Eur. Phys. J. C (2026) 86:901
https://doi.org/10.1140/epjc/s10052-026-15699-9

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Search for heavy resonances decaying into two Higgs bosons in the $b\bar{b}\tau^+\tau^-$ final state in proton–proton collisions at $\sqrt{s} = 13\,\text{TeV}$

CMS Collaboration*

CERN, 1211 Geneva 23, Switzerland

Received: 27 January 2026 / Accepted: 11 April 2026

Abstract A search is presented for massive narrow-width resonances in the mass range of 1–4.5 TeV, decaying into pairs of Higgs bosons (HH). The search uses proton–proton collision data at a center-of-mass energy of 13 TeV collected with the CMS detector at the CERN LHC during 2016–2018, corresponding to an integrated luminosity of 138 fb^{-1}. The analysis targets final states where one Higgs boson decays into a pair of bottom quarks and the other into a pair of tau leptons, $X \rightarrow HH \rightarrow b\bar{b}\tau^+\tau^-$. It uses a single large radius jet to reconstruct the $H \rightarrow b\bar{b}$ decay, while the $H \rightarrow \tau^+\tau^-$ decay products can either be contained within a single large radius jet or appear as two isolated tau leptons. The observed data are consistent with standard model background expectations. Upper limits at 95% confidence level are set on the production cross section for resonant HHproduction for masses between 1 and 4.5 TeV. This analysis sets the most sensitive limits to date on $X \rightarrow HH \rightarrow b\bar{b}\tau^+\tau^-$ decays in the mass range of 1.4–4.5 TeV.

1 Introduction

The discovery of the Higgs boson (H) by the CMS [1,2] and ATLAS [3,4] experiments confirmed the standard model (SM) as a robust theoretical framework for describing high-energy interactions. However, unresolved questions within the SM, such as the hierarchy problem [5], have driven the search for beyond-the-SM (BSM) physics.

The observation of the Hboson has opened new avenues for probing BSM scenarios. In fact, many BSM theories predict the existence of heavy resonances (X) with masses exceeding 1 TeV that can decay into a pair of Higgs bosons (HH). The production of Higgs boson pairs is a crucial, but rare, process in the SM. If resonant HHproduction occurs through BSM physics, it can significantly enhance the cross section. An example of a well-motivated theoretical framework predicting such enhancements is the warped extra dimensions model proposed by Randall and Sundrum (RS) [6,7], which leads to the existence of new neutral, spin-0 radions [8–10] and spin-2 Kaluza–Klein gravitons [11,12]. The analysis presented in this paper is designed to be model independent, with a single strategy for both spin-0 and spin-2 resonances, each decaying into a pair of Higgs bosons in the $b\bar{b}\tau^+\tau^-$ final state. A representative diagram illustrating the production of such a resonance is shown in Fig. 1.

This search targets resonance masses between 1 and 4.5 TeV using the CMS proton–proton (pp) collision data sample collected at a center-of-mass energy of 13 TeV during the years 2016–2018. A previous CMS search for heavy resonant HHproduction in the same final state [13] is based on a smaller data set, using only the 2016 pp collision data, corresponding to 35.9 fb^{-1}. The observed data in that analysis are consistent with SM expectations, and upper limits are set at 95% confidence level (CL) on the production cross section for spin-0 and spin-2 resonance masses between 0.9 and 4.0 TeV. The analysis performed by the ATLAS Collaboration in the boosted topology is based on the ppdata collected in 2015–2018 and covers resonance masses from 1 to 3 TeV [14]. No significant excess is observed in that search either, and 95% CL exclusion limits are set in the signal range of 1–3 TeV. A separate ATLAS search on the same data set targets spin-0 resonances, decaying to HH, with masses from 251 GeVto 1.6 TeV [15]. While this ATLAS search primarily targets the resolved topology, it covers the same signal mass range as the present analysis, that is, between 1 and 1.6 TeV. The data are also found to be compatible with the background-only hypothesis, with the largest deviation at a mass of 1 TeV, corresponding to local and global significances of 3.1 and 2.0 standard deviations, respectively.

This paper focuses on the fully hadronic ($\tau_h\tau_h$) and the mixture of one leptonic and one hadronic decay ($\ell\tau_h$) of the $\tau^+\tau^-$pair in resonant Higgs boson pair production, where one Hboson decays into $b\bar{b}$ and the other into $\tau^+\tau^-$. The individual hadronically-decaying tau leptons are denoted as

Deceased: M. Finger, G. M. Bilei, M. Arneodo, P. de Barbaro

* e-mail: cms-publication-committee-chair@cern.ch (corresponding author)

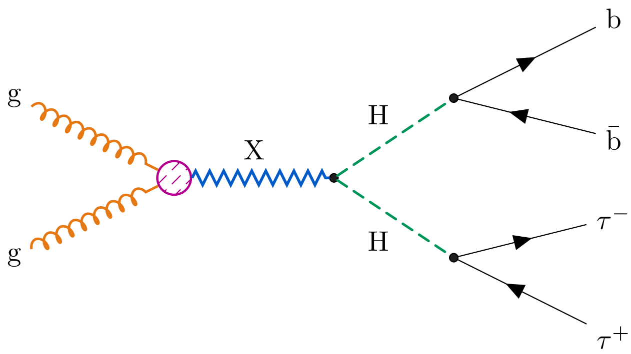

Fig. 1 A representative diagram for the production of a spin-0 radion or a spin-2 graviton X, which decays into two SM Higgs bosons. One Higgs boson decays into a $\mathrm{b\bar{b}}$ pair and the other into a $\tau^+\tau^-$pair

τ_h, while ℓ denotes an electron or muon. In addition to $\mathrm{X} \rightarrow \mathrm{HH} \rightarrow \mathrm{b\bar{b}}\tau^+\tau^-$, other resonant HHprocesses that can contribute to the same final states are also included as signal, namely $\mathrm{X} \rightarrow \mathrm{HH} \rightarrow \mathrm{b\bar{b}WW} \rightarrow \mathrm{b\bar{b}}\ell^\ddagger\nu\mathrm{qq}$ and $\mathrm{X} \rightarrow \mathrm{HH} \rightarrow \mathrm{b\bar{b}VV} \rightarrow \mathrm{b\bar{b}}\ell^\ddagger\ell^\ddagger\nu\nu$. Here, $\ell^\ddagger$ denotes a charged lepton of any flavor (e, μ, or τ), qrepresents a quark, and Vdenotes a massive SM vector boson (Wor Z), as used throughout this paper. In the simulated signal samples of $\mathrm{H} \rightarrow \tau^+\tau^-$, the τ leptons decay inclusively according to their SM branching fractions, while for $\mathrm{H} \rightarrow \mathrm{WW}$ and $\mathrm{H} \rightarrow \mathrm{ZZ}$ decays, we restrict the V decays to the final states listed above, i.e., $\mathrm{WW} \rightarrow \ell^\ddagger\nu\ell^\ddagger\nu$, $\ell^\ddagger\nu\mathrm{qq}$, and $\mathrm{ZZ} \rightarrow \ell^\ddagger\ell^\ddagger\nu\nu$. Therefore, the corresponding SM branching fractions [16,17] of Wand Zbosons to these final states are taken into account when calculating the signal yields.

This analysis assumes a narrow resonance width, i.e., the natural width of the resonance (1 MeV) is significantly smaller than the experimental resolution (around 10% of the mass of the resonance). The two bottom quarks from the Higgs boson decay are produced with a small angular separation and often merge into a single jet after hadronization. These jets are identified with a graph convolutional neural network called the PARTICLENET jet tagger [18]. In this Lorentz-boosted regime, the decay products of the τ lepton pair, whether $\ell\tau_\mathrm{h}$or $\tau_\mathrm{h}\tau_\mathrm{h}$, tend to overlap spatially, making di-τ reconstruction particularly challenging. The reconstruction of such boosted τ leptons was first addressed in a similar CMS search using 8 TeV pp collision data [19]. In this analysis, we enhance the sensitivity of these methods by employing a dedicated DEEPTAU [20] based tagger, optimized specifically for the reconstruction of boosted τ leptons. The SM processes with the largest contributions to the background are $\mathrm{t\bar{t}}$+jets(top quark-antiquark pair production), W+jets, and Z+jetsproduction, although the precise composition depends on the specific channel under consideration.

The structure of this paper is as follows: Sect. 2 provides an overview of the CMS detector, while Sect. 3 describes the CMS data set and the simulation of physics processes. Section 4 details the object and event reconstruction, followed by Sect. 5, which outlines the event selection and categorization. The methods used for background modeling are discussed in Sect. 6, and systematic uncertainties are addressed in Sect. 7. Finally, the results are presented in Sect. 8, and the paper is summarized in Sect. 9. Tabulated results for this analysis are provided in HEPData [21].

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6m internal diameter, providing a magnetic field of 3.8T. 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 (η) coverage provided by the barrel and endcap detectors. Muons are detected in gas ionization chambers interleaved with the layers of the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Refs. [22] and [23].

Events of interest are selected using a two-tiered trigger system [24–26]. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100kHz within a time interval of less than 4 μs. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to a few kHz before data storage.

3 Data and simulated samples

This search utilizes data recorded by the CMS detector from 2016 to 2018, corresponding to an integrated luminosity of 138 fb^{-1}. Events are selected using a set of triggers that require either missing transverse momentum ($p_\mathrm{T}^\mathrm{miss}$) or missing hadronic transverse momentum ($H_\mathrm{T}^\mathrm{miss}$) to exceed 110 GeV, often in conjunction with additional criteria, such as the presence of a jet with $p_\mathrm{T} > 80$ GeV. The primary vertex (PV) [27] is defined as the vertex with the largest p_T^2 sum of the physics objects originating from that vertex. Here, the physics objects are the charged leptons, the AK4 jets, and the $p_\mathrm{T}^\mathrm{miss}$. The missing transverse momentum vector $\mathbf{p}_\mathrm{T}^\mathrm{miss}$ is defined as the negative vector sum of the momentum of all reconstructed particle candidates associated with the PV, projected onto the plane perpendicular to the beam direction. The missing transverse momentum $p_\mathrm{T}^\mathrm{miss}$is defined as the magnitude of $\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}$. The observable $H_{\mathrm{T}}^{\mathrm{miss}}$is defined as the magnitude of the vectorial p_{T}sum of all jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 3.0$. The particle and jet reconstruction are described in detail in Sect. 4.

Monte Carlo (MC) simulated samples of the main SM backgrounds and of the signal processes are used to optimize the event selection and to improve the background estimation. Simulated events of $\mathrm{t\bar{t}}$+jets production and single top quark processes (t-, s-, and tW-channels) are generated at next-to-leading order (NLO) in quantum chromodynamics (QCD) using the POWHEGv1 and v2 [28, 29] event generators. For the $\mathrm{t\bar{t}}$+jets process, the top quark p_{T}distribution is reweighted to match next-to-next-to-leading order (NNLO) theoretical computations [30]. Samples of Z+jetsand W+jetsare generated at leading order (LO) using MADGRAPH5_aMC@NLOv2.6.5 [31] with the MLM prescription [32] for matching jets from the matrix element calculation to the parton shower. Dedicated electroweak [33–38] and QCD (calculated with MADGRAPH5_aMC@NLO) NLO/LO k-factors, parameterized as functions of the generated boson p_{T}, are applied to Z+jetsand W+jetsevents. The QCD multijet events are simulated at LO either using the PYTHIA [39] or MADGRAPH5_aMC@NLOevent generators, with MLM matching [40] for the latter. Other processes with smaller contributions, such as diboson production, are generated at NLO using either MADGRAPH5_aMC@NLOwith FxFx [41] matching or POWHEGv2. All background samples are normalized using the most precise cross section evaluations available, which generally are calculated at NLO or NNLO.

Signal samples of narrow-width $\Gamma_{\mathrm{X}} = 1\,\mathrm{MeV}$ spin-0 and spin-2 resonances, produced via gluon fusion and decaying to HH, are simulated at LO using MADGRAPH5_aMC@NLO. The spin-0 (spin-2) signal is modeled as a radion-like scalar (graviton-like) resonance, with spin correlations handled through the corresponding matrix elements. Resonance masses range from 1 to 4.5 TeV. For spin-0 resonances, mass points are spaced by 200 GeVbetween 1 and 2 TeV, and by 500 GeVabove 2 TeV. For spin-2 resonances, the spacing is 250 GeVbetween 1 and 2 TeV, and 500 GeVabove 2 TeV.

The initial-state partons are modeled with the NNPDF 3.1 NNLO [42] parton distribution function (PDF) set. Parton showering and hadronization are handled by PYTHIAv8.230 [39] using the CP5 tune [43] for most samples. All signal and background samples are processed using GEANT4 [44] to provide a full simulation of the CMS detector, including simulation of the triggers. The effects of additional ppinteractions in the same or adjacent bunch crossings, referred to as pileup, are included in all simulated samples. To match the simulated distribution of pileup interactions with the one observed in data, a reweighting procedure is implemented. Correction factors are derived and applied to the simulated samples to match the trigger efficiencies measured in data. Additional corrections are applied to cover residual differences between data and simulation that arise from the lepton identification and reconstruction efficiencies, as well as from identification efficiencies for jets identified to originate from bquarks.

4 Event reconstruction

A particle-flow (PF) algorithm [45] reconstructs and identifies each individual particle through an optimized combination of information from the various elements of the CMS detector. The energy of each electron is determined from a combination of the electron momentum as measured 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 energies of muons are obtained from the curvature of the corresponding track. The energies of charged hadrons are determined from a combination of their momenta 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 energies of neutral hadrons are obtained from the corresponding corrected ECAL and HCAL energies.

The identified particles are clustered into jets using the anti-k_{T}algorithm [46], implemented in the FASTJET package [47]. Two distance parameters are used in the analysis, 0.4 and 0.8, yielding jet collections referred to as AK4 and AK8 jets, respectively. The PF candidates and AK4 jets are used in the definitions of $p_{\mathrm{T}}^{\mathrm{miss}}$and $H_{\mathrm{T}}^{\mathrm{miss}}$. The AK4 jets are used primarily to reject or select events with top quarks, while the larger AK8 jets are used to identify and contain hadronically decaying Hboson candidates.

Additional selection criteria are applied to each event to remove spurious jet-like features originating from isolated noise patterns in certain HCAL regions [48]. The AK4 and AK8 jets must have $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and $p_{\mathrm{T}} > 200\,\mathrm{GeV}$, respectively and $|\eta| < 2.4$, to be considered in the subsequent steps of the analysis.

To improve the stability of the jet mass and substructure variables in events with high pileup, the pileup-per-particle identification (PUPPI) algorithm [49] is applied to the AK8 jets used to identify hadronic boson decays. The PUPPI algorithm uses the local distribution of particles, event pileup properties, and tracking information to compute a weight describing the likelihood for each particle to originate from a pileup interaction. The weight is used to rescale the particle four-momentum, superseding the need for further jet-based pileup corrections.

Large AK8 jets originating from the dominant $\mathrm{b\bar{b}}$ decays of Hbosons are likely to have two displaced vertices because of the long lifetime and large mass of the bquarks. A graph convolutional neural network, PARTICLENET [18], is used to distinguish Hboson decays into $b\bar{b}$ from background jets by leveraging the properties of jet PF constituents as input features. As with all heavy-flavor jet classifiers, displaced tracks and secondary vertices are among the most important features. The multiclass PARTICLENET algorithm provides several output scores, each ranging from 0 to 1, representing the probability that a jet originates from a specific process, such as Hboson decay to bquarks ($P(H \rightarrow b\bar{b})$), or a light-flavor quark or gluon ($P(\mathrm{QCD})$). Following the standard approach for constructing a binary discriminant to distinguish Hboson jets from the dominant QCD multijet background [50], the PARTICLENET score is defined as $P(H \rightarrow b\bar{b})/(P(H \rightarrow b\bar{b}) + P(\mathrm{QCD}))$. In addition to classification, PARTICLENET performs a regression task to estimate the mass of the AK8 jet, referred to in this work as the PARTICLENET regressed mass $M_{H(b\bar{b})}$. In this analysis, we define a signal-enriched region (SR), defined as $100 < M_{H(b\bar{b})} < 150\,\mathrm{GeV}$, and a second region, called the sideband (SB), defined as $M_{H(b\bar{b})} < 100\,\mathrm{GeV}$ or $M_{H(b\bar{b})} > 150\,\mathrm{GeV}$, enriched in background processes.

The AK4 jets originating from bquarks are identified using the DEEPJET algorithm [51], a deep neural network that combines secondary vertex information, track-based variables, and PF jet constituents (neutral and charged-particle candidates). Events are vetoed if they contain at least one b-tagged AK4 jet that does not overlap with the selected AK8 jet or the leptons in the event, to further suppress the $\bar{t}$ background.

A series of dedicated algorithms are used to reconstruct and identify Hbosons decaying to $\tau^+\tau^-$pairs with either $\tau_h\tau_h$or $\ell\tau_h$signatures. These procedures are described in the rest of this section.

Highly collimated $\tau_h\tau_h$or $\ell\tau_h$pairs are quite challenging to reconstruct and require the use of a special boosted reconstruction algorithm [52]. The procedure begins by using the Cambridge–Aachen algorithm [53] with a distance parameter of 0.8 to identify jets with a large cone size, called CA8 jets. For each CA8 jet with $p_T > 100\,\mathrm{GeV}$, the last step of the clustering is retracted, resulting in two subjets. If these subjets are found to have $p_T > 10\,\mathrm{GeV}$ and satisfy the mass drop condition, which requires $\max(m_{\mathrm{subjet\,1}}, m_{\mathrm{subjet\,2}})/m_{\mathrm{CA8\ jet}} < 2/3$, the two subjets are used as inputs to the standard τ lepton reconstruction, the "hadron-plus-strips" (HPS) algorithm [54], to build the $\tau_h$candidates. Here, $m_{\mathrm{subjet\,1}}$and $m_{\mathrm{subjet\,2}}$are the masses of the two subjets, and $m_{\mathrm{CA8\ jet}}$is the mass of the original CA8 jet. If the $p_T$and mass drop conditions are not met, the unclustering and identification procedures are repeated iteratively for the most energetic subjet. We will refer to τ leptons reconstructed in this fashion as boosted τ_h.

The boosted reconstruction algorithm is not well suited for Hbosons with lower Lorentz boost, as is typical of lower resonance mass signal hypotheses around 1 to 1.5 TeV. To cover this topology, we instead reconstruct single $\tau_h$candidates using AK4 jets as inputs to the same HPS algorithm. These are referred to as standard τ_h.

The final selection of $\tau_h$candidates, whether boosted or standard, requires $|\eta| < 2.5$ and $p_T > 20\,\mathrm{GeV}$, along with a convolutional neural network based tagger score above a specified threshold corresponding to per-$\tau_h$signal efficiency greater than 95%. The identification of boosted $\tau_h$candidates was developed specifically for this analysis and is based on the DEEPTAU architecture originally designed for standard τ leptons. This tagger, referred to as BOOSTEDDEEPTAU throughout the article, is trained to distinguish genuine boosted τ leptons from background jets by leveraging both high-level features derived from the boosted τ reconstruction and low-level detector information. Among its important inputs are a global event-level variable related to the average energy deposition in the event and 42 high-level variables that capture the kinematic properties, isolation, and finite lifetime signature of boosted τ leptons. Many of these variables have also proven effective in previously developed τ identification algorithms, such as a discriminator based on a boosted decision tree (MVA Iso) [52].

The training of the BOOSTEDDEEPTAU algorithm is performed using simulated samples. Genuine boosted τ leptons are taken from simulated spin-0 signal samples, while the dominant backgrounds—QCD multijet, $t\bar{t}$, and Drell–Yan processes—are included to ensure comprehensive coverage of the relevant phase space. The training samples include various mass points and are shuffled to balance the boosted τ lepton population across p_T, η, and other relevant variables. The resultant BOOSTEDDEEPTAU tagger shows a discrimination power that is a factor 2–4 better than MVA Iso evaluated on boosted τ leptons for $p_T < 100\,\mathrm{GeV}$ and more than a factor of 10 better for $p_T > 100\,\mathrm{GeV}$. Additional information about the BOOSTEDDEEPTAU algorithm can be found in Ref. [55].

Electrons from leptonic tau decays are reconstructed in the region $|\eta| < 2.5$ by matching energy deposits in the ECAL with tracks reconstructed in the tracker [56]. Electron identification is based on the distribution of energy deposited along the electron trajectory, and the direction and momentum of the track in the inner tracker. Additional requirements are applied to remove electrons produced through photon conversions. Electrons are also required to be isolated from other particles in the detector, by imposing an upper threshold on the relative isolation parameter. The electron isolation parameter is defined as the magnitude of the $p_T$sum of all the PF candidates (excluding the electron) within $\Delta R < 0.3$ around the electron direction, after the contributions from pileup and particles associated with reconstructed $\tau_h$candidates within the isolation cone have been removed. The resulting sum is then divided by the electron p_T, yielding a corrected relative isolation variable I^{e}_{rel}, which is required to satisfy $I^{e}_{\mathrm{rel}} < 0.112 + 0.506/p_T$ in the ECAL barrel

($|\eta| < 1.479$) and $I_{\mathrm{rel}}^{\mathrm{e}} < 0.108 + 0.963/p_{\mathrm{T}}$ in the ECAL endcaps ($1.479 < |\eta| < 2.5$), with p_{T}in GeV.

Muons from leptonic tau decays are reconstructed within the acceptance of the CMS muon system, $|\eta| < 2.4$, using information from both the muon spectrometer and the silicon tracker [57]. Muon candidates are identified based on the compatibility of tracks reconstructed in the silicon tracker with tracks reconstructed from a combination of hits in both the tracker and the muon detector. In addition, the trajectory is required to be compatible with originating from the primary vertex, and to have a sufficient number of hits in the tracker and muon systems. Muons are required to be isolated by applying a relative isolation criterion. Specifically, the scalar sum of the $p_{\mathrm{T}}$of all PF candidates within a cone of $\Delta R < 0.4$ around the muon direction—excluding the muon itself—is computed. Contributions from particles associated with reconstructed τ_{h}candidates within the isolation cone are subtracted. The resulting sum is then divided by the muon p_{T}, yielding a corrected relative isolation variable I_{rel}^{μ}, which is required to satisfy $I_{\mathrm{rel}}^{\mu} < 0.25$. This procedure is very similar to that followed for the electrons.

The standard (boosted) τ_{h}candidates are either combined with another standard (boosted) τ_{h}candidate or with a leptonic τ decay identified as an electron or a muon, to form $\tau^+\tau^-$pairs. Both standard $\tau_{\mathrm{h}}$and boosted τ_{h}candidates are required to be distinct from the selected AK8 jet in the event.

5 Event selection

As mentioned earlier in Sect. 3, events are selected using a suite of $p_{\mathrm{T}}^{\mathrm{miss}}$and $H_{\mathrm{T}}^{\mathrm{miss}}$triggers. For the heavy parent resonance masses considered in this analysis, the H bosons are produced with large Lorentz boosts. As a result, the neutrinos from the $\tau^+\tau^-$decay carry substantial momentum, and signal events are therefore expected to exhibit large $p_{\mathrm{T}}^{\mathrm{miss}}$, ensuring high efficiency of the $p_{\mathrm{T}}^{\mathrm{miss}}$and $H_{\mathrm{T}}^{\mathrm{miss}}$triggers. A stringent offline requirement of $p_{\mathrm{T}}^{\mathrm{miss}} > 180\,\mathrm{GeV}$ is applied after the full event reconstruction, to ensure a stable trigger efficiency and to suppress the background contribution from multijet events. The efficiency of the trigger for events satisfying the offline event selection, measured in an independent sample of events selected with muon triggers, is found to be greater than 95%, with an uncertainty of 1.1%.

All events are required to contain one Hboson candidate decaying to either $\ell\tau_{\mathrm{h}}$ or $\tau_{\mathrm{h}}\tau_{\mathrm{h}}$. If multiple candidate pairs are possible, the pair with the highest visible $p_{\mathrm{T}}$is selected. The other Hboson candidate decaying to $\mathrm{b\bar{b}}$ is reconstructed as an AK8 jet that does not overlap with the $\tau^+\tau^-$system. The same AK8 jet kinematic selection and identification requirements are applied in both channels. If multiple AK8 jet candidates are present, the jet with the highest $p_{\mathrm{T}}$is selected. The $\mathrm{H} \to \mathrm{b\bar{b}}$ candidate jet is also required to satisfy the PARTICLENET $\mathrm{b\bar{b}}$ tagging requirement corresponding to a working point with 80% efficiency for selecting signal jets from $\mathrm{H} \to \mathrm{b\bar{b}}$ decays. This criterion significantly suppresses background from QCD multijet events and jets produced in association with vector bosons. Events with top quark pairs or single top quarks are suppressed by vetoing events with b-tagged AK4 jets that do not overlap with the AK8 $\mathrm{H} \to \mathrm{b\bar{b}}$ candidate and are distinct from the identified $\mathrm{H} \to \tau^+\tau^-$ objects.

Additional selection criteria are applied to suppress SM contributions, including those from meson and baryon resonances, W+jets, $\mathrm{t\bar{t}}$, and single top quark production. To reduce contamination from misidentified τ leptons in W+jetsevents, the angular separation $\Delta R_{\tau^+\tau^-}$ between the two τ candidates is required to be less than 1.5. Additionally, we require the difference in the azimuthal angle between the AK8 jet, identified as the Hboson through the $\mathrm{H} \to \mathrm{b\bar{b}}$ decay, and $\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}$to be greater than 1. This requirement ensures that the Higgs boson candidate and the missing transverse momentum are well separated in the transverse plane, typically appearing on opposite sides of the event, as expected in signal-like topologies. To reduce contributions from low-p_{T}radiation, the soft-drop (SD) [58] jet mass of the $\mathrm{H} \to \mathrm{b\bar{b}}$ candidate jet is required to be greater than 30 GeV. Furthermore, the visible mass of the Hboson decaying into $\tau^+\tau^-$must be greater than 20 GeVto suppress low-mass and quarkonium backgrounds.

An algorithm called FASTMTT [59], based on a dynamical likelihood approach, is used to reconstruct the four momentum of the di-τ system, including the missing information from neutrinos. This method incorporates the measured momentum of the visible τ decay products, the reconstructed $p_{\mathrm{T}}^{\mathrm{miss}}$, and its resolution to enhance the reconstruction accuracy. To speed up the computation, the algorithm applies the collinear approximation [60], which assumes that the neutrinos from τ decays are collinear with the visible decay products. The $\mathrm{H} \to \mathrm{b\bar{b}}$ candidate four-momentum is formed using kinematic variables obtained from the standard AK8 jet reconstruction algorithm, to which energy and resolution corrections are applied to match the response in data.

The reconstructed resonance candidate mass M_{X}, defined as the invariant mass of the tagged $\mathrm{H} \to \mathrm{b\bar{b}}$ candidate jet and the FASTMTT reconstructed di-τ system, is required to be larger than 750 GeVto ensure full trigger and reconstruction efficiencies. All selections, except for the PARTICLENET $\mathrm{b\bar{b}}$-tagging and the AK4 b-tagged event veto, are collectively referred to as the “pre-selection” in this analysis. The distributions of important kinematic variables for the full event selection are shown in Figs. 2 and 3.

The full event selection efficiency, including the trigger selections, for spin-0 (spin-2) resonances ranges from 2% (2.7%) to 13.5% (14.4%) in the $\tau_{\mathrm{h}}\tau_{\mathrm{h}}$ channel and from 4% (5.4%) to 11% (11.8%) in the $\ell\tau_{\mathrm{h}}$ channel, depending on the mass of the resonance. Additionally, events from the $\mathrm{HH} \to \mathrm{b\bar{b}\,VV}$ processes contribute approximately 20% of the total

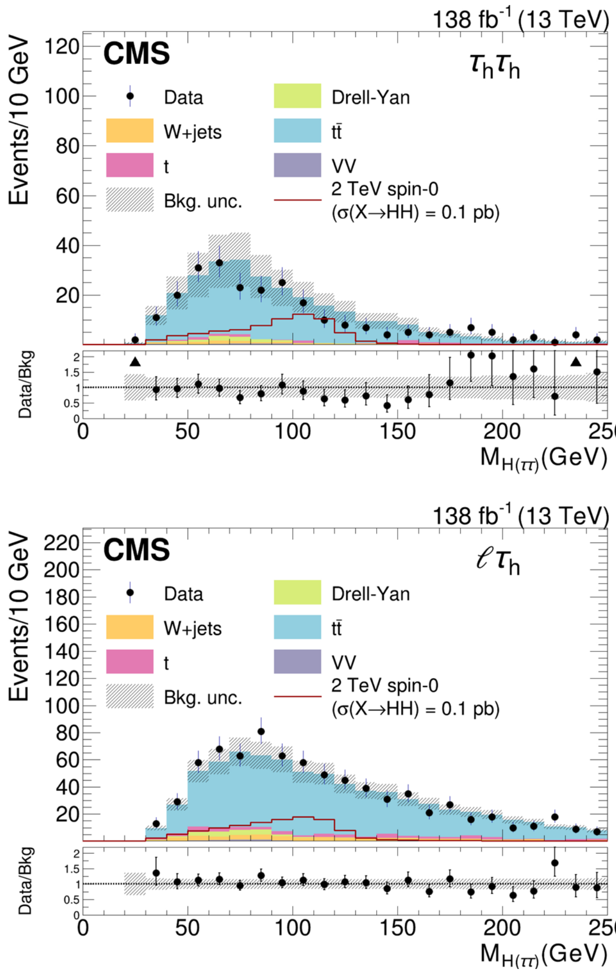

Fig. 2 Distribution of the invariant mass of the di-τ system, reconstructed with the FastMTT algorithm, after the full event selection in the $\tau_h\tau_h$(upper) and $\ell\tau_h$(lower) channels. The data (solid circles) are compared to the background simulation (filled histograms), where the gray bands represent the total background uncertainty, obtained from the post-fit values of the dominant systematic uncertainties and the statistical uncertainties in the simulated samples. The X → HH signal simulation (solid red line) is overlaid and normalized to $\sigma(X \to HH) = 0.1$ pb for illustration. The ratio between the data and the total expected background contribution is shown in the lower panel, where a solid black triangle indicates those bins where the ratio exceeds the axis range

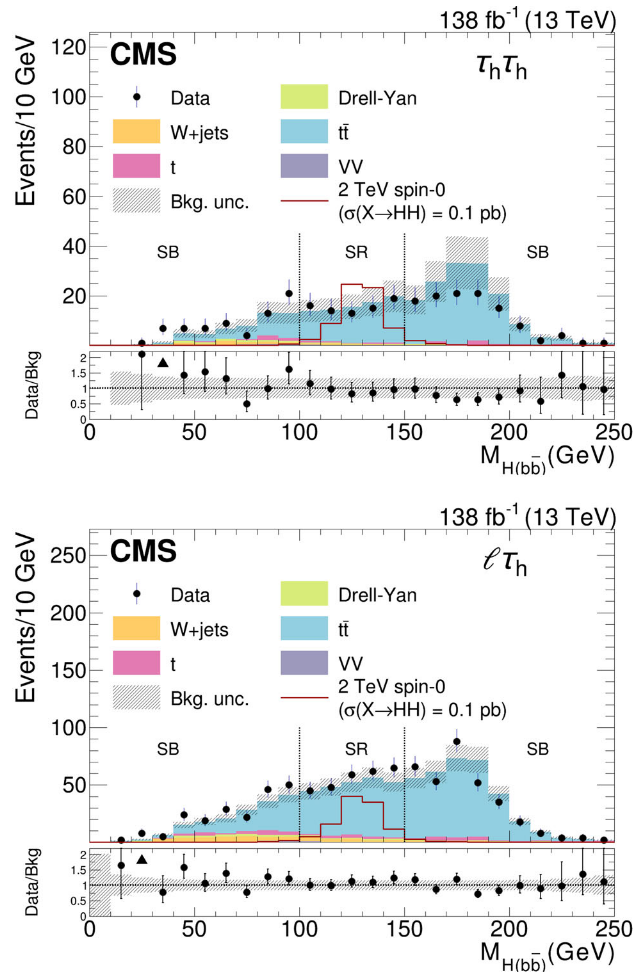

Fig. 3 Distribution of $M_{H(b\bar{b})}$obtained from the leading AK8 jet in the event after the full event selection for the $\tau_h\tau_h$(upper) and $\ell\tau_h$(lower) channels. The signal-enriched region (SR) is defined as $100 < M_{H(b\bar{b})} < 150$ GeV. The sideband (SB) is immediately adjacent to the SR, on either side. The data (solid circles) are compared to the background simulation (filled histograms), where the gray bands represent the total background uncertainty, obtained from the post-fit values of the dominant systematic uncertainties and the statistical uncertainties in the simulated samples. The X → HH signal simulation (solid red line) is overlaid and normalized to $\sigma(X \to HH) = 0.1$ pb for illustration. The ratio between the data and the total expected background contribution is shown in the lower panel, where a solid black triangle indicates those bins where the ratio exceeds the axis range

yield of the HH $\to b\bar{b}\tau^+\tau^-$ signal. Around 90% of the selected HH $\to b\bar{b}$VV events originate from genuine $\ell\tau_h$ or $\tau_h\tau_h$ final states.

To extract a potential resonant HHsignal, a maximum likelihood fit is performed using the M_X distributions in data in the $\ell\tau_h$and $\tau_h\tau_h$channels. These fits are performed using the CMS statistical analysis tool Combine [61], which is based on the RooFit [62] and RooStats [63] frameworks. Accurate modeling of the major backgrounds is essential for the signal extraction. The strategy for estimating this is described in the following section.

6 Background estimation

After the event pre-selection, the leading SM background contributions in the different regions are from $t\bar{t}$, Z+jets, and W+jetsproduction. Following the full event selection, the $t\bar{t}$ process becomes the dominant background, as shown in Figs. 2 and 3. The QCD multijet contribution is negligible owing to the lepton requirement in the $\ell\tau_h$channel, and the combined effect of the BoostedDeepTau/DeepTau and the ParticleNet-based AK8 H $\to b\bar{b}$ selections in the $\tau_h\tau_h$channel.

The SR and SB regions are defined using the reconstructed $M_{\mathrm{H(b\bar{b})}}$ distribution, as shown in Fig. 3. The $M_{\mathrm{H(b\bar{b})}}$ distribution is used only to categorize events into regions, whereas the final discriminant used in the fit is the M_{X} distribution. We use the data in the SB to constrain the normalization and the M_{X} shape of the top quark background in the SR, where the top quark background in both the SR and the SB combines the contributions from $\mathrm{t\bar{t}}$ and single top quark production. This is achieved by introducing unconstrained, bin-by-bin multiplicative parameters for each bin of the M_{X} distribution. These parameters simultaneously adjust the yield of the top quark background per M_{X} bin in both the SR and SB for the corresponding channel during the fit.

7 Systematic uncertainties

Various sources of systematic uncertainties are taken into account, in most cases affecting both the signal and the background. We distinguish between two types of systematic uncertainties: those that affect only the overall normalization of a process and those that also impact the shape of the reconstructed resonance mass spectrum, which serves as the primary fit observable in the analysis (Table 1).

The following sources of uncertainty are taken into account using constrained nuisance parameters in the fit for all processes. These parameters are used to encode the impact of systematic uncertainties on the expected signal and background yields and shapes. Unless specified otherwise, these are considered correlated across the data taking years. An exception is made for the top quark background. The constrained nuisance parameters included for the top quark background account only for the statistical uncertainties. Systematic uncertainties that impact the top quark background are included in the simultaneous fit to data in the SR and SB through unconstrained bin-by-bin multiplicative parameters, as described in Sect. 6. The resulting post-fit uncertainties in these parameters reflect the fit uncertainty in the top quark background prediction.

– *Integrated luminosity*: The integrated luminosities for the 2016, 2017, and 2018 data-taking years have 1.2–2.5% individual uncertainties [64,65], while the overall uncertainty for the 2016–2018 period is 1.6%.
– p_T^{miss} *trigger*: A normalization uncertainty of 1.1% is assigned to all processes, based on the level of agreement observed between data and simulation.
– *Lepton identification and isolation*: A normalization uncertainty is assigned to account for the residual differences between data and simulation in the lepton identification and isolation efficiencies after applying all corrections. In the $\ell\tau_{\mathrm{h}}$ channel, a 0.4% uncertainty is applied for both electron identification and isolation, and 1% (0.1%) for muon identification (isolation), affecting all processes.
– ParticleNet *AK8* $\mathrm{b\bar{b}}$*-tagging*: A 5% normalization uncertainty is applied to signal AK8 jets to account for the residual data-to-simulation mismodeling of btagging. This uncertainty reflects the relatively uniform effect of the btagging uncertainty across the p_{T}spectrum of the AK8 jets.

The following sources of uncertainty affect the shape of the distributions, as well as the normalization of the various backgrounds and the signal, and are applied to all search channels.

– *PDF uncertainties*: Uncertainties from the PDFs are estimated by reweighting the samples with the NNPDF3.0 [66] replicas [67] for the 2016 data set and NNPDF3.1 [42] for the 2017 and 2018 data sets. The variations across the replicas are used to construct an envelope that captures the spread in predictions, which is then taken as the systematic uncertainty.
– *Factorization and renormalization scales*: Variations in the renormalization and factorization scales by factors of 0.5 and 2.0 are considered independently with the exception of simultaneously varying both. Their impact is calculated from the envelope of these variations and included as systematic uncertainties for all processes.
– *Pileup modeling*. Systematic uncertainties from pileup modeling are taken into account by varying the total inelastic cross section used to calculate pileup distributions in simulation by ±4.6% [68].
– *Jet energy scale and resolution*: Reconstructed jet four-momenta in the simulation are varied according to the uncertainties in the jet energy scale, which are split into 11 different sources. Additionally, the $p_{\mathrm{T}}$of the jets is stochastically changed within the detector resolution. These uncertainties are coherently propagated to all observables, including $p_{\mathrm{T}}^{\mathrm{miss}}$ [69]. Some of the 11 sources are uncorrelated across the data taking years. The average effect from these sources of uncertainty ranges from 2 to 5%.
– p_T^{miss} *mismodeling*: An additional source of uncertainty specific to $p_{\mathrm{T}}^{\mathrm{miss}}$arises from unclustered energy, primarily due to calorimeter deposits not associated with any reconstructed object. This unclustered energy is varied within its uncertainties, and the resulting impact is propagated to the $p_{\mathrm{T}}^{\mathrm{miss}}$.
– *b tagging*: The btagging and light-flavor misidentification efficiency scale factors, along with their associated uncertainties, are measured using independent control samples [70]. The uncertainties in these scale factors are then propagated to the analysis. Some sources of these uncertainties are uncorrelated across data taking years.

Table 1 Summary of the dominant systematic uncertainty sources and the typical size of their inferred variation in the resonance yield. Unless otherwise specified, the impact is the same for the $\tau_h\tau_h$ and $\ell\tau_h$ channels. Sources with an overall impact of less than 1% on the resonance yield, such as electron or muon reconstruction and identification, are not listed in the table

Systematic source	Variation
Boosted τ_h lepton identification	20% for $\tau_h\tau_h$, 10% for $\ell\tau_h$
τ_h energy scale	10%
Renormalization and factorization scales	5–10%
PDF uncertainties	5–7%
PARTICLENET AK8 $b\bar{b}$ tagging	5% (signal jets)
Jet energy scale and resolution	2–5%
Pileup modelling	1–5%
Electroweak and QCD k-factors for V+jets	1–5%
Integrated luminosity	1.6%
p_T^{miss} trigger	1.1%

- *Simulation sample size*: Uncertainties due to the limited size of the simulated signal and background samples are included by allowing each bin of the distributions used in the signal extraction to fluctuate independently according to the statistical uncertainties in simulation [71].
- *Uncertainty related to ECAL mistiming*: Partial mistiming of signals in the forward regions of the ECAL endcaps led to a minor reduction in trigger efficiency. Simulations are corrected to emulate the behavior of the data, and the uncertainty in these corrections is propagated to the distributions used in the signal extraction.
- *Electroweak and QCD k-factors*: Uncertainties in the NLO/LO k-factors [33–38] calculated for W+jetsand Z+jetsprocesses are considered. These uncertainties account for missing higher-order corrections. For QCD, this comes from variations of the factorization and renormalization scales. For electroweak processes, an estimate of the size of the missing higher-order corrections is obtained by taking the difference between applying and not applying the NLO/LO electroweak k factors.
- *Hadronically decaying τ lepton identification*: Uncertainties in the DEEPTAU efficiency corrections, for the discrimination of genuine τ_h against jet, electron, and muon are correlated across τ decay modes and years for the standard τ leptons. Correction factors are derived to account for differences between data and simulation in the identification of boosted τ leptons from the BOOSTEDDEEPTAU algorithm. These were derived using boosted Zboson decays, utilizing events with a spatially close muon–τ pair. A simultaneous fit is then performed in the $\mu\tau_h$ SR and a dimuon control region, with the latter constraining the normalization of the Drell–Yan process. The data-to-simulation factors were found to be 0.90 per identified boosted τ lepton, with an associated uncertainty of 10%. This corresponds to a normalization uncertainty of 20% in the $\tau_h\tau_h$ channel and 10% in the $\ell\tau_h$ channel [55].
- *Hadronically decaying τ lepton energy scale*: For the τ_h energy scale contribution to the systematic uncertainty, the four-momenta of reconstructed and identified τ_h, including both standard and boosted τ_h objects, are varied by $\pm 3\%$ [52]. The resulting variations are propagated to all kinematic observables used in the analysis. For minor backgrounds, this effect is accounted for by a 10% normalization uncertainty, while for the signal a dedicated shape systematic is assigned.

8 Results

The analysis follows a blinded strategy, with all aspects of the event selection, background estimation, and statistical fitting procedure defined prior to unblinding data in the SR. The post-fit distributions in M_X are shown in Fig. 4 for the SR and SB. In the lower mass region, where the expected background yield is higher, we use a binning comparable to the expected signal width. For resonance masses above 2 TeV, the background event counts become sparse. We therefore merge adjacent bins to avoid empty bins. The content of the final bin also includes events in the overflow region. The data are found to be in agreement with the SM background predictions within the uncertainties. We place upper limits on the production cross section for a heavy resonance Xdecaying to a pair of Higgs bosons.

The 95% CLupper limits on the $X \to HH$ production for spin-0 and spin-2 resonances in the mass range from 1 to 4.5 TeV, computed using the modified frequentist CL_s method with a profile likelihood ratio test statistic, are shown in Fig. 5. The distributions of the test statistic under the signal-plus-background and background-only hypotheses are obtained from ensembles of pseudo-experiments. The results are scaled by the SM branching fractions of the Hbosons and the subsequent decays included in this analysis. The observed (expected) upper limits reach down to 62.2 fb (76.2 fb) for spin-0 and 42.5 fb (51.8 fb) for spin-2 at 1 TeV.

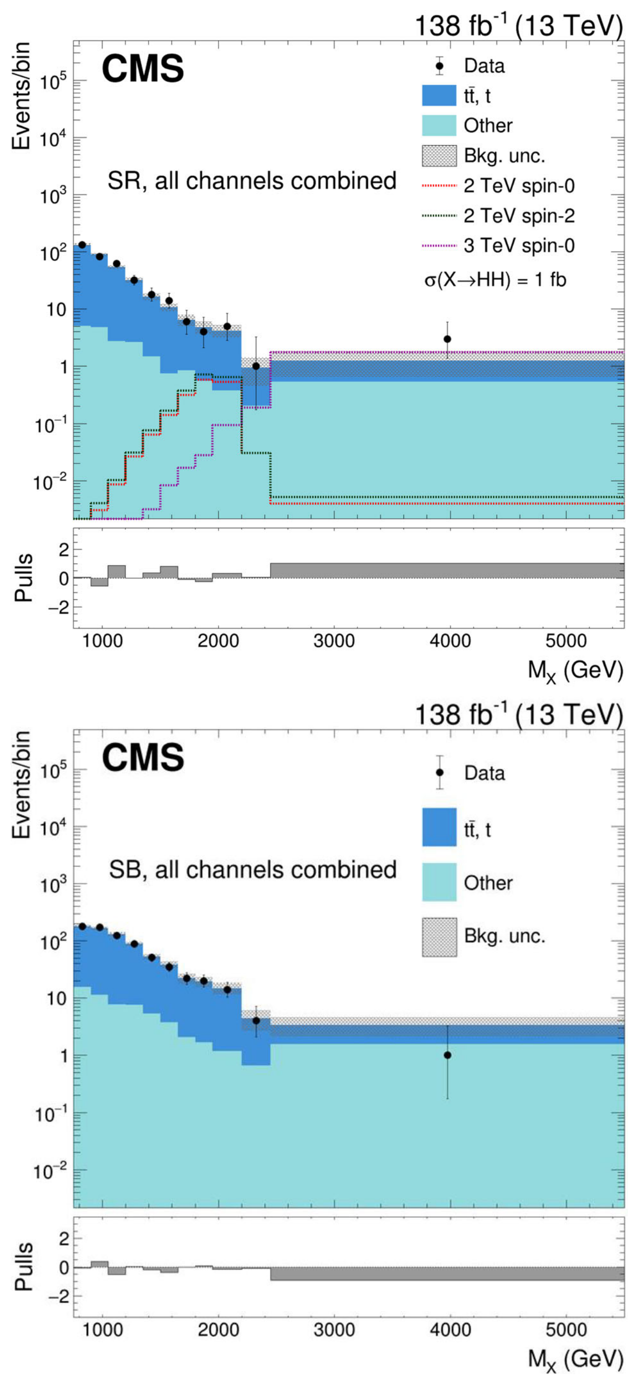

Fig. 4 Post-fit reconstructed mass distribution of resonance Xin the SR (upper) and SB (lower) after applying all selection criteria, for the sum of the $\tau_h\tau_h$and $\ell\tau_h$channels. Minor background contributions are grouped into a single category labeled "Other". Also shown are several signal predictions in dashed colored lines for visualization only. The lower panels show the "Pull" defined as (Data - Prediction)/Total uncertainty

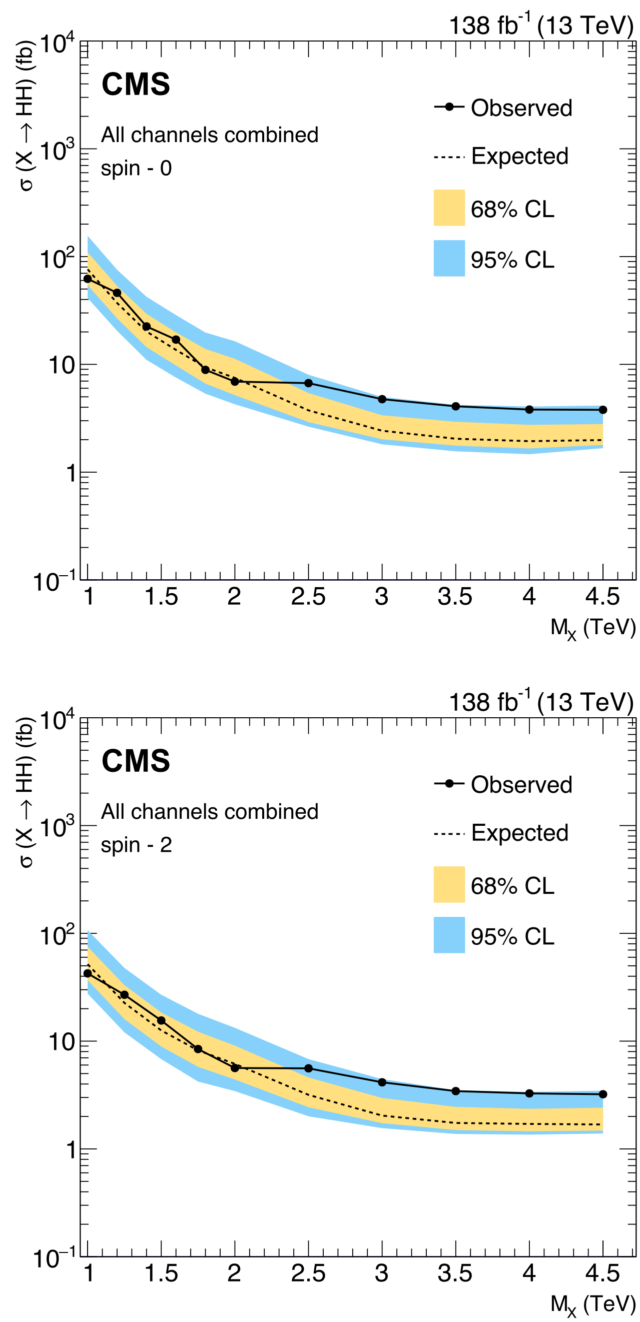

Fig. 5 Expected and observed upper limits at 95% CL on the production cross section of resonant HHproduction for a spin-0 (upper) and spin-2 (lower) narrow resonance. This calculation assumes SM branching fractions of the Hboson as discussed in Section 1. The observed limits are higher than the expected limits for mass points above 2.5 TeV, primarily because of the excess of events visible in the highest bin of Fig. 4 (upper)

At 4.5 TeV, the observed (expected) upper limits are 3.8 fb (2 fb) for spin-0 and 3.2 fb (1.7 fb) for spin-2. The results for spin-2 are broadly similar to those for spin-0. However, the p_T^{miss}spectrum for spin-2 signals is shifted toward higher values, which slightly increases the signal efficiency. This effect is visible in the superimposed signal templates for spin-0 and spin-2 in Fig. 4 and is reflected in the slightly stronger expected limits for the spin-2 scenario. The observed limits are higher than the expected limits for mass points above 2.5

TeV, primarily because of the excess of events visible in the highest bin of Fig. 4 (upper).

This analysis improves upon the spin-0 resolved ATLAS search [15] for resonance masses above 1.4 TeV. Furthermore, it is significantly better than the spin-0 search from ATLAS in the Lorentz-boosted regime [14], covering the 1–3 TeV mass range, across the entire mass range considered in that analysis. The results presented in this paper represent the most sensitive upper limits to date in the resonance mass range of 1.4–4.5 TeV in the $b\bar{b}\tau^+\tau^-$ final state.

9 Summary

A search has been presented for heavy resonant Higgs boson pair (HH) production in the $b\bar{b}\tau^+\tau^-$ final state, exploring resonance masses between 1 and 4.5 TeV. The analysis is based on pp collision data collected with the CMS detector during 2016–2018, corresponding to an integrated luminosity of 138 fb^{-1}at a center-of-mass energy of 13 TeV. In this mass regime, the Hbosons produced are boosted sufficiently to result in collimated decay products. The reconstruction and identification of such boosted objects are enhanced using advanced machine learning techniques, including a graph convolutional neural network for merged $b\bar{b}$ jets and a convolutional neural network for boosted $\tau^+\tau^-$identification.

No significant deviation from the standard model background expectation is observed, and 95% confidence level upper limits are set on the production cross section of a heavy resonance decaying to HH, evaluated independently for both spin-0 and spin-2 hypotheses. This analysis sets the most sensitive upper bounds to date on the production of $X \rightarrow HH \rightarrow b\bar{b}\tau^+\tau^-$ in the mass range of 1.4–4.5 TeV.

Acknowledgements We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers 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, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: SC (Armenia), BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); ERC PRG, TARISTU24-TK10 and MoER TK202 (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); SRNSF (Georgia); BMFTR, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIT and NRF (Republic of Korea); MES (Latvia); LMTLT (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES, NSC, and NAWA (Poland); FCT (Portugal); MESTD (Serbia); MICIU/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI (Thailand); TUBITAK and TENMAK (Türkiye); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA). Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract nos. 675440, 724704, 752730, 758316, 765710, 824093, 101115353, 101002207, 101001205, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Science Committee, project no. 22rl-037 (Armenia); the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA) and Fonds voor Wetenschappelijk Onderzoek contract no. 1228724N (Belgium); the Beijing Municipal Science and Technology Commission, No. Z191100007219010, the Fundamental Research Funds for the Central Universities, the Ministry of Science and Technology of China under Grant no. 2023YFA1605804, the Natural Science Foundation of China under Grant no. 12535004, and USTC Research Funds of the Double First-Class Initiative No. YD2030002017 (China); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Shota Rustaveli National Science Foundation, Grant FR-22-985 (Georgia); the Deutsche Forschungsgemeinschaft (DFG), among others, under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306, and under project number 400140256 - GRK2497; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Hungarian Academy of Sciences, the New National Excellence Program - ÚNKP, the NKFIH research Grants K 131991, K 133046, K 138136, K 143460, K 143477, K 146913, K 146914, K 147048, 2020-2.2.1-ED-2021-00181, TKP2021-NKTA-64, and 2025-1.1.5-NEMZ_KI-2025-00004 (Hungary); the Council of Science and Industrial Research, India; ICSC – National Research Center for High Performance Computing, Big Data and Quantum Computing, FAIR – Future Artificial Intelligence Research, and CUP I53D23001070006 (Mission 4 Component 1), funded by the NextGenerationEU program (Italy); the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369, 2021/43/B/ST2/01552, 2023/49/B/ST2/03273, and the NAWA contract BPN/PPO/2021/1/00011 (Poland); the Fundação para a Ciência e a Tecnologia, Grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MICIU/AEI/10.13039/501100011033, ERDF/EU, "European Union NextGenerationEU/PRTR", and Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, the National Science, Research and Innovation Fund program IND_FF_68_369_2300_097, and the Program Management Unit for Human Resources and Institutional Development, Research and Innovation, Grant B39G680009 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

Data Availability Statement Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, re-use and open access policy.

Code Availability Statement This manuscript has associated code/software in a data repository. [Author's comment: The CMScore software is publicly available on GitHub (https://github.com/cms-sw/cmssw).]

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Funded by SCOAP[3].

References

1. CMS Collaboration, Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. Phys. Lett. B **716**, 30 (2012). https://doi.org/10.1016/j.physletb.2012.08.021. arXiv:1207.7235
2. CMS Collaboration, Observation of a new boson with mass near 125 GeV in pp collisions at $\sqrt{s} = 7$ and 8 TeV. JHEP **06**, 081 (2013). https://doi.org/10.1007/JHEP06(2013)081. arXiv:1303.4571
3. 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**, 1 (2012). https://doi.org/10.1016/j.physletb.2012.08.020. arXiv:1207.7214
4. ATLAS Collaboration, Evidence for the spin-0 nature of the Higgs boson using ATLAS data. Phys. Lett. B **726**, 120 (2013). https://doi.org/10.1016/j.physletb.2013.08.026. arXiv:1307.1432
5. M.E. Peskin, What is the hierarchy problem? Nucl. Phys. B **1018**, 116971 (2025). https://doi.org/10.1016/j.nuclphysb.2025.116971. arXiv:2505.00694
6. L. Randall, R. Sundrum, A large mass hierarchy from a small extra dimension. Phys. Rev. Lett. **83**, 3370 (1999). https://doi.org/10.1103/PhysRevLett.83.3370. arXiv:hep-ph/9905221
7. L. Randall, R. Sundrum, An alternative to compactification. Phys. Rev. Lett. **83**, 4690 (1999). https://doi.org/10.1103/PhysRevLett.83.4690. arXiv:hep-th/9906064
8. W.D. Goldberger, M.B. Wise, Modulus stabilization with bulk fields. Phys. Rev. Lett. **83**, 4922 (1999). https://doi.org/10.1103/PhysRevLett.83.4922. arXiv:hep-ph/9907447
9. O. DeWolfe, D. Freedman, S.S. Gubser, A. Karch, Modeling the fifth dimension with scalars and gravity. Phys. Rev. D **62**, 046008 (2000). https://doi.org/10.1103/PhysRevD.62.046008. arXiv:hep-th/9909134
10. C. Csaki, M. Graesser, L. Randall, J. Terning, Cosmology of brane models with radion stabilization. Phys. Rev. D **62**, 045015 (2000). https://doi.org/10.1103/PhysRevD.62.045015. arXiv:hep-ph/9911406
11. H. Davoudiasl, J. Hewett, T. Rizzo, Phenomenology of the Randall–Sundrum gauge hierarchy model. Phys. Rev. Lett. **84**, 2080 (2000). https://doi.org/10.1103/PhysRevLett.84.2080. arXiv:hep-ph/9909255
12. K. Agashe, H. Davoudiasl, G. Perez, A. Soni, Warped gravitons at the CERN LHC and beyond. Phys. Rev. D **76**, 036006 (2007). https://doi.org/10.1103/PhysRevD.76.036006. arXiv:hep-ph/0701186
13. CMS Collaboration, Search for heavy resonances decaying into two Higgs bosons or into a Higgs boson and a W or Z boson in proton-proton collisions at 13 TeV. JHEP **01**, 051 (2019). https://doi.org/10.1007/JHEP01(2019)051. arXiv:1808.01365
14. ATLAS Collaboration, Reconstruction and identification of boosted di-τ systems in a search for Higgs boson pairs using 13TeV proton-proton collision data in ATLAS. JHEP **11**, 163 (2020). https://doi.org/10.1007/JHEP11(2020)163. arXiv:2007.14811
15. ATLAS Collaboration, Search for resonant and non-resonant Higgs boson pair production in the $b\bar{b}\tau^+\tau-$ decay channel using 13 TeV pp collision data from the ATLAS detector. JHEP **07**, 040 (2023). https://doi.org/10.1007/JHEP07(2023)040. arXiv:2209.10910
16. LHC Higgs Cross Section Working Group, Handbook of LHC Higgs cross sections: 4. Deciphering the nature of the Higgs sector. CERN Report CERN-2017-002-M, 2016. https://doi.org/10.23731/CYRM-2017-002. arXiv:1610.07922
17. Particle Data Group, S. Navas et al., Review of particle physics. Phys. Rev. D **110**, 030001 (2024). https://doi.org/10.1103/PhysRevD.110.030001
18. H. Qu, L. Gouskos, Jet tagging via particle clouds. Phys. Rev. D **101**, 056019 (2020). https://doi.org/10.1103/PhysRevD.101.056019. arXiv:1902.08570
19. CMS Collaboration, Search for narrow high-mass resonances in proton–proton collisions at $\sqrt{s} = 8$ TeV decaying to Z and Higgs bosons. Phys. Lett. B **748**, 255 (2015). https://doi.org/10.1016/j.physletb.2015.07.011. arXiv:1502.04994
20. CMS Collaboration, Identification of hadronic tau lepton decays using a deep neural network. JINST **17**, P07023 (2022). https://doi.org/10.1088/1748-0221/17/07/P07023. arXiv:2201.08458
21. HEPData record for this analysis, 2026. https://doi.org/10.17182/hepdata.166218
22. CMS Collaboration, The CMS experiment at the CERN LHC. JINST **3**, S08004 (2008). https://doi.org/10.1088/1748-0221/3/08/S08004
23. CMS Collaboration, Development of the CMS detector for the CERN LHC Run 3. JINST **19**, P05064 (2024). https://doi.org/10.1088/1748-0221/19/05/P05064. arXiv:2309.05466
24. CMS Collaboration, The CMS trigger system. JINST **12**, P01020 (2017). https://doi.org/10.1088/1748-0221/12/01/P01020. arXiv:1609.02366
25. CMS Collaboration, Performance of the CMS Level-1 trigger in proton–proton collisions at $\sqrt{s} = 13$ TeV. JINST **15**, P10017 (2020). https://doi.org/10.1088/1748-0221/15/10/P10017. arXiv:2006.10165
26. CMS Collaboration, Performance of the CMS high-level trigger during LHC Run 2. JINST **19**, P11021 (2024). https://doi.org/10.1088/1748-0221/19/11/P11021. arXiv:2410.17038
27. CMS Collaboration, Technical proposal for the Phase-II upgrade of the Compact Muon Solenoid. CMS Technical Proposal CERN-LHCC-2015-010, CMS-TDR-15-02, 2015. https://doi.org/10.17181/CERN.VU8I.D59J
28. S. Frixione, P. Nason, C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method. JHEP **11**, 070 (2007). https://doi.org/10.1088/1126-6708/2007/11/070. arXiv:0709.2092
29. S. Alioli, P. Nason, C. Oleari, E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX. JHEP **06**, 043 (2010). https://doi.org/10.1007/JHEP06(2010)043. arXiv:1002.2581
30. M. Czakon et al., Top-pair production at the LHC through NNLO QCD and NLO EW. JHEP **10**, 186 (2017). https://doi.org/10.1007/JHEP10(2017)186. arXiv:1705.04105
31. 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**, 079 (2014). https://doi.org/10.1007/JHEP07(2014)079. arXiv:1405.0301
32. M.L. Mangano, M. Moretti, F. Piccinini, M. Treccani, Matching matrix elements and shower evolution for top-pair production in hadronic collisions. JHEP **01**, 013 (2007). https://doi.org/10.1088/1126-6708/2007/01/013. arXiv:hep-ph/0611129
33. A. Denner, S. Dittmaier, T. Kasprzik, A. Muck, Electroweak corrections to W+jet hadroproduction including leptonic W-boson decays. JHEP **08**, 075 (2009). https://doi.org/10.1088/1126-6708/2009/08/075. arXiv:0906.1656
34. A. Denner, S. Dittmaier, T. Kasprzik, A. Muck, Electroweak corrections to dilepton+jet production at hadron colliders. JHEP **06**, 069 (2011). https://doi.org/10.1007/JHEP06(2011)069. arXiv:1103.0914
35. A. Denner, S. Dittmaier, T. Kasprzik, A. Maeck, Electroweak corrections to monojet production at the LHC. Eur. Phys. J. C **73**, 2297 (2013). https://doi.org/10.1140/epjc/s10052-013-2297-x. arXiv:1211.5078
36. J.H. Kuhn, A. Kulesza, S. Pozzorini, M. Schulze, Electroweak corrections to hadronic photon production at large transverse momenta. JHEP **03**, 059 (2006). https://doi.org/10.1088/1126-6708/2006/03/059. arXiv:hep-ph/0508253
37. S. Kallweit et al., NLO electroweak automation and precise predictions for W+multijet production at the LHC. JHEP **04**, 012 (2015). https://doi.org/10.1007/JHEP04(2015)012. arXiv:1412.5157
38. S. Kallweit et al., NLO QCD+EW predictions for V+jets including off-shell vector-boson decays and multijet merging. JHEP **04**, 021 (2016). https://doi.org/10.1007/JHEP04(2016)021. arXiv:1511.08692
39. T. Sjöstrand et al., An introduction to PYTHIA 8.2. Comput. Phys. Commun. **191**, 159 (2015). https://doi.org/10.1016/j.cpc.2015.01.024. arXiv:1410.3012
40. 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**, 473 (2008). https://doi.org/10.1140/epjc/s10052-007-0490-5. arXiv:0706.2569
41. R. Frederix, S. Frixione, Merging meets matching in MC@NLO. JHEP **12**, 061 (2012). https://doi.org/10.1007/JHEP12(2012)061. arXiv:1209.6215
42. NNPDF Collaboration, Parton distributions from high-precision collider data. Eur. Phys. J. C **77**, 663 (2017). https://doi.org/10.1140/epjc/s10052-017-5199-5. arXiv:1706.00428
43. CMS Collaboration, Extraction and validation of a new set of CMS PYTHIA 8 tunes from underlying-event measurements. Eur. Phys. J. C **80**, 4 (2020). https://doi.org/10.1140/epjc/s10052-019-7499-4. arXiv:1903.12179
44. GEANT4 Collaboration, GEANT4—a simulation toolkit. Nucl. Instrum. Methods. A **506**, 250 (2003). https://doi.org/10.1016/S0168-9002(03)01368-8
45. CMS Collaboration, Particle-flow reconstruction and global event description with the CMS detector. JINST **12**, P10003 (2017). https://doi.org/10.1088/1748-0221/12/10/P10003. arXiv:1706.04965
46. M. Cacciari, G.P. Salam, G. Soyez, The anti-k_T jet clustering algorithm. JHEP **04**, 063 (2008). https://doi.org/10.1088/1126-6708/2008/04/063. arXiv:0802.1189
47. M. Cacciari, G.P. Salam, G. Soyez, FASTJET user manual. Eur. Phys. J. C **72**, 1896 (2012). https://doi.org/10.1140/epjc/s10052-012-1896-2. arXiv:1111.6097
48. CMS Collaboration, Performance of missing transverse momentum reconstruction in proton–proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector. JINST **14**, P07004 (2019). https://doi.org/10.1088/1748-0221/14/07/P07004. arXiv:1903.06078
49. D. Bertolini, P. Harris, M. Low, N. Tran, Pileup per particle identification. JHEP **10**, 059 (2014). https://doi.org/10.1007/JHEP10(2014)059. arXiv:1407.6013
50. CMS Collaboration, Performance of heavy-flavour jet identification in Lorentz-boosted topologies in proton–proton collisions at $\sqrt{s} = 13$ TeV. JINST **20**, P11006 (2025). https://doi.org/10.1088/1748-0221/20/11/P11006. arXiv:2510.10228
51. E. Bols et al., Jet flavour classification using DeepJet. JINST **15**, P12012 (2020). https://doi.org/10.1088/1748-0221/15/12/P12012. arXiv:2008.10519
52. C.M.S. Collaboration, Performance of reconstruction and identification of τ leptons decaying to hadrons and ν_τ in pp collisions at $\sqrt{s} = 13$ TeV. JINST **13**, P10005 (2018). https://doi.org/10.1088/1748-0221/13/10/P10005. arXiv:1809.02816
53. M. Wobisch, T. Wengler, Hadronization corrections to jet cross-sections in deep inelastic scattering, in *Proceedings of the Workshop on Monte Carlo generators for HERA physics, Hamburg, Germany*. (1998). arXiv:hep-ph/9907280
54. CMS Collaboration, Reconstruction and identification of τ lepton decays to hadrons and ντ at CMS. JINST **7**, P01001 (2012). https://doi.org/10.1088/1748-0221/7/01/P01001. arXiv:1109.6034
55. CMS Collaboration, Performance of boosted tau lepton identification with DeepTau Framework (Boosted DeepTau). CMS Detector Performance Summary CMS-DP-2025-047 (2025). https://cds.cern.ch/record/2941434
56. CMS Collaboration, Performance of electron reconstruction and selection with the CMS detector in proton–proton collisions at $\sqrt{s} = 8$TeV. JINST **10**, P06005 (2015). https://doi.org/10.1088/1748-0221/10/06/P06005. arXiv:1502.02701
57. CMS Collaboration, Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$TeV. JINST **7**, P10002 (2012). https://doi.org/10.1088/1748-0221/7/10/P10002. arXiv:1206.4071
58. A.J. Larkoski, S. Marzani, G. Soyez, J. Thaler, Soft drop. JHEP **05**, 146 (2014). https://doi.org/10.1007/JHEP05(2014)146. arXiv:1402.2657
59. W. Matyszkiewicz, A. Kalinowski, Tau-pair invariant mass estimation using maximum likelihood estimation and collinear approximation. Acta Phys. Polon. Suppl. **18**, 5 (2025). https://doi.org/10.5506/APhysPolBSupp.18.5-A21
60. R.K. Ellis, I. Hinchliffe, M. Soldate, J.J. van der Bij, Higgs decay to $\tau^+\tau^-$: a possible signature of intermediate mass Higgs bosons at high energy hadron colliders. Nucl. Phys. B **297**, 221 (1988). https://doi.org/10.1016/0550-3213(88)90019-3
61. C.M.S. Collaboration, The CMS statistical analysis and combination tool: combine. Comput. Softw. Big Sci. **8**, 19 (2024). https://doi.org/10.1007/s41781-024-00121-4. arXiv:2404.06614
62. W. Verkerke, D. Kirkby, The RooFit toolkit for data modeling, in *Proceedings 13th International Conference on Computing in High Energy and Nuclear Physics (CHEP 2003): La Jolla CA, United States, March 24–28*. (2003). arXiv:physics/0306116
63. L. Moneta et al., The RooStats project, in *Proc. 13th International Workshop on Advanced Computing and Analysis Techniques in Physics Research (ACAT 2010): Jaipur, India, February 22–27*. (2010). https://doi.org/10.22323/1.093.0057. arXiv:1009.1003. [PoS (ACAT2010) 057]
64. CMS Collaboration, Precision luminosity measurement in proton–proton collisions at $\sqrt{s} = 13$TeV in 2015 and 2016 at CMS. Eur. Phys. J. C **81**, 800 (2021). https://doi.org/10.1140/epjc/s10052-021-09538-2. arXiv:2104.01927
65. CMS Collaboration, Precision luminosity measurement in proton–proton collisions at $\sqrt{s} = 13$TeV with the CMS detector. CMS Physics Analysis Summary CMS-PAS-LUM-20-001 (2025). https://cds.cern.ch/record/2940794
66. NNPDF Collaboration, Parton distributions for the LHC run II. JHEP **04**, 040 (2015). https://doi.org/10.1007/JHEP04(2015)040. arXiv:1410.8849
67. J. Butterworth et al., PDF4LHC recommendations for LHC Run II. J. Phys. G **43**, 023001 (2016). https://doi.org/10.1088/0954-3899/43/2/023001. arXiv:1510.03865

68. CMS Collaboration, Measurement of the inelastic proton–proton cross section at $\sqrt{s} = 13$TeV″. JHEP **07**, 161 (2018). https://doi.org/10.1007/JHEP07(2018)161. arXiv:1802.02613
69. CMS Collaboration, Jet energy scale and resolution in the CMS experiment in pp collisions at 8TeV. JINST **12**, P02014 (2017). https://doi.org/10.1088/1748-0221/12/02/P02014. arXiv:1607.03663
70. CMS Collaboration, Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV. JINST **13**, P05011 (2018). https://doi.org/10.1088/1748-0221/13/05/P05011. arXiv:1712.07158
71. R. Barlow, C. Beeston, Fitting using finite Monte Carlo samples. Comput. Phys. Commun. **77**, 219 (1993). https://doi.org/10.1016/0010-4655(93)90005-W

CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A. Hayrapetyan, V. Makarenko, A. Tumasyan[1]

Institut für Hochenergiephysik, Vienna, Austria
W. Adam, L. Benato, T. Bergauer, M. Dragicevic, P. S. Hussain, M. Jeitler[2], N. Krammer, A. Li, D. Liko, M. Matthewman, J. Schieck[2], R. Schöfbeck[2], M. Shooshtari, M. Sonawane, W. Waltenberger, C.-E. Wulz[2]

Universiteit Antwerpen, Antwerpen, Belgium
T. Janssen, H. Kwon, D. Ocampo Henao, T. Van Laer, P. Van Mechelen

Vrije Universiteit Brussel, Brussel, Belgium
J. Bierkens, N. Breugelmans, J. D'Hondt, S. Dansana, A. De Moor, M. Delcourt, F. Heyen, Y. Hong, P. Kashko, S. Lowette, I. Makarenko, D. Müller, S. Tavernier, M. Tytgat[3], G. P. Van Onsem, S. Van Putte, D. Vannerom

Université Libre de Bruxelles, Bruxelles, Belgium
B. Bilin, B. Clerbaux, A. K. Das, I. De Bruyn, G. De Lentdecker, H. Evard, L. Favart, P. Gianneios, A. Khalilzadeh, F. A. Khan, A. Malara, M. A. Shahzad, A. Sharma, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer, F. Zhang

Ghent University, Ghent, Belgium
M. De Coen, D. Dobur, C. Giordano, G. Gokbulut, K. Kaspar, D. Kavtaradze, D. Marckx, K. Skovpen, A. M. Tomaru, N. Van Den Bossche, J. van der Linden, J. Vandenbroeck

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
H. Aarup Petersen, S. Bein, A. Benecke, A. Bethani, G. Bruno, A. Cappati, J. De Favereau De Jeneret, C. Delaere, F. Gameiro Casalinho, A. Giammanco, A. O. Guzel, V. Lemaitre, J. Lidrych, P. Malek, P. Mastrapasqua, S. Turkcapar

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G. A. Alves, M. Barroso Ferreira Filho, E. Coelho, C. Hensel, D. Matos Figueiredo, T. Menezes De Oliveira, C. Mora Herrera, P. Rebello Teles, M. Soeiro, E. J. Tonelli Manganote[4], A. Vilela Pereira

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W. L. Aldá Júnior, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[5], M. Costa Reis, E. M. Da Costa, G. G. Da Silveira[6], D. De Jesus Damiao, S. Fonseca De Souza, R. Gomes De Souza, S. S. Jesus, T. Laux Kuhn[6], M. Macedo, K. Mota Amarilo, L. Mundim, H. Nogima, J. P. Pinheiro, A. Santoro, A. Sznajder, M. Thiel, F. Torres Da Silva Araujo[7]

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil
C. A. Bernardes, L. Calligaris, F. Damas, T. R. Fernandez Perez Tomei, E. M. Gregores, B. Lopes Da Costa, I. Maietto Silverio, P. G. Mercadante, S. F. Novaes, Sandra S. Padula, V. Scheurer

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
A. Aleksandrov, G. Antchev, P. Danev, R. Hadjiiska, P. Iaydjiev, M. Shopova, G. Sultanov

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

Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile
S. Keshri, D. Laroze, S. Thakur

Universidad Tecnica Federico Santa Maria, Valparaiso, Chile
W. Brooks

Beihang University, Beijing, China
T. Cheng, T. Javaid, L. Wang, L. Yuan

Department of Physics, Tsinghua University, Beijing, China
Z. Hu, Z. Liang, J. Liu, X. Wang, H. Yang

Institute of High Energy Physics, Beijing, China
G. M. Chen[8], H. S. Chen[8], M. Chen[8], Y. Chen, Q. Hou, X. Hou, F. Iemmi, C. H. Jiang, H. Liao, G. Liu, Z.-A. Liu[9], J. N. Song[9], S. Song, J. Tao, C. Wang[8], J. Wang, H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. Ban, A. Carvalho Antunes De Oliveira, S. Deng, B. Guo, Q. Guo, C. Jiang, A. Levin, C. Li, Q. Li, Y. Mao, S. Qian, S. J. Qian, X. Qin, C. Quaranta, X. Sun, D. Wang, J. Wang, M. Zhang, Y. Zhao, C. Zhou

State Key Laboratory of Nuclear Physics and Technology, Institute of Quantum Matter, South China Normal University, Guangzhou, China
S. Yang

Sun Yat-Sen University, Guangzhou, China
Z. You

University of Science and Technology of China, Hefei, China
N. Lu

Nanjing Normal University, Nanjing, China
G. Bauer[10,11], Z. Cui[11], B. Li[12], H. Wang, K. Yi[13], J. Zhang

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE)-Fudan University, Shanghai, China
Y. Li, Y. Zhou[14]

Zhejiang University, Hangzhou, Zhejiang, China
Z. Lin, C. Lu, M. Xiao[15]

Universidad de Los Andes, Bogota, Colombia
C. Avila, D. A. Barbosa Trujillo, A. Cabrera, C. Florez, J. Fraga, J. A. Reyes Vega

Universidad de Antioquia, Medellin, Colombia
C. Rendón, M. Rodriguez, A. A. Ruales Barbosa, J. D. Ruiz Alvarez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
N. Godinovic, D. Lelas, A. Sculac

University of Split, Faculty of Science, Split, Croatia
M. Kovac, A. Petkovic, T. Sculac

Institute Rudjer Boskovic, Zagreb, Croatia
P. Bargassa, V. Brigljevic, B. K. Chitroda, D. Ferencek, K. Jakovcic, A. Starodumov, T. Susa

University of Cyprus, Nicosia, Cyprus
A. Attikis, K. Christoforou, S. Konstantinou, C. Leonidou, L. Paizanos, F. Ptochos, P. A. Razis, H. Rykaczewski, H. Saka, A. Stepennov

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

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

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

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
A. A. Abdelalim[16,17], B. El-mahdy[18]

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
A. Hussein, H. Mohammed

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
K. Jaffel, M. Kadastik, T. Lange, C. Nielsen, J. Pata, M. Raidal, N. Seeba, L. Tani

Department of Physics, University of Helsinki, Helsinki, Finland
E. Brücken, A. Milieva, K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
F. Garcia, P. Inkaew, K. T. S. Kallonen, R. Kumar Verma, T. Lampén, K. Lassila-Perini, B. Lehtela, S. Lehti, T. Lindén, N. R. Mancilla Xinto, M. Myllymäki, M. m. Rantanen, S. Saariokari, N. T. Toikka, J. Tuominiemi

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland
N. Bin Norjoharuddeen, H. Kirschenmann, P. Luukka, H. Petrow

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, P. Devouge, J. L. Faure, F. Ferri, P. Gaigne, S. Ganjour, P. Gras, F. Guilloux, G. Hamel de Monchenault, M. Kumar, V. Lohezic, Y. Maidannyk, J. Malcles, F. Orlandi, L. Portales, S. Ronchi, M. Ö. Sahin, P. Simkina, M. Titov, M. Tornago

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
R. Amella Ranz, F. Beaudette, G. Boldrini, P. Busson, C. Charlot, M. Chiusi, T. D. Cuisset, O. Davignon, A. De Wit, T. Debnath, I. T. Ehle, S. Ghosh, A. Gilbert, R. Granier de Cassagnac, L. Kalipoliti, M. Manoni, M. Nguyen, S. Obraztsov, C. Ochando, R. Salerno, J. B. Sauvan, Y. Sirois, G. Sokmen, Y. Song, L. Urda Gómez, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[19], J. Andrea, D. Bloch, J.-M. Brom, E. C. Chabert, C. Collard, G. Coulon, S. Falke, U. Goerlach, R. Haeberle, A.-C. Le Bihan, M. Meena, O. Poncet, G. Saha, A. Savoy-Navarro[20], P. Vaucelle

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
A. Di Florio, B. Orzari

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
D. Amram, S. Beauceron, B. Blancon, G. Boudoul, N. Chanon, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, E. Fillaudeau, S. Gascon, M. Gouzevitch, C. Greenberg, G. Grenier, B. Ille, E. Jourd'Huy, M. Lethuillier, B. Massoteau, L. Mirabito, A. Purohit, M. Vander Donckt, C. Verollet, J. Xiao

Georgian Technical University, Tbilisi, Georgia
G. Adamov, I. Lomidze, Z. Tsamalaidze[21]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
V. Botta, S. Consuegra Rodríguez, L. Feld, K. Klein, M. Lipinski, P. Nattland, V. Oppenländer, A. Pauls, D. Pérez Adán, N. Röwert

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
C. Daumann, S. Diekmann, N. Eich, D. Eliseev, F. Engelke, J. Erdmann, M. Erdmann, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, A. Jung, N. Kumar, M. y. Lee, F. Mausolf, M. Merschmeyer, A. Meyer, A. Pozdnyakov, W. Redjeb, H. Reithler, U. Sarkar, V. Sarkisovi, A. Schmidt, C. Seth, A. Sharma, J. L. Spah, V. Vaulin, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
M. R. Beckers, C. Dziwok, G. Flügge, N. Hoeflich, T. Kress, A. Nowack, O. Pooth, A. Stahl, A. Zotz

Deutsches Elektronen-Synchrotron, Hamburg, Germany
A. Abel, M. Aldaya Martin, J. Alimena, S. Amoroso, Y. An, I. Andreev, J. Bach, S. Baxter, H. Becerril Gonzalez, O. Behnke, A. Belvedere, F. Blekman[22], K. Borras[23], A. Campbell, S. Chatterjee, L. X. Coll Saravia, G. Eckerlin, D. Eckstein, E. Gallo[22], A. Geiser, M. Guthoff, A. Hinzmann, L. Jeppe, M. Kasemann, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, W. Lange, D. Leyva Pernia, K.-Y. Lin, K. Lipka[24], W. Lohmann[25], J. Malvaso, R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, A. B. Meyer, G. Milella, K. Moral Figueroa, A. Mussgiller, L. P. Nair, J. Niedziela, A. Nürnberg, J. Park, E. Ranken, A. Raspereza, D. Rastorguev, L. Rygaard, M. Scham[23,26], S. Schnake[23], P. Schütze, C. Schwanenberger[22], D. Schwarz, D. Selivanova, K. Sharko, M. Shchedrolosiev, D. Stafford, M. Torkian, A. Ventura Barroso, R. Walsh, D. Wang, Q. Wang, K. Wichmann, L. Wiens[23], C. Wissing, Y. Yang, S. Zakharov, A. Zimermmane Castro Santos

University of Hamburg, Hamburg, Germany
A. R. Alves Andrade, M. Antonello, S. Bollweg, M. Bonanomi, L. Ebeling, K. El Morabit, Y. Fischer, M. Frahm, E. Garutti, A. Grohsjean, A. A. Guvenli, J. Haller, D. Hundhausen, G. Kasieczka, P. Keicher, R. Klanner, W. Korcari, T. Kramer, C. c. Kuo, F. Labe, J. Lange, A. Lobanov, J. Matthiesen, L. Moureaux, K. Nikolopoulos, A. Paasch, K. J. Pena Rodriguez, N. Prouvost, B. Raciti, M. Rieger, D. Savoiu, P. Schleper, M. Schröder, J. Schwandt, M. Sommerhalder, H. Stadie, G. Steinbrück, R. Ward, B. Wiederspan, M. Wolf, C. Yede

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
S. Brommer, A. Brusamolino, E. Butz, Y. M. Chen, T. Chwalek, A. Dierlamm, G. G. Dincer, D. Druzhkin, U. Elicabuk, N. Faltermann, M. Giffels, A. Gottmann, F. Hartmann[27], M. Horzela, F. Hummer, U. Husemann, J. Kieseler, M. Klute, J. Knolle, R. Kunnilan Muhammed Rafeek, O. Lavoryk, J. M. Lawhorn, S. Maier, A. A. Monsch, M. Mormile, T h. Müller, E. Pfeffer, M. Presilla, G. Quast, K. Rabbertz, B. Regnery, R. Schmieder, N. Shadskiy, I. Shvetsov, H. J. Simonis, L. Sowa, L. Stockmeier, K. Tauqeer, M. Toms, B. Topko, N. Trevisani, C. Verstege, T. Voigtländer, R. F. Von Cube, J. Von Den Driesch, C. Winter, R. Wolf, W. D. Zeuner, X. Zuo

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, A. Kyriakis

National and Kapodistrian University of Athens, Athens, Greece
G. Melachroinos, Z. Painesis, I. Paraskevas, N. Saoulidou, K. Theofilatos, E. Tziaferi, E. Tzovara, K. Vellidis, I. Zisopoulos

National Technical University of Athens, Athens, Greece
T. Chatzistavrou, G. Karapostoli, K. Kousouris, E. Siamarkou, G. Tsipolitis

University of Ioánnina, Ioánnina, Greece
I. Bestintzanos, I. Evangelou, C. Foudas, P. Katsoulis, P. Kokkas, P. G. Kosmoglou Kioseoglou, N. Manthos, I. Papadopoulos, J. Strologas

HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
C. Hajdu, D. Horvath[28,29], Á. Kadlecsik, C. Lee, K. Márton, A. J. Rádl[30], F. Sikler, V. Veszpremi

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanád, K. Farkas, A. Fehérkuti[31], M. M. A. Gadallah[32], M. León Coello, G. Pásztor, G. I. Veres

Faculty of Informatics, University of Debrecen, Debrecen, Hungary
B. Ujvari, G. Zilizi

HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary
G. Bencze, S. Czellar, J. Molnar, Z. Szillasi

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
T. Csorgo[31], F. Nemes[31], T. Novak, I. Szanyi[33]

IIT Bhubaneswar, Bhubaneswar, India
S. Bahinipati, S. Nayak, R. Raturi

Panjab University, Chandigarh, India
S. Bansal, S. B. Beri, V. Bhatnagar, S. Chauhan, N. Dhingra[34], A. Kaur, H. Kaur, M. Kaur, S. Kumar, T. Sheokand, J. B. Singh, A. Singla

University of Delhi, Delhi, India
A. Bhardwaj, A. Chhetri, B. C. Choudhary, A. Kumar, A. Kumar, M. Naimuddin, S. Phor, K. Ranjan, M. K. Saini

Indian Institute of Technology Mandi (IIT-Mandi), Himachal Pradesh, India
P. Palni

University of Hyderabad, Hyderabad, India
S. Acharya[35], B. Gomber

Indian Institute of Technology Kanpur, Kanpur, India
S. Mukherjee

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
S. Bhattacharya, S. Das Gupta, S. Dutta, S. Dutta, S. Sarkar

Indian Institute of Technology Madras, Madras, India
M. M. Ameen, P. K. Behera, S. Chatterjee, G. Dash, A. Dattamunsi, P. Jana, P. Kalbhor, S. Kamble, J. R. Komaragiri[36], T. Mishra, P. R. Pujahari, A. K. Sikdar, R. K. Singh, P. Verma, S. Verma, A. Vijay

IISER Mohali, India, Mohali, India
B. K. Sirasva

Tata Institute of Fundamental Research-A, Mumbai, India
L. Bhatt, S. Dugad, G. B. Mohanty, M. Shelake, P. Suryadevara

Tata Institute of Fundamental Research-B, Mumbai, India
A. Bala, S. Banerjee, S. Barman[37], R. M. Chatterjee, M. Guchait, S h. Jain, A. Jaiswal, S. Kumar, M. Maity[37], G. Majumder, K. Mazumdar, S. Parolia, R. Saxena, A. Thachayath

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India
D. Maity[38], P. Mal, K. Naskar[38], A. Nayak[38], K. Pal, P. Sadangi, S. K. Swain, S. Varghese[38], D. Vats[38]

Indian Institute of Science Education and Research (IISER), Pune, India
S. Dube, P. Hazarika, B. Kansal, A. Laha, R. Sharma, S. Sharma, K. Y. Vaish

Indian Institute of Technology Hyderabad, Telangana, India
S. Ghosh

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[39], A. Jafari[40], V. Sedighzadeh Dalavi, M. Zeinali[41]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Bashiri, S. Chenarani[42], S. M. Etesami, Y. Hosseini, M. Khakzad, E. Khazaie, M. Mohammadi Najafabadi, S. Tizchang[43]

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

INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy
M. Abbrescia[a,b], M. Barbieri[a,b], M. Buonsante[a,b], A. Colaleo[a,b], D. Creanza[a,c], N. De Filippis[a,c], M. De Palma[a,b], W. Elmetenawee[a,b,16], N. Ferrara[a,c], L. Fiore[a], L. Generoso[a,b], L. Longo[a], M. Louka[a,b], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a], V. Mastrapasqua[a,b], S. My[a,b], F. Nenna[a,b], S. Nuzzo[a,b], A. Pellecchia[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a,b], D. Ramos[a], A. Ranieri[a], L. Silvestris[a], F. M. Simone[a,c], Ü. Sözbilir[a], A. Stamerra[a,b], D. Troiano[a,b], R. Venditti[a,b], P. Verwilligen[a], A. Zaza[a,b]

INFN Sezione di Bologna[a], Università di Bologna[b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], P. Capiluppi[a,b], F. R. Cavallo[a], M. Cuffiani[a,b], G. M. Dallavalle[a], T. Diotalevi[a,b], F. Fabbri[a], R. Farinelli[a], D. Fasanella[a], P. Giacomelli[a], C. Grandi[a], S. Lo Meo[a,44], M. Lorusso[a,b], L. Lunerti[a], S. Marcellini[a], G. Masetti[a], F. L. Navarria[a,b], G. Paggi[a,b], A. Perrotta[a], A. M. Rossi[a,b], S. Rossi Tisbeni[a,b], T. Rovelli[a,b], G. P. Siroli[a,b]

INFN Sezione di Catania[a], Università di Catania[b], Catania, Italy
S. Costa[a,b,45], A. Di Mattia[a], A. Lapertosa[a], R. Potenza[a,b], A. Tricomi[a,b,45]

INFN Sezione di Firenze[a], Università di Firenze[b], Firenze, Italy
J. Altork[a,b], P. Assiouras[a], G. Barbagli[a], G. Bardelli[a], M. Bartolini[a,b], A. Calandri[a,b], B. Camaiani[a,b], A. Cassese[a], R. Ceccarelli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], L. Damenti[a,b], E. Focardi[a,b], T. Kello[a], G. Latino[a,b], P. Lenzi[a,b], M. Lizzo[a], M. Meschini[a], S. Paoletti[a], A. Papanastassiou[a,b], G. Sguazzoni[a], L. Viliani[a]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, S. Meola[46], D. Piccolo

INFN Sezione di Genova[a], Università di Genova[b], Genoa, Italy
M. Alves Gallo Pereira[a], F. Ferro[a], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca[a], Università di Milano-Bicocca[b], Milan, Italy
A. Benaglia[a], F. Brivio[a], V. Camagni[a,b], F. Cetorelli[a,b], F. De Guio[a,b], M. E. Dinardo[a,b], P. Dini[a], S. Gennai[a], R. Gerosa[a,b], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a], M. R. Kim[a], G. Lavizzari[a,b], M. T. Lucchini[a,b], M. Malberti[a], S. Malvezzi[a], A. Massironi[a], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], S. Palluotto[a,b], D. Pedrini[a], A. Perego[a,b], G. Pizzati[a,b], T. Tabarelli de Fatis[a,b]

INFN Sezione di Napoli[a], Università di Napoli 'Federico II'[b], Napoli, Italy; Università della Basilicata[c], Potenza, Italy; Scuola Superiore Meridionale (SSM)[d], Naples, Italy
S. Buontempo[a], C. Di Fraia[a,b], F. Fabozzi[a,c], L. Favilla[a,d], A. O. M. Iorio[a,b], L. Lista[a,b,47], P. Paolucci[a,27], B. Rossi[a]

INFN Sezione di Padova[a], Università di Padova[b], Padova, Italy; Universita degli Studi di Cagliari[c], Cagliari, Italy
P. Azzi[a], N. Bacchetta[a,48], D. Bisello[a,b], L. Borella[a], P. Bortignon[a,c], G. Bortolato[a,b], A. C. M. Bulla[a,c], P. Checchia[a], T. Dorigo[a,49], F. Gasparini[a,b], U. Gasparini[a,b], S. Giorgetti[a], E. Lusiani[a], M. Margoni[a,b], G. Maron[a,50], A. T. Meneguzzo[a,b], J. Pazzini[a,b], F. Primavera[a,b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], M. Tosi[a,b], A. Triossi[a,b], S. Ventura[a], M. Zanetti[a,b], P. Zotto[a,b], A. Zucchetta[a,b]

INFN Sezione di Pavia[a], Università di Pavia[b], Pavia, Italy
A. Braghieri[a], M. Brunoldi[a,b], S. Calzaferri[a,b], P. Montagna[a,b], M. Pelliccioni[a,b], V. Re[a], C. Riccardi[a,b], P. Salvini[a], I. Vai[a,b], P. Vitulo[a,b]

INFN Sezione di Perugia[a], Università di Perugia[b], Perugia, Italy
S. Ajmal[a,b], M. E. Ascioti[a,b], G. M. Bilei[a], C. Carrivale[a,b], D. Ciangottini[a,b], L. Della Penna[a,b], L. Fanò[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,51], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a], T. Tedeschi[a,b]

INFN Sezione di Pisa[a], Università di Pisa[b], Scuola Normale Superiore di Pisa[c], Pisa, Italy; Università di Siena[d], Siena, Italy
C. Aimè[a,b], C. A. Alexe[a,c], P. Asenov[a,b], P. Azzurri[a], G. Bagliesi[a], L. Bianchini[a,b], T. Boccali[a], E. Bossini[a], D. Bruschini[a,c], R. Castaldi[a], F. Cattafesta[a,c], M. A. Ciocci[a,d], M. Cipriani[a,b], R. Dell'Orso[a], S. Donato[a,b], R. Forti[a,b], A. Giassi[a], F. Ligabue[a,c], A. C. Marini[a,b], A. Messineo[a,b], S. Mishra[a], V. K. Muraleedharan Nair Bindhu[a,b], S. Nandan[a], F. Palla[a], M. Riggirello[a,c], A. Rizzi[a,b], G. Rolandi[a,c], S. Roy Chowdhury[a,52], T. Sarkar[a], A. Scribano[a], P. Solanki[a,b], P. Spagnolo[a], F. Tenchini[a,b], R. Tenchini[a], G. Tonelli[a,b], N. Turini[a,d], F. Vaselli[a,c], A. Venturi[a], P. G. Verdini[a]

INFN Sezione di Roma[a], Sapienza Università di Roma[b], Rome, Italy
P. Akrap[a,b], C. Basile[a,b], S. C. Behera[a], F. Cavallari[a], L. Cunqueiro Mendez[a,b], F. De Riggi[a,b], D. Del Re[a,b], M. Del Vecchio[a,b], E. Di Marco[a], M. Diemoz[a], F. Errico[a], L. Frosina[a,b], R. Gargiulo[a,b], B. Harikrishnan[a,b], F. Lombardi[a,b], E. Longo[a,b], L. Martikainen[a,b], J. Mijuskovic[a,b], G. Organtini[a,b], N. Palmeri[a,b], R. Paramatti[a,b], T. Pauletto[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], L. Soffi[a], V. Vladimirov[a,b]

INFN Sezione di Torino[a], Università di Torino[b], Torino, Italy; Università del Piemonte Orientale[c], Novara, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a,c], R. Bellan[a,b], A. Bellora[a,b], C. Biino[a], C. Borca[a,b], N. Cartiglia[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], L. Finco[a], M. Grippo[a,b], B. Kiani[a,b], L. Lanteri[a,b], F. Legger[a], F. Luongo[a,b], C. Mariotti[a], S. Maselli[a], A. Mecca[a,b], L. Menzio[a,b], P. Meridiani[a], E. Migliore[a,b], M. Monteno[a], M. M. Obertino[a,b], G. Ortona[a], L. Pacher[a,b], N. Pastrone[a], M. Ruspa[a,c], F. Siviero[a,b], V. Sola[a,b], A. Solano[a,b], A. Staiano[a], C. Tarricone[a,b], D. Trocino[a], G. Umoret[a,b], E. Vlasov[a,b], R. White[a,b]

INFN Sezione di Trieste[a], Università di Trieste[b], Trieste, Italy
J. Babbar[a,b,52], S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], K. De Leo[a], G. Della Ricca[a,b], R. Delli Gatti[a,b]

Kyungpook National University, Daegu, Korea
S. Dogra, J. Hong, J. Kim, T. Kim, D. Lee, H. Lee, J. Lee, S. W. Lee, C. S. Moon, Y. D. Oh, S. Sekmen, B. Tae, Y. C. Yang

Department of Mathematics and Physics - GWNU, Gangneung, Korea
M. S. Kim

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
G. Bak, P. Gwak, H. Kim, D. H. Moon, J. Seo

Hanyang University, Seoul, Korea
E. Asilar, F. Carnevali, J. Choi[53], T. J. Kim, Y. Ryou, J. Song

Korea University, Seoul, Korea
S. Ha, S. Han, B. Hong, J. Kim, K. Lee, K. S. Lee, S. Lee, J. Yoo

Department of Physics, Kyung Hee University, Seoul, Korea
J. Goh, J. Shin, S. Yang

Sejong University, Seoul, Korea
Y. Kang, H. S. Kim, Y. Kim, B. Ko, S. Lee

Seoul National University, Seoul, Korea
J. Almond, J. H. Bhyun, J. Choi, J. Choi, W. Jun, H. Kim, J. Kim, T. Kim, Y. Kim, Y. W. Kim, S. Ko, H. Lee, J. Lee, J. Lee, B. H. Oh, J. Shin, U. K. Yang, I. Yoon

University of Seoul, Seoul, Korea
W. Jang, D. Kim, S. Kim, J. S. H. Lee, Y. Lee, I. C. Park, Y. Roh, I. J. Watson

Department of Physics, Yonsei University, Seoul, Korea
G. Cho, K. Hwang, B. Kim, S. Kim, K. Lee, H. D. Yoo

Sungkyunkwan University, Suwon, Korea
Y. Lee, I. Yu

College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait
T. Beyrouthy, Y. Gharbia

Kuwait University-College of Science-Department of Physics, Safat, Kuwait
F. Alazemi

Riga Technical University, Riga, Latvia
K. Dreimanis, O. M. Eberlins, A. Gaile, C. Munoz Diaz, D. Osite, G. Pikurs, R. Plese, A. Potrebko, M. Seidel, D. Sidiropoulos Kontos

University of Latvia (LU), Riga, Latvia
N. R. Strautnieks

Vilnius University, Vilnius, Lithuania
M. Ambrozas, A. Juodagalvis, S. Nargelas, A. Rinkevicius, G. Tamulaitis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Yusuff[54], Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J. F. Benitez, A. Castaneda Hernandez, A. Cota Rodriguez, L. E. Cuevas Picos, H. A. Encinas Acosta, L. G. Gallegos Maríñez, J. A. Murillo Quijada, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
G. Ayala, H. Castilla-Valdez, H. Crotte Ledesma, R. Lopez-Fernandez, J. Mejia Guisao, R. Reyes-Almanza, A. Sánchez Hernández

Universidad Iberoamericana, Mexico City, Mexico
C. Oropeza Barrera, D. L. Ramirez Guadarrama, M. Ramírez García

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
I. Bautista, F. E. Neri Huerta, I. Pedraza, H. A. Salazar Ibarguen, C. Uribe Estrada

University of Montenegro, Podgorica, Montenegro
I. Bubanja, N. Raicevic

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

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. I. Asghar, A. Awais, M. I. M. Awan, W. A. Khan

AGH University of Krakow, Krakow, Poland
V. Avati, L. Forthomme, L. Grzanka, M. Malawski, K. Piotrzkowski

National Centre for Nuclear Research, Swierk, Poland
M. Bluj, M. Górski, M. Kazana, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, A. Muhammad

Warsaw University of Technology, Warsaw, Poland
P. Fokow, K. Pozniak, W. Zabolotny

Laboratório de Instrumentação e Física Experimental de Partículas, Lisbon, Portugal
M. Araujo, D. Bastos, C. Beirão Da Cruz Silva, A. Boletti, M. Bozzo, T. Camporesi, G. Da Molin, M. Gallinaro, J. Hollar, N. Leonardo, G. B. Marozzo, A. Petrilli, M. Pisano, J. Seixas, J. Varela, J. W. Wulff

Faculty of Physics, University of Belgrade, Belgrade, Serbia
P. Adzic, L. Markovic, P. Milenovic, V. Milosevic

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
D. Devetak, M. Dordevic, J. Milosevic, L. Nadderd, V. Rekovic, M. Stojanovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Alcalde Martinez, J. Alcaraz Maestre, Cristina F. Bedoya, J. A. Brochero Cifuentes, Oliver M. Carretero, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, D. Fernández Del Val, J. P. Fernández Ramos, J. Flix, M. C. Fouz, M. Gonzalez Hernandez, O. Gonzalez Lopez, S. Goy Lopez, J. M. Hernandez, M. I. Josa, J. Llorente Merino, C. Martin Perez, E. Martin Viscasillas, D. Moran, C. M. Morcillo Perez, Á. Navarro Tobar, R. Paz Herrera, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, J. Vazquez Escobar

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

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
B. Alvarez Gonzalez, J. Ayllon Torresano, A. Cardini, J. Cuevas, J. Del Riego Badas, D. Estrada Acevedo, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, P. Leguina, M. Obeso Menendez, E. Palencia Cortezon, J. Prado Pico, A. Soto Rodríguez, P. Vischia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
S. Blanco Fernández, I. J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, G. Gomez, C. Lasaosa García, R. Lopez Ruiz, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, E. Navarrete Ramos, J. Piedra Gomez, C. Quintana San Emeterio, L. Scodellaro, I. Vila, R. Vilar Cortabitarte, J. M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
B. Kailasapathy[55], D. D. C. Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W. G. D. Dharmaratna[56], K. Liyanage, N. Perera

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, C. Amendola, R. Ardino, E. Auffray, J. Baechler, D. Barney, J. Bendavid, M. Bianco, A. Bocci, L. Borgonovi, C. Botta, A. Bragagnolo, C. E. Brown, C. Caillol, G. Cerminara, P. Connor, K. Cormier, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M. M. Defranchis, M. Deile, M. Dobson, P. J. Fernández Manteca, B. A. Fontana Santos Alves, E. Fontanesi, W. Funk, A. Gaddi, S. Giani, D. Gigi, K. Gill, F. Glege, M. Glowacki, A. Gruber, J. Hegeman, J. K. Heikkilä, R. Hofsaess, B. Huber, T. James, P. Janot, O. Kaluzinska, O. Karacheban[25], G. Karathanasis, S. Laurila, P. Lecoq, E. Leutgeb, C. Lourenço, A.-M. Lyon, M. Magherini, L. Malgeri, M. Mannelli, A. Mehta, F. Meijers, J. A. Merlin, S. Mersi, E. Meschi, M. Migliorini, F. Monti, F. Moortgat, M. Mulders, M. Musich, I. Neutelings, S. Orfanelli, F. Pantaleo, M. Pari, G. Petrucciani, A. Pfeiffer, M. Pierini, M. Pitt, H. Qu, D. Rabady, A. Reimers, B. Ribeiro Lopes, F. Riti, P. Rosado, M. Rovere, H. Sakulin, R. Salvatico, S. Sanchez Cruz, S. Scarfi, M. Selvaggi, K. Shchelina, P. Silva, P. Sphicas[57], A. G. Stahl Leiton, A. Steen, S. Summers, D. Treille, P. Tropea, E. Vernazza, J. Wanczyk[58], S. Wuchterl, M. Zarucki, P. Zehetner, P. Zejdl, G. Zevi Della Porta

PSI Center for Neutron and Muon Sciences, Villigen, Switzerland
L. Caminada[59], W. Erdmann, R. Horisberger, Q. Ingram, H. C. Kaestli, D. Kotlinski, C. Lange, U. Langenegger, A. Nigamova, L. Noehte[59], T. Rohe, A. Samalan

ETH Zurich-Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
T. K. Aarrestad, M. Backhaus, T. Bevilacqua[2,7], G. Bonomelli, C. Cazzaniga, K. Datta, P. De Bryas Dexmiers D'Archiacchiac[2,6], A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Glessgen, C. Grab, N. Härringer, T. G. Harte, W. Lustermann, M. Malucchi, R. A. Manzoni, L. Marchese,

A. Mascellani[58], F. Nessi-Tedaldi, F. Pauss, B. Ristic, R. Seidita, J. Steggemann[58], A. Tarabini, D. Valsecchi, R. Wallny

Universität Zürich, Zurich, Switzerland
C. Amsler[60], P. Bärtschi, F. Bilandzija, M. F. Canelli, G. Celotto, V. Guglielmi, A. Jofrehei, B. Kilminster, T. H. Kwok, S. Leontsinis, V. Lukashenko, A. Macchiolo, F. Meng, M. Missiroli, J. Motta, P. Robmann, E. Shokr, F. Stäger, R. Tramontano, P. Viscone

National Central University, Chung-Li, Taiwan
D. Bhowmik, C. M. Kuo, P. K. Rout, S. Taj, P. C. Tiwari[36]

National Taiwan University (NTU), Taipei, Taiwan
L. Ceard, K. F. Chen, Z. g. Chen, A. De Iorio, W.-S. Hou, T. h. Hsu, Y. w. Kao, S. Karmakar, G. Kole, Y. y. Li, R.-S. Lu, E. Paganis, X. f. Su, J. Thomas-Wilsker, L. s. Tsai, D. Tsionou, H. y. Wu, E. Yazgan

High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand
C. Asawatangtrakuldee, N. Srimanobhas

Tunis El Manar University, Tunis, Tunisia
Y. Maghrbi

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
D. Agyel, F. Dolek, I. Dumanoglu[61], Y. Guler[62], E. Gurpinar Guler[62], C. Isik, O. Kara[63], A. Kayis Topaksu, Y. Komurcu, G. Onengut, K. Ozdemir[64], B. Tali[65], U. G. Tok, E. Uslan, I. S. Zorbakir

Hacettepe University, Ankara, Turkey
S. Sen

Physics Department, Middle East Technical University, Ankara, Turkey
M. Yalvac[66]

Bogazici University, Istanbul, Turkey
B. Akgun, I. O. Atakisi[67], E. Gülmez, M. Kaya[68], O. Kaya[69], M. A. Sarkisla[70], S. Tekten[71]

Istanbul Technical University, Istanbul, Turkey
D. Boncukcu, A. Cakir, K. Cankocak[61,72]

Istanbul University, Istanbul, Turkey
B. Hacisahinoglu, I. Hos[73], B. Kaynak, S. Ozkorucuklu, O. Potok, H. Sert, C. Simsek, C. Zorbilmez

Yildiz Technical University, Istanbul, Turkey
S. Cerci, C. Dozen[74], B. Isildak, E. Simsek, D. Sunar Cerci, T. Yetkin[74]

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine
A. Boyaryntsev, O. Dadazhanova, B. Grynyov

National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine
L. Levchuk

University of Bristol, Bristol, UK
J. J. Brooke, A. Bundock, F. Bury, E. Clement, D. Cussans, D. Dharmender, H. Flacher, J. Goldstein, H. F. Heath, M.-L. Holmberg, L. Kreczko, S. Paramesvaran, L. Robertshaw, M. S. Sanjrani[39], J. Segal, V. J. Smith

Rutherford Appleton Laboratory, Didcot, UK
A. H. Ball, K. W. Bell, A. Belyaev[75], C. Brew, R. M. Brown, D. J. A. Cockerill, A. Elliot, K. V. Ellis, J. Gajownik, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, M. Moallemi, D. M. Newbold, E. Olaiya, D. Petyt, T. Reis, A. R. Sahasransu, G. Salvi, T. Schuh, C. H. Shepherd-Themistocleous, I. R. Tomalin, K. C. Whalen, T. Williams

Imperial College, London, UK
I. Andreou, R. Bainbridge, P. Bloch, O. Buchmuller, C. A. Carrillo Montoya, D. Colling, I. Das, P. Dauncey, G. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, H. R. Hoorani, A. Howard, G. Iles, C. R. Knight, P. Krueper, J. Langford, K. H. Law, J. León Holgado, L. Lyons, A.-M. Magnan, B. Maier, S. Mallios, A. Mastronikolis, M. Mieskolainen, J. Nash[76], M. Pesaresi, P. B. Pradeep, B. C. Radburn-Smith, A. Richards, A. Rose, L. Russell, K. Savva, R. Schmitz, C. Seez, R. Shukla, A. Tapper, K. Uchida, G. P. Uttley, T. Virdee[27], M. Vojinovic, N. Wardle, D. Winterbottom

Brunel University, Uxbridge, UK
J. E. Cole, A. Khan, P. Kyberd, I. D. Reid

Baylor University, Waco, TX, USA
S. Abdullin, A. Brinkerhoff, E. Collins, M. R. Darwish, J. Dittmann, K. Hatakeyama, V. Hegde, J. Hiltbrand, B. McMaster, J. Samudio, S. Sawant, C. Sutantawibul, J. Wilson

Bethel University, St. Paul, MN, USA
J. M. Hogan

Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez, S. Raj, B. Sahu, A. E. Simsek, S. S. Yu

The University of Alabama, Tuscaloosa, AL, USA
B. Bam, A. Buchot Perraguin, S. Campbell, R. Chudasama, S. I. Cooper, C. Crovella, G. Fidalgo, S. V. Gleyzer, A. Khukhunaishvili, K. Matchev, E. Pearson, P. Rumerio[77], E. Usai, R. Yi

Boston University, Boston, MA, USA
S. Cholak, G. De Castro, Z. Demiragli, C. Erice, C. Fangmeier, C. Fernandez Madrazo, J. Fulcher, F. Golf, S. Jeon, J. O'Cain, I. Reed, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, E. Wurtz, A. G. Zecchinelli

Brown University, Providence, RI, USA
G. Barone, G. Benelli, D. Cutts, S. Ellis, L. Gouskos, M. Hadley, U. Heintz, K. W. Ho, T. Kwon, L. Lambrecht, G. Landsberg, K. T. Lau, J. Luo, S. Mondal, J. Roloff, T. Russell, S. Sagir[78], X. Shen, M. Stamenkovic, N. Venkatasubramanian

University of California, Davis, Davis, CA, USA
S. Abbott, S. Baradia, B. Barton, R. Breedon, H. Cai, M. Calderon De La Barca Sanchez, E. Cannaert, M. Chertok, M. Citron, J. Conway, P. T. Cox, F. Eble, R. Erbacher, O. Kukral, G. Mocellin, S. Ostrom, I. Salazar Segovia, J. S. Tafoya Vargas, W. Wei, S. Yoo

University of California, Los Angeles, CA, USA
K. Adamidis, M. Bachtis, D. Campos, R. Cousins, S. Crossley, G. Flores Avila, J. Hauser, M. Ignatenko, M. A. Iqbal, T. Lam, Y. f. Lo, E. Manca, A. Nunez Del Prado, D. Saltzberg, V. Valuev

University of California, Riverside, Riverside, CA, USA
R. Clare, J. W. Gary, G. Hanson

University of California, San Diego, La Jolla, CA, USA
A. Aportela, A. Arora, J. G. Branson, S. Cittolin, S. Cooperstein, B. D'Anzi, D. Diaz, J. Duarte, L. Giannini, Y. Gu, J. Guiang, V. Krutelyov, R. Lee, J. Letts, H. Li, M. Masciovecchio, F. Mokhtar, S. Mukherjee, M. Pieri, D. Primosch, M. Quinnan, V. Sharma, M. Tadel, E. Vourliotis, F. Würthwein, A. Yagil, Z. Zhao

Department of Physics, University of California, Santa Barbara, Santa Barbara, CA, USA
A. Barzdukas, L. Brennan, C. Campagnari, S. Carron Montero[79], K. Downham, C. Grieco, M. M. Hussain, J. Incandela, M. W. K. Lai, A. J. Li, P. Masterson, J. Richman, S. N. Santpur, D. Stuart, T. Á. Vámi, X. Yan, D. Zhang

California Institute of Technology, Pasadena, CA, USA
A. Albert, S. Bhattacharya, A. Bornheim, O. Cerri, R. Kansal, H. B. Newman, G. Reales Gutiérrez, T. Sievert, M. Spiropulu, J. R. Vlimant, R. A. Wynne, S. Xie

Carnegie Mellon University, Pittsburgh, PA, USA
J. Alison, S. An, M. Cremonesi, V. Dutta, E. Y. Ertorer, T. Ferguson, T. A. Gómez Espinosa, A. Harilal, A. Kallil Tharayil, M. Kanemura, C. Liu, M. Marchegiani, P. Meiring, S. Murthy, P. Palit, K. Park, M. Paulini, A. Roberts, A. Sanchez, W. Terrill

University of Colorado Boulder, Boulder, CO, USA
J. P. Cumalat, W. T. Ford, A. Hart, S. Kwan, J. Pearkes, C. Savard, N. Schonbeck, K. Stenson, K. A. Ulmer, S. R. Wagner, N. Zipper, D. Zuolo

Cornell University, Ithaca, NY, USA
J. Alexander, X. Chen, J. Dickinson, A. Duquette, J. Fan, X. Fan, J. Grassi, S. Hogan, P. Kotamnives, J. Monroy, G. Niendorf, M. Oshiro, J. R. Patterson, A. Ryd, J. Thom, P. Wittich, R. Zou, L. Zygala

Fermi National Accelerator Laboratory, Batavia, IL, USA
M. Albrow, M. Alyari, O. Amram, G. Apollinari, A. Apresyan, L. A. T. Bauerdick, D. Berry, J. Berryhill, P. C. Bhat, K. Burkett, J. N. Butler, A. Canepa, G. B. Cerati, H. W. K. Cheung, F. Chlebana, C. Cosby, G. Cummings, I. Dutta, V. D. Elvira, J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, A. Grummer, S. Grünendahl, D. Guerrero, O. Gutsche, R. M. Harris, J. Hirschauer, V. Innocente, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, R. S. Kim, B. Klima, S. Lammel, D. Lincoln, R. Lipton, T. Liu, K. Maeshima, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, D. Noonan, S. Norberg, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[80], C. E. Perez Lara, V. Perovic, F. Ravera, A. Reinsvold Hall[81], L. Ristori, M. Safdari, E. Sexton-Kennedy, E. Smith, N. Smith, A. Soha, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N. V. Tran, L. Uplegger, E. W. Vaandering, C. Wang, I. Zoi

University of Florida, Gainesville, FL, USA
C. Aruta, P. Avery, D. Bourilkov, P. Chang, V. Cherepanov, R. D. Field, C. Huh, E. Koenig, M. Kolosova, J. Konigsberg, A. Korytov, G. Mitselmakher, K. Mohrman, A. Muthirakalayil Madhu, N. Rawal, S. Rosenzweig, V. Sulimov, Y. Takahashi, J. Wang

Florida State University, Tallahassee, FL, USA
T. Adams, A. Al Kadhim, A. Askew, S. Bower, R. Goff, R. Hashmi, A. Hassani, T. Kolberg, G. Martinez, M. Mazza, H. Prosper, P. R. Prova, R. Yohay

Florida Institute of Technology, Melbourne, FL, USA
B. Alsufyani, S. Butalla, S. Das, M. Hohlmann, M. Lavinsky, E. Yanes

University of Illinois Chicago, Chicago, IL, USA
M. R. Adams, N. Barnett, A. Baty, C. Bennett, R. Cavanaugh, R. Escobar Franco, O. Evdokimov, C. E. Gerber, H. Gupta, M. Hawksworth, A. Hingrajiya, D. J. Hofman, Z. Huang, J. h. Lee, C. Mills, S. Nanda, G. Nigmatkulov, B. Ozek, T. Phan, D. Pilipovic, R. Pradhan, E. Prifti, P. Roy, T. Roy, D. Shekar, N. Singh, A. Thielen, M. B. Tonjes, N. Varelas, M. A. Wadud, J. Yoo

The University of Iowa, Iowa City, IA, USA
M. Alhusseini, D. Blend, K. Dilsiz[82], O. K. Köseyan, A. Mestvirishvili[83], O. Neogi, H. Ogul[84], Y. Onel, A. Penzo, C. Snyder, E. Tiras[85]

Johns Hopkins University, Baltimore, MD, USA
B. Blumenfeld, J. Davis, A. V. Gritsan, L. Kang, S. Kyriacou, P. Maksimovic, M. Roguljic, S. Sekhar, M. V. Srivastav, M. Swartz

The University of Kansas, Lawrence, KS, USA
A. Abreu, L. F. Alcerro Alcerro, J. Anguiano, S. Arteaga Escatel, P. Baringer, A. Bean, R. Bhattacharya,

Z. Flowers, D. Grove, J. King, G. Krintiras, M. Lazarovits, C. Le Mahieu, J. Marquez, M. Murray, M. Nickel, S. Popescu[86], C. Rogan, C. Royon, S. Rudrabhatla, S. Sanders, C. Smith, G. Wilson

Kansas State University, Manhattan, KS, USA
B. Allmond, N. Islam, A. Ivanov, K. Kaadze, Y. Maravin, J. Natoli, G. G. Reddy, D. Roy, G. Sorrentino

University of Maryland, College Park, MD, USA
A. Baden, A. Belloni, J. Bistany-riebman, S. C. Eno, N. J. Hadley, S. Jabeen, R. G. Kellogg, T. Koeth, B. Kronheim, S. Lascio, P. Major, A. C. Mignerey, C. Palmer, C. Papageorgakis, M. M. Paranjpe, E. Popova[87], A. Shevelev, L. Zhang

Massachusetts Institute of Technology, Cambridge, MA, USA
C. Baldenegro Barrera, H. Bossi, S. Bright-Thonney, I. A. Cali, Y. c. Chen, P. c. Chou, M. D'Alfonso, J. Eysermans, C. Freer, G. Gomez-Ceballos, M. Goncharov, G. Grosso, P. Harris, D. Hoang, G. M. Innocenti, K. Ivanov, G. Kopp, D. Kovalskyi, J. Krupa, L. Lavezzo, Y.-J. Lee, K. Long, C. Mcginn, A. Novak, M. I. Park, C. Paus, C. Reissel, C. Roland, G. Roland, S. Rothman, T. a. Sheng, G. S. F. Stephans, D. Walter, J. Wang, Z. Wang, B. Wyslouch, T. J. Yang

University of Minnesota, Minneapolis, MN, USA
A. Alpana, B. Crossman, W. J. Jackson, C. Kapsiak, M. Krohn, D. Mahon, J. Mans, B. Marzocchi, R. Rusack, O. Sancar, R. Saradhy, N. Strobbe

University of Nebraska-Lincoln, Lincoln, NE, USA
K. Bloom, D. R. Claes, G. Haza, J. Hossain, C. Joo, I. Kravchenko, K. H. M. Kwok, A. Rohilla, J. E. Siado, W. Tabb, A. Vagnerini, A. Wightman, F. Yan

State University of New York at Buffalo, Buffalo, NY, USA
H. Bandyopadhyay, L. Hay, H. w. Hsia, I. Iashvili, A. Kalogeropoulos, A. Kharchilava, A. Mandal, M. Morris, D. Nguyen, S. Rappoccio, H. Rejeb Sfar, A. Williams, D. Yu

Northeastern University, Boston, MA, USA
A. Aarif, G. Alverson, E. Barberis, J. Bonilla, B. Bylsma, M. Campana, J. Dervan, Y. Haddad, Y. Han, I. Israr, A. Krishna, M. Lu, N. Manganelli, R. Mccarthy, D. M. Morse, T. Orimoto, L. Skinnari, C. S. Thoreson, E. Tsai, D. Wood

Northwestern University, Evanston, IL, USA
S. Dittmer, K. A. Hahn, M. Mcginnis, Y. Miao, D. G. Monk, M. H. Schmitt, A. Taliercio, M. Velasco, J. Wang

University of Notre Dame, Notre Dame, IN, USA
G. Agarwal, R. Band, R. Bucci, S. Castells, A. Das, A. Datta, A. Ehnis, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, T. Ivanov, C. Jessop, A. Karneyeu, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, J. Mariano, N. Marinelli, T. McCauley, C. Mcgrady, C. Moore, Y. Musienko[21], H. Nelson, M. Osherson, A. Piccinelli, R. Ruchti, A. Townsend, Y. Wan, M. Wayne, H. Yockey

The Ohio State University, Columbus, OH, USA
M. Carrigan, R. De Los Santos, L. S. Durkin, C. Hill, M. Joyce, D. A. Wenzl, B. L. Winer, B. R. Yates

Princeton University, Princeton, NJ, USA
H. Bouchamaoui, G. Dezoort, P. Elmer, A. Frankenthal, M. Galli, B. Greenberg, N. Haubrich, K. Kennedy, Y. Lai, D. Lange, A. Loeliger, D. Marlow, I. Ojalvo, J. Olsen, F. Simpson, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, PR, USA
S. Malik, R. Sharma

Purdue University, West Lafayette, IN, USA
S. Chandra, A. Gu, L. Gutay, M. Huwiler, M. Jones, A. W. Jung, D. Kondratyev, J. Li, M. Liu,

G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, N. R. Saha, J. F. Schulte, F. Wang, A. Wildridge, W. Xie, Y. Yao, Y. Zhong

Purdue University Northwest, Hammond, IN, USA
N. Parashar, A. Pathak, E. Shumka

Rice University, Houston, TX, USA
D. Acosta, A. Agrawal, C. Arbour, T. Carnahan, P. Das, K. M. Ecklund, F. J. M. Geurts, T. Huang, I. Krommydas, N. Lewis, W. Li, J. Lin, O. Miguel Colin, B. P. Padley, R. Redjimi, J. Rotter, C. Vico Villalba, M. Wulansatiti, E. Yigitbasi, Y. Zhang

University of Rochester, Rochester, NY, USA
O. Bessidskaia Bylund, A. Bodek, P. de Barbaro, R. Demina, A. Garcia-Bellido, H. S. Hare, O. Hindrichs, N. Parmar, P. Parygin[87], H. Seo, R. Taus, Y. h. Yu

Rutgers, The State University of New Jersey, Piscataway, NJ, USA
B. Chiarito, J. P. Chou, S. V. Clark, S. Donnelly, D. Gadkari, Y. Gershtein, E. Halkiadakis, C. Houghton, D. Jaroslawski, A. Kobert, I. Laflotte, A. Lath, J. Martins, M. Perez Prada, B. Rand, J. Reichert, P. Saha, S. Salur, S. Somalwar, R. Stone, S. A. Thayil, S. Thomas, J. Vora

University of Tennessee, Knoxville, TN, USA
D. Ally, A. G. Delannoy, S. Fiorendi, J. Harris, T. Holmes, A. R. Kanuganti, N. Karunarathna, J. Lawless, L. Lee, E. Nibigira, B. Skipworth, S. Spanier

Texas A&M University, College Station, TX, USA
D. Aebi, M. Ahmad, T. Akhter, K. Androsov, A. Basnet, A. Bolshov, O. Bouhali[88], A. Cagnotta, V. D'Amante, R. Eusebi, P. Flanagan, J. Gilmore, Y. Guo, T. Kamon, S. Luo, R. Mueller, A. Safonov

Texas Tech University, Lubbock, TX, USA
N. Akchurin, J. Damgov, Y. Feng, N. Gogate, W. Jin, S. W. Lee, C. Madrid, A. Mankel, T. Peltola, I. Volobouev

Vanderbilt University, Nashville, TN, USA
E. Appelt, Y. Chen, S. Greene, A. Gurrola, W. Johns, R. Kunnawalkam Elayavalli, A. Melo, D. Rathjens, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, J. Viinikainen, J. Zhang

University of Virginia, Charlottesville, VA, USA
B. Cardwell, H. Chung, B. Cox, J. Hakala, G. Hamilton Ilha Machado, R. Hirosky, M. Jose, A. Ledovskoy, C. Mantilla, C. Neu, C. Ramón Álvarez, Z. Wu

Wayne State University, Detroit, MI, USA
S. Bhattacharya, P. E. Karchin

University of Wisconsin-Madison, Madison, WI, USA
A. Aravind, S. Banerjee, K. Black, T. Bose, E. Chavez, S. Dasu, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Herve, C. K. Koraka, S. Lomte, R. Loveless, A. Mallampalli, A. Mohammadi, S. Mondal, T. Nelson, G. Parida, L. Pétré, D. Pinna, A. Savin, V. Shang, V. Sharma, W. H. Smith, D. Teague, A. Warden

Authors affiliated with an international laboratory covered by a cooperation agreement with CERN, Geneva, Switzerland
S. Afanasiev, V. Alexakhin, Y u. Andreev, T. Aushev, D. Budkouski, R. Chistov, M. Danilov, T. Dimova, A. Ershov, S. Gninenko, I. Gorbunov, A. Kamenev, V. Karjavine, M. Kirsanov, V. Klyukhin, O. Kodolova[89], V. Korenkov, I. Korsakov, A. Kozyrev, N. Krasnikov, A. Lanev, A. Malakhov, V. Matveev, A. Nikitenko[89,90], V. Palichik, V. Perelygin, S. Petrushanko, O. Radchenko, M. Savina, V. Shalaev, S. Shmatov, S. Shulha, Y. Skovpen, K. Slizhevskiy, V. Smirnov, O. Teryaev, I. Tlisova, A. Toropin, N. Voytishin, A. Zarubin, I. Zhizhin

Authors affiliated with an institute formerly covered by a cooperation agreement with CERN, Geneva, Switzerland
E. Boos, V. Bunichev, M. Dubinin[80], A. Gribushin, V. Savrin, A. Snigirev, L. Dudko, V. Kim[21], V. Murzin, V. Oreshkin, D. Sosnov

1: Also at Yerevan State University, Yerevan, Armenia
2: Also at TU Wien, Vienna, Austria
3: Also at Ghent University, Ghent, Belgium
4: Also at FACAMP - Faculdades de Campinas, Sao Paulo, Brazil
5: Also at Universidade Estadual de Campinas, Campinas, Brazil
6: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
7: Also at The University of the State of Amazonas, Manaus, Brazil
8: Also at University of Chinese Academy of Sciences, Beijing, China
9: Also at University of Chinese Academy of Sciences, Beijing, China
10: Also at School of Physics, Zhengzhou University, Zhengzhou, China
11: Now at Henan Normal University, Xinxiang, China
12: Also at University of Shanghai for Science and Technology, Shanghai, China
13: Also at The University of Iowa, Iowa City, Iowa, USA
14: Also at Nanjing Normal University, Nanjing, China
15: Also at Center for High Energy Physics, Peking University, Beijing, China
16: Also at Helwan University, Cairo, Egypt
17: Now at Zewail City of Science and Technology, Zewail, Egypt
18: Also at Cairo University, Cairo, Egypt
19: Also at Université de Haute Alsace, Mulhouse, France
20: Also at Purdue University, West Lafayette, Indiana, USA
21: Also at an Institute Formerly Covered by a Cooperation Agreement with CERN, Geneva, Switzerland
22: Also at University of Hamburg, Hamburg, Germany
23: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
24: Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
25: Also at Brandenburg University of Technology, Cottbus, Germany
26: Also at Forschungszentrum Jülich, Juelich, Germany
27: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
28: Also at HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary
29: Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
30: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
31: Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
32: Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
33: Also at The University of Kansas, Lawrence, Kansas, USA
34: Also at Punjab Agricultural University, Ludhiana, India
35: Also at University of Hyderabad, Hyderabad, India
36: Also at Indian Institute of Science (IISc), Bangalore, India
37: Also at University of Visva-Bharati, Santiniketan, India
38: Also at Institute of Physics, Bhubaneswar, India
39: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
40: Also at Isfahan University of Technology, Isfahan, Iran
41: Also at Sharif University of Technology, Tehran, Iran
42: Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
43: Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran
44: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
45: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
46: Also at Università degli Studi Guglielmo Marconi, Roma, Italy
47: Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
48: Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
49: Also at Lulea University of Technology, Lulea, Sweden

50: Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy
51: Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
52: Also at UPES - University of Petroleum and Energy Studies, Dehradun, India
53: Also at Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
54: Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
55: Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
56: Also at Saegis Campus, Nugegoda, Sri Lanka
57: Also at National and Kapodistrian University of Athens, Athens, Greece
58: Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
59: Also at Universität Zürich, Zurich, Switzerland
60: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
61: Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
62: Also at Konya Technical University, Konya, Turkey
63: Also at Istanbul Topkapi University, Istanbul, Turkey
64: Also at Izmir Bakircay University, Izmir, Turkey
65: Also at Adiyaman University, Adiyaman, Turkey
66: Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
67: Also at Istanbul Sabahattin Zaim University, Istanbul, Turkey
68: Also at Marmara University, Istanbul, Turkey
69: Also at Milli Savunma University, Istanbul, Turkey
70: Also at Informatics and Information Security Research Center, Gebze/Kocaeli, Turkey
71: Also at Kafkas University, Kars, Turkey
72: Now at Istanbul Okan University, Istanbul, Turkey
73: Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
74: Also at Istinye University, Istanbul, Turkey
75: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
76: Also at Monash University, Faculty of Science, Clayton, Australia
77: Also at Università di Torino, Torino, Italy
78: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
79: Also at California Lutheran University;, Thousand Oaks, California, USA
80: Also at California Institute of Technology, Pasadena, California, USA
81: Also at United States Naval Academy, Annapolis, Maryland, USA
82: Also at Bingol University, Bingol, Turkey
83: Also at Georgian Technical University, Tbilisi, Georgia
84: Also at Sinop University, Sinop, Turkey
85: Also at Erciyes University, Kayseri, Turkey
86: Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania
87: Now at Another Institute Formerly Covered by a Cooperation Agreement with CERN, Geneva, Switzerland
88: Also at Hamad Bin Khalifa University (HBKU), Doha, Qatar
89: Also at Yerevan Physics Institute, Yerevan, Armenia
90: Also at Imperial College, London, United Kingdom