turkey
69: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
70: Also at Texas A&M University at Qatar, Doha, Qatar
71: Also at Kyungpook National University, Daegu, Korea