



Search for the decay of the Higgs boson to a pair of light pseudoscalar bosons in the final state with four bottom quarks in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

A search is presented for the decay of the 125 GeV Higgs boson (H) to a pair of new light pseudoscalar bosons (a), followed by the prompt decay of each a boson to a bottom quark-antiquark pair, $H \rightarrow aa \rightarrow b\bar{b}b\bar{b}$. The analysis is performed using a data sample of proton-proton collisions collected with the CMS detector at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 138 fb^{-1} . To reduce the background from standard model processes, the search requires the Higgs boson to be produced in association with a leptonically decaying W or Z boson. The analysis probes the production of new light bosons in a $15 < m_a < 60 \text{ GeV}$ mass range. Assuming the standard model predictions for the Higgs boson production cross sections for $pp \rightarrow WH$ and ZH , model independent upper limits at 95% confidence level are derived for the branching fraction $\mathcal{B}(H \rightarrow aa \rightarrow b\bar{b}b\bar{b})$. The combined WH and ZH observed upper limit on the branching fraction ranges from 1.10 for $m_a = 20 \text{ GeV}$ to 0.36 for $m_a = 60 \text{ GeV}$, complementing other measurements in the $\mu\mu\tau\tau$, $\tau\tau\tau\tau$ and $b\bar{b}\ell\bar{\ell}$ ($\ell = \mu, \tau$) channels.

Published in the Journal of High Energy Physics as doi:10.1007/JHEP06(2024)097.

1 Introduction

A Higgs boson with a mass of 125 GeV was discovered [1–3] in 2012 by the ATLAS and CMS Collaborations at the CERN LHC. Studies [4, 5] of this particle, here denoted H, have indicated its compatibility with the Higgs boson of the standard model (SM) of particle physics. Notwithstanding this compatibility, present experimental limits allow a significant branching fraction of the H boson to beyond-the-SM particles up to 16% [5]. Observation of such H boson decays could point the way for the SM to be extended to a more fundamental theory.

Many models of physics beyond the SM predict an extended Higgs sector. Examples include two-Higgs-doublet models (2HDM) [6], the 2HDM with a scalar singlet field (2HDM+S) [7], and the next-to-minimal supersymmetric SM (NMSSM) [8]. In the 2HDM+S model, the Higgs sector contains seven physical scalar and pseudoscalar particles. One of the scalar states can be identified with the 125 GeV H boson while one of the pseudoscalar states, denoted a , can be light enough to allow $H \rightarrow aa$ decays. These decays can occur with a significant branching fraction ($\gtrsim 10\%$) if they are kinematically allowed [7]. For virtually all 2HDM+S scenarios, the dominant pseudoscalar decay mode is $a \rightarrow b\bar{b}$ (with b a bottom quark) so long as the pseudoscalar mass m_a is at least twice the bottom quark mass.

In this paper, we present a search for the Higgs boson decay $H \rightarrow aa \rightarrow b\bar{b}b\bar{b}$. The decays are assumed to be prompt, i.e., not leading to long-lived new particles. The analysis is based on a sample of proton-proton (pp) collision events at a center-of-mass energy of 13 TeV recorded with the CMS detector in 2016–2018, corresponding to an integrated luminosity of 138 fb^{-1} . The search makes use of $V = W$ or Z boson associated production, in which the V boson decays leptonically, $W \rightarrow \ell\nu$ or $Z \rightarrow \ell^+\ell^-$, with ℓ an electron or muon. The leptonic signature suppresses SM background processes such as those with four b jets produced through quantum chromodynamics (QCD) interactions (multijet background).

The $H \rightarrow aa \rightarrow b\bar{b}b\bar{b}$ channel was previously explored by the ATLAS Collaboration [9–11]. The present work represents the first search in this channel from the CMS Collaboration. The ATLAS results [10, 11] were based on a data sample of about 36 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$. Thus, the present study utilizes a data sample that is approximately four times larger. Beyond $H \rightarrow aa \rightarrow b\bar{b}b\bar{b}$, searches for prompt $H \rightarrow aa$ decays have been performed in many other channels. At $\sqrt{s} = 7$ or 8 TeV , these include $H \rightarrow aa \rightarrow eeee$ [12], $\mu\mu\mu\mu$ [12–14], $ee\mu\mu$ [12], $\mu\mu\tau\tau$ [15], $\tau\tau\tau\tau$ [15, 16], $\gamma\gamma\gamma\gamma$ [17], and $bb\mu\mu$ [15]. At $\sqrt{s} = 13 \text{ TeV}$, these include $H \rightarrow aa \rightarrow eeee$ [18], $\mu\mu\mu\mu$ [18, 19], $ee\mu\mu$ [18], $\mu\mu\tau\tau$ [20–22], $\gamma\gamma\gamma\gamma$ [23–25], $bb\mu\mu$ [26–28], $bb\tau\tau$ [28, 29], and $\gamma\gamma jj$ (where j is a jet) [30]. These searches for the new particle a cover a mass range $0.2 < m_a < 62.5 \text{ GeV}$. The sensitivity of these searches as a function of m_a has recently been summarized in Ref. [31]. Searches in the $bb\tau\tau$, $\tau\tau\tau\tau$, and $bbbb$ final states reach branching fraction sensitivities in the range from 1% to 50% for $m_a \geq 2m_b \approx 10 \text{ GeV}$.

Backgrounds to $H \rightarrow aa \rightarrow b\bar{b}b\bar{b}$ from SM processes arise from several sources. The dominant background arises from $t\bar{t}$ +jets production in which one or both top quarks decay leptonically. The next-largest backgrounds are from Z +jets and W +jets production with a V boson that decays leptonically: the main background process in this case is from $V + b\bar{b}$ production plus one or two mistagged b jets. Smaller backgrounds arise from various electroweak processes. These include events with diboson $VV^{(\prime)}$ or triboson $VVV^{(\prime)}$ production, events with a single top quark, and rare electroweak processes such as events with $t\bar{t}V$ or $t\bar{t}\gamma$ production. The SM associated production of the Higgs boson in the VH channel, with $H \rightarrow b\bar{b}$, is also expected to comprise a background component in this search. Background from multijet production arises when jets or other reconstructed objects are erroneously identified as leptons or when genuine

leptons are produced through hadron decays.

Tabulated results for the study are provided in the HEPData record for this analysis [32].

2 Detector and trigger

A detailed description of the CMS detector, along with a definition of the coordinate system and pertinent kinematic variables, is presented in Ref. [33]. Briefly, a cylindrical superconducting solenoid with an inner diameter of 6 m provides a 3.8 T axial magnetic field. 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). The tracking detectors cover the pseudorapidity range $|\eta| < 2.5$. The ECAL and HCAL, each with a barrel and two endcap sections, cover $|\eta| < 3.0$. Forward calorimeters extend the coverage to $|\eta| < 5.0$. Muons are detected within $|\eta| < 2.4$ by gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. The detector is nearly hermetic, permitting accurate measurements of missing transverse momentum.

The CMS trigger system is described in Refs. [34, 35]. For this analysis, signal event candidates are selected using a combination of triggers requiring either at least one electron or muon, or, with lower transverse momentum (p_T) thresholds on the leptons, at least two electrons or muons. The trigger efficiency for signal events is measured in data and is found to exceed 95% for events satisfying the event selection criteria described below.

3 Event simulation

With the exception of the multijet background, which is determined from data, the background from SM processes is evaluated from simulation using Monte Carlo (MC) event generators. The $t\bar{t}$ +jets background is simulated at next-to-leading order (NLO) accuracy with the POWHEG2.0 [36–38] generator. A reweighting is applied to the top quark p_T to improve the modeling in the $t\bar{t}$ +jets simulation. The reweighting factors are defined as the ratio of the top quark p_T measured in data, unfolded to the parton level, with respect to the theory predictions at NNLO, and are taken from Ref. [39]. The V +jets background is simulated at leading order (LO) accuracy with the MADGRAPH5_aMC@NLO generator (version 2.2.2 for the simulation of the 2016 data and version 2.4.2 for the 2017–2018 data) [40], with cross sections normalized to NLO. For the V +jets processes, we apply NLO electroweak corrections as a function of the V boson p_T at the generator level, as documented in Ref. [41]. Diboson (triboson) processes are simulated at LO (NLO) accuracy with the PYTHIA8.212 (POWHEG2.0) generator. Single top quark production and the rare electroweak processes are simulated at NLO with a combination of the POWHEG2.0 and MADGRAPH5_aMC@NLO generators. Samples generated at NLO with the MADGRAPH5_aMC@NLO generator employ the FxFx matching and merging scheme [42], while those generated at LO with the same generator use the MLM matching and merging scheme [43].

Signal events, namely events with associated VH production followed by the decay $H \rightarrow a\bar{a}$, are simulated at LO using the MADGRAPH5_aMC@NLO (version 2.6.5) generator. The cross sections are normalized to the values presented in Refs. [44–47] and include NNLO QCD and NLO electroweak corrections. The pseudoscalar bosons are required to decay via $a \rightarrow b\bar{b}$, while the W and Z bosons are required to decay through the e , μ , or τ leptonic channels. The leptonic decays of the τ lepton are treated as a signal contribution. We require at least one lepton (e or μ) with p_T greater than 10 GeV and $|\eta|$ less than 2.5: this results in a filter efficiency

of about 61% for the WH channel and 75% for the ZH channel. Signal event samples are generated for pseudoscalar mass values $m_a = 15, 20, 25, 30, 40, 50,$ and 60 GeV.

The parton distribution function (PDF) set used in the simulations is NLO NNPDF3.1 for the NLO samples and LO NNPDF3.1 for the LO samples [48]. Parton showering and hadronization are described for all MC samples using the PYTHIA8 generator. For the simulation of the 2016 data, the CUETP8M1 tune [49, 50] is used. For the 2017–2018 data, we use the CP5 tune [51]. The detector response is evaluated using GEANT4 [52]. The contribution of additional pp interactions within the same or nearby bunch crossing (pileup) is modeled by adding simulated minimum bias events to the MC samples, with the distribution of additional interactions per event adjusted to agree with observation.

4 Event reconstruction

The particle-flow (PF) algorithm [53] is used to reconstruct and identify individual photons, electrons, muons, charged hadrons, and neutral hadrons (PF candidates) by combining information from individual subdetectors in an optimal fashion. To improve the quality of the reconstruction, requirements beyond the PF criteria are imposed on electron and muon candidates. For electron candidates, these requirements are based on the shower shape of the associated energy cluster in the ECAL, the angular matching of the electron track candidate with the cluster, and the consistency of the track with originating from the primary pp interaction vertex (PV) [54]. Electrons compatible with photon conversion in the detector material are removed. For muon candidates, these requirements are based on the number of energy deposits recorded for the candidate in the silicon tracker and muon system, the fit quality of the candidate, and the consistency of the candidate with originating from the PV [55]. Electron candidates are restricted to $|\eta| < 2.5$ and muon candidates to $|\eta| < 2.4$.

The PV is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone as described in Section 9.4.1 of Ref. [56]. The PV is required to lie within 24 cm of the center of the detector in the direction along the beam axis and within 2 cm in the plane transverse to that axis.

Leptons from V boson decays are generally isolated from the jets in an event, unlike leptons from sources such as hadron decays. We therefore require electron and muon candidates to be isolated. An isolation variable I_{iso} is defined as the sum of the scalar p_T of charged hadron, neutral hadron, and photon PF candidates within a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ around the electron or muon candidate direction, where ϕ is the azimuthal angle. A correction is applied to account for the contribution of pileup. For electrons, this correction is performed using the jet area method described in Ref. [57]. For muons, the correction is performed by subtracting half the sum of scalar p_T of charged-particle tracks within the cone, but using only those tracks that do not originate from the PV. We require the ratio of I_{iso} to the p_T value of the muon to be less than 0.15. For electrons, the I_{iso} selection requirements are optimized via a multivariate analysis, and are chosen to be $0.059 (0.029 + 0.506p_T)$ and $0.057 (0.044 + 0.963p_T)$ in the ECAL barrel and endcap, respectively, for the 2016 (2017–2018) data-taking period.

The combined reconstruction, identification, and isolation efficiency for electrons and muons is determined in data using Z boson decays with a tag-and-probe method [58]. The efficiencies range from 70 to 90% for electrons and from 90 to 97% for muons, depending on the lepton p_T and η .

Jets are reconstructed by clustering PF candidates using the anti- k_T jet algorithm [59, 60] with

a distance parameter of 0.4. Charged-particle tracks not associated with the PV are excluded from the clustering. The jet energies are corrected as explained in Ref. [61] to account for the nonlinear response of the detector and for the expected contributions of neutral particles from pileup. The jets are required to satisfy $p_T > 20 \text{ GeV}$ and $|\eta| < 2.5$. The number of selected jets in an event is denoted N_j .

Bottom quark jets are identified by applying the DEEPCSV algorithm [62] to the selected jets (the p_T threshold is maintained at 20 GeV). The medium working point of this algorithm is used, for which the tagging efficiency is 68% for b quark jets with $p_T \approx 30 \text{ GeV}$. The corresponding misidentification probability for light jets (i.e., gluon and light quark jets) is 1.6%, while that for charm quark jets is 13%. The number of b-tagged jets in an event is denoted N_b .

The missing transverse momentum vector \vec{p}_T^{miss} is defined as the projection onto the plane perpendicular to the beam axis of the negative vector sum of the momenta of all reconstructed PF candidates in an event. Its magnitude is referred to as p_T^{miss} . Calibration and pileup effects are accounted for as described in Ref. [63]. The p_T^{miss} variable is used to measure the undetected momentum in an event, such as is carried by neutrinos in leptonic W boson decays or as can arise spuriously from the misreconstruction of jet p_T .

For the WH channel we also consider the transverse mass m_T , defined by

$$m_T = \sqrt{2p_T^{\text{miss}} p_{T,\ell} (1 - \cos \phi_{p_T^{\text{miss}},\ell})}, \quad (1)$$

where $p_{T,\ell}$ is the transverse momentum of the lepton and $\phi_{p_T^{\text{miss}},\ell}$ is the azimuthal angle between \vec{p}_T^{miss} and the $p_{T,\ell}$ vector. For WH events, m_T represents the W boson mass calculated using transverse momentum only [64].

5 Analysis procedure

5.1 Baseline selection

A set of baseline selection criteria are applied in order to identify events that are consistent with the signal processes considered.

Single-lepton triggers are used to identify events in the WH channel. The p_T threshold for electrons was 27 GeV in 2016 and 32 GeV in 2017–2018. The corresponding thresholds for muons were 24 and 27 GeV, respectively. Dilepton triggers are used to identify events in the ZH channel. For electrons, the p_T thresholds on the two leptons were 23 and 12 GeV, while for muons they were 17 and 8 GeV, for all data-taking periods. For muons, the triggers in 2017–2018 differ from those in 2016 by the additional requirement that the dimuon invariant mass be larger than 3.8 GeV. The triggers require the leptons to satisfy stringent identification criteria and to be isolated from other tracks and energy deposits in the calorimeters.

For the WH channel, events must contain exactly one electron or muon, and no other electron (muon) with p_T above 15 (10) GeV. For the 2016 (2017–2018) data, electrons must have $p_T > 30$ (35) GeV and muons $p_T > 25$ (30) GeV. Higher thresholds are used for the 2017–2018 data to account for the increase in the online trigger thresholds. To suppress the multijet background, WH events must satisfy $p_T^{\text{miss}} > 25 \text{ GeV}$ and $m_T > 50 \text{ GeV}$.

For the ZH channel, events must contain exactly one e^+e^- or $\mu^+\mu^-$ pair and no other electron or muon with p_T above 15 (10) GeV. For electron pairs, one of the two legs must have $p_T > 25 \text{ GeV}$ and the other $p_T > 15 \text{ GeV}$. For muon pairs, the corresponding requirements are $p_T >$

Table 1: Signal region (SR) and control region (CR) requirements in (N_b, N_j) for the WH and ZH channels, where N_b is the number of b-tagged jets in an event and N_j is the total number of jets in an event.

Label	(N_b, N_j)	Description
WH channel		
SR (3b)	(3b, 3–4j)	3b signal region
SR (4b)	(4b, 4j)	4b signal region
CR (3b)	(2b, 3j)	W/ $t\bar{t}$ +jets control region
CR (4b)	(2b, 4j)	$t\bar{t}$ +jets control region
ZH channel		
SR (3b)	(3b, $\geq 3j$)	3b signal region
SR (4b)	(4b, $\geq 4j$)	4b signal region
CR (3b)	(2b, 3j)	DY control region
CR (4b)	(2b, 4j)	DY control region

20 GeV and $p_T > 10$ GeV. To reduce the background from $t\bar{t}$ +jets events, the invariant mass of the lepton pair must lie within 20 GeV of the nominal Z boson mass. No requirements are imposed on p_T^{miss} or m_T .

For both WH and ZH events, we require $N_j \geq 3$ and $N_b \geq 2$.

5.2 Analysis overview

The selected events are categorized in terms of N_b and N_j . Events in the signal region (SR) are divided into two categories depending on whether they have $N_b = 3$ (denoted the 3b category) or $N_b = 4$ (denoted the 4b category). The 4b category corresponds to events in which all four b jets in $H \rightarrow aa \rightarrow b\bar{b}b\bar{b}$ decays have been reconstructed. The 3b category accounts for events in which two b quarks are merged in a single jet or one of the b quarks is rather soft and fails to be reconstructed. The latter case is expected to have a small impact on the Higgs boson kinematics.

For WH events, the signal region is defined by $(N_b, N_j) = (3b, 3-4j)$ and $(4b, 4j)$, where 3–4j refers to events with either exactly three or exactly four jets. For ZH events, the SR is defined by $(3b, \geq 3j)$ and $(4b, \geq 4j)$. These regions are summarized in Table 1. The H boson is formed from the four b-tagged jets in the 4b category and from the three b-tagged jets in the 3b category. For WH events, the W boson is defined by the electron or muon and the \vec{p}_T^{miss} vector. For ZH events, the Z boson is defined by the e^+e^- or $\mu^+\mu^-$ pair.

A multivariate discriminator based on a boosted decision tree (BDT) [65] is used to help separate signal and background events. Different BDTs are constructed for the WH and ZH channels, and the 3b and 4b event categories. The input variables for the BDT are:

- p_T^H : the vector sum of the transverse momenta of the three or four b-tagged jets forming the H boson candidate;
- m_H : the invariant mass of the three or four b-tagged jets forming the H boson candidate;
- p_T^V : for W boson candidates, the magnitude of the vector sum of the p_T of the electron or muon and p_T^{miss} ; for Z boson candidates, the p_T of the dilepton pair;
- H_T : the scalar sum of the p_T of the three or four b-tagged jets that define the H boson candidate;

- $\langle \Delta R(b, b') \rangle$: the separation in the η - ϕ plane between any two b-tagged jets in an event, averaged over all such combinations;
- $|\Delta\phi(V, H)|$: the azimuthal angle between the directions of the W or Z and the H boson candidates;
- $|\Delta\phi(j, p_T^{\text{miss}})|^{\text{min}}$: the smallest azimuthal angle between the \vec{p}_T^{miss} direction and a jet;
- p_T^ℓ : for WH events, the p_T of the electron or muon; for ZH events, the p_T of the leading electron or muon;
- p_T^{miss} : the magnitude of the missing transverse momentum;
- m_T (defined only for WH events): the transverse mass defined in Section 4;
- $\Delta m_{b\bar{b}}^{\text{min}} = |m_{b\bar{b},1} - m_{b\bar{b},2}|^{\text{min}}$ (defined only for the 4b category): the minimum difference between two dijet masses formed from all possible combinations with the four b-tagged jets. The four b-tagged jets can be grouped in three different ways to form a pair of a $\rightarrow b\bar{b}$ candidates. The $\Delta m_{b\bar{b}}^{\text{min}}$ variable represents the grouping that results in the smallest difference between the masses of the two pseudoscalar candidates.

The BDTs are trained on signal events, combining all pseudoscalar boson mass points, and on background events, combining all considered SM processes. The shapes of the BDT distributions are not strongly dependent on the assumed value of m_a , allowing the same BDT to be used for all signal mass values.

We perform a maximum likelihood fit of the signal and background components to the observed distribution of the BDT discriminant. The fit is performed simultaneously across the SRs and control regions (CRs). The CRs are described in Section 5.3. The templates for signal events are derived from simulation. The templates for background events are determined as described in Section 5.3.

5.3 Background modeling and control regions

A major source of background in our study is from $t\bar{t}$ +jets production, as mentioned in the introduction. To evaluate this background, simulated $t\bar{t}$ +jets events are categorized based on the parton-level flavor content of additional particle-level jets not originating from the decay of the $t\bar{t}$ +jets system. Events that contain at least one additional particle-level jet matched to a b hadron are labeled as $t\bar{t}+b\bar{b}$. Events that contain at least one additional particle jet matched to a c hadron and no b hadron are labeled as $t\bar{t}+c\bar{c}$. The $t\bar{t}+c\bar{c}$ and $t\bar{t}+b\bar{b}$ categories, with heavy-flavor (HF) production, are referred to as the “ $t\bar{t}$ +HF” background. This background mostly arises from events with gluon splitting, $g \rightarrow c\bar{c}$ or $b\bar{b}$. The remaining $t\bar{t}$ +jets events are referred to as the “ $t\bar{t}$ +LF” background, where “LF” refers to light flavor. The $t\bar{t}$ +LF category also includes events with no additional particle-level jets. One source of this background is $t\bar{t}+q\bar{q}$ ($q = u, d, s$) events in which light-flavored jets are erroneously identified as b jets.

The template for the $t\bar{t}$ +LF background is taken from simulation, both for its shape and normalization. In contrast to $t\bar{t}$ +LF events, the rate of $t\bar{t}$ +HF events is not well predicted by simulation because it is dominated by the gluon splitting process, which is not yet well understood to adequate precision [66]. Therefore, while the shapes of the templates and the relative rate of $t\bar{t}+b\bar{b}$ to $t\bar{t}+c\bar{c}$ production are taken from simulation, the overall normalization is determined from the fit to data.

The W+jets and Z+jets backgrounds mostly arise when a W or Z boson is produced in association with b quark jets. Like $t\bar{t}$ +HF production, the rates of these processes are difficult to model [67, 68]. Thus, for the W+jets background to the WH channel and the Z+jets back-

ground to the ZH channel, the shapes of the templates are taken from simulation while the normalizations are determined in the fit. There is a small Z+jets background to the WH channel. The template for this background is taken from simulation for both the shape and normalization. The W+jets background to the ZH channel is negligible and is therefore ignored.

The CRs used to constrain the normalizations of the $t\bar{t} + \text{HF}$, W+jets, and Z+jets processes are obtained by selecting events with one less b-tagged jet with respect to the SRs. This requirement enables a collection of events predominantly governed by these background processes, while simultaneously depleting the signal content but closely aligning with the SRs. The (N_b, N_j) criteria for the CRs are as listed in Table 1. In the (2b, 3j) and (2b, 4j) categories, any variable that depends on N_b is constructed by adding “fake” b tags using the untagged jet(s) with highest DEEPCSV discriminator value(s). For the WH channel, we define a W/ $t\bar{t}$ +LF CR in the (2b, 3j) category and a $t\bar{t}$ +LF CR in the (2b, 4j) category. For the ZH channel, we define a Z+jets CR in the (2b, 3j) and (2b, 4j) categories. The modeling of the $t\bar{t} + \text{HF}$ background is validated in signal-depleted regions of the SR bins corresponding to BDT scores $\lesssim 0.1$. The modeling of the various backgrounds has been studied through comparison with observations in the CRs. The degree of agreement for shape variations between CR data and pre-fit estimates is validated to within $\approx 10\%$.

For the small backgrounds from diboson, triboson, single-top quark, rare electroweak processes, and the SM VH process with $H \rightarrow b\bar{b}$, both the shape and normalization are taken from simulation. Because of the presence of two isolated leptons, the multijet background to the ZH channel is negligible and is ignored. In the WH channel, for which only one isolated lepton is required, the multijet background is expected to be small. We estimate this background contribution from data, as described below.

To evaluate the multijet background to the WH channel, we select data events by inverting the lepton isolation requirements of Section 4. All other selection criteria are the same as for signal events. We call this sample the inverted-isolation sample. The multijet background template is given by the measured BDT distribution of events in the inverted-isolation sample, normalized by a scale factor \mathcal{F} calculated in a low- p_T^{miss} data sideband. The low- p_T^{miss} sideband is defined by $p_T^{\text{miss}} < 25 \text{ GeV}$ and $m_T < 50 \text{ GeV}$. We choose a sideband in p_T^{miss} and m_T because, for multijet background events, these variables are largely uncorrelated with the lepton isolation variable.

We thus consider the following four quantities:

- D_A : The BDT distribution of multijet background events in the SR;
- D_B : The BDT distribution of multijet background events in the inverted-isolation sample;
- N_C : The number of multijet background events in the low- p_T^{miss} sideband that satisfy the lepton isolation requirements;
- N_D : The number of multijet background events in the low- p_T^{miss} sideband that fail the lepton isolation requirements.

The multijet background estimate is given by $D_A = \mathcal{F} D_B$ with $\mathcal{F} \equiv N_C / N_D$. The contributions of nonmultijet background events to D_B , N_C , and N_D are subtracted using simulation before calculating D_A . Because the multijet background is expected to be small compared to other backgrounds, and because the statistical precision in this background estimate is limited, the estimate is assigned a conservative uncertainty of 50%. The closure or self-consistency of the estimate is tested in the 3b and 4b CRs, where the contribution of multijet events is small. The predicted multijet background in these CRs is found to be in reasonable agreement with the

data, to within the assigned uncertainty, once the nonmultijet contributions in data have been subtracted.

The same procedure is used to account for the multijet background contributions to the $t\bar{t}$ +HF and W +jets CRs for the WH channel.

5.4 Systematic uncertainties

The overall uncertainty in the determination of the integrated luminosity over the 2016–2018 data-taking period is 1.6% [69–71]. Systematic uncertainties related to the event simulation include those associated with the PDFs, the value of the strong coupling strength α_s , and the renormalization and factorization scales. We evaluate these uncertainties by altering the PDFs and scales of the simulated background samples according to the PDF4LHC prescription of Ref. [72]. Their effect on the yields is estimated to be 4–5%. The differences between the NNPDF3.1 and PDF4LHC uncertainties are found to be small compared to the statistical uncertainties in the background templates. The uncertainties in the signal cross section arising from the perturbative QCD calculations, PDF, and the α_s scales have a negligible effect on the shape of the signal. Their effects on the yield correspond to 0.7 and 1.9%, respectively, for WH production, and to 3.8 and 1.6%, respectively, for ZH production [44], and are taken into account by introducing nuisance parameters with log-normal distributions into the fit. We assign the following theoretical uncertainties on the cross sections for those simulated backgrounds whose normalization is not determined in the fit: $t\bar{t}$ +LF events (6%) [73], single top quark events (5%) [74, 75], diboson and triboson events (50%) [76, 77], Z+jets events in the WH channel (2%) [78], and rare electroweak processes (15%).

Tables 2 and 3 summarize the other systematic uncertainties that are considered in the analysis. For those, the shape variations are taken into account in the template fit, while their effect on the background and signal yield has been evaluated for illustration purposes. For signal events, the estimate of these uncertainties are shown for two choices of the pseudoscalar mass: $m_a = 20$ and 60 GeV.

The uncertainties related to the trigger efficiency and the lepton identification and isolation requirements are evaluated using data (this latter uncertainty, at 2%, is the same for electrons and muons). The uncertainties associated with the lepton energy scale, the jet energy scale, and the jet energy resolution are evaluated as a function of lepton or jet p_T and η . The uncertainty associated with the lepton energy scale is found to be negligible. In Tables 2 and 3, the uncertainty quoted for the jet energy scale is the maximum that is found for the various p_T and η bins. A related uncertainty, relevant for WH channel, is in the energy scale of unclustered p_T^{miss} , where unclustered p_T^{miss} refers to signals in the detector that are not associated to reconstructed physics objects, namely muons, electrons, photons, hadronically decaying taus and jets [63]. The uncertainties in the efficiencies for b tagging and for the mistagging of c quark and light-flavored jets are evaluated as described in Ref. [62]. Sources of systematic uncertainty that affect the data-to-simulation corrections of the b-tagging efficiency and misidentification rate are the jet energy scale, the cross contamination between light flavor or gluon jets with heavy flavor jets, and the statistical fluctuations in the data and MC. These uncertainties are split into 15 p_T and η bins and consist of 9 independent sources. Except for their statistical component, they are treated as correlated between the three data-taking periods. To evaluate the uncertainty associated with pileup, the total inelastic pp cross section is varied by $\pm 5\%$ [79]. The uncertainty from the mismodeling of the top quark p_T is assessed for the $t\bar{t}$ +jets MC by comparing results with and without reweighting. This uncertainty is negligible compared to the other uncertainties in the ZH channel.

Table 2: Summary of systematic uncertainties and their effect on the background and signal event yields in the WH channel. Uncertainties that are negligible are indicated with a dash (—).

Source	Uncertainty (%)						
	$t\bar{t}+b\bar{b}$	$t\bar{t}+c\bar{c}$	$t\bar{t}+LF$	W+jets	Z+jets	WH (20 GeV)	WH (60 GeV)
Lepton trigger, identification & isolation	2	2	2	2	2	2	2
Jet energy scale	0.5	0.5	0.5	2	2	1	1
Jet energy resolution	0.5	0.5	0.5	4	5	1	0.5
Energy scale of unclustered p_T^{miss}	0.5	0.5	0.5	2	2	1	0.8
b quark tagging	6	4	4	4.5	5	9	8.5
c quark mistagging	1.5	6.5	—	4	2.5	0.3	0.1
Light-flavor mistagging	1.5	1	9	7	9.5	1	0.5
Limited MC statistical precision	6	1.5	1	8	7	1	1
Pileup	0.5	1	2.5	4	4	0.5	0.5
t quark p_T mismodeling	2.5	1.3	1.5	—	—	—	—

Table 3: Summary of systematic uncertainties and their effect on the background and signal event yields in the ZH channel. Uncertainties that are negligible are indicated with a dash (—).

Source	Uncertainty (%)					
	$t\bar{t}+b\bar{b}$	$t\bar{t}+c\bar{c}$	$t\bar{t}+LF$	Z+jets	ZH (20 GeV)	ZH (60 GeV)
Lepton trigger, identification & isolation	2	2	2	2	2	2
Jet energy scale	1	—	—	0.5	0.1	0.1
Jet energy resolution	0.1	0.1	0.1	0.1	0.1	0.1
b quark tagging	6.5	4	4	5	9	8
c quark mistagging	0.5	9	—	2.5	0.3	0.1
Light-flavor mistagging	1	2	10	6	1	0.5
Limited MC statistical precision	8	5	1	5	1	1
Pileup	1	1	4	3	0.5	0.5

To account for the finite sizes of the simulated event samples, each bin of the simulated signal-plus-background templates is allowed to vary within its statistical uncertainty, independently from the other bins in the distribution. A bin-by-bin statistical uncertainty is considered by assigning a Poisson nuisance parameter per bin to distributions in those samples [80].

5.5 Maximum likelihood fit

A maximum likelihood fit of the signal and background terms to the observed distribution of the BDT discriminant is performed simultaneously across the SRs and CRs. The fits are performed separately for the WH and ZH channels and also with the WH and ZH channels combined.

For the WH channel, there are two SRs and two CRs, as indicated in the upper portion of Table 1, for a total of four independent data regions. In addition, the electron and muon samples are treated as separate event categories in the fit. We also treat each of the three years of data collection separately. There are therefore 24 data regions that are fitted simultaneously. The fitted parameters are the signal strength modifier, a global scale factor for $t\bar{t}+HF$ production, a global scale factor for W+jets production, and various nuisance parameters, where the nuisance parameters represent the systematic uncertainties from Section 5.4. The signal strength modifier μ is defined by the equation: $s = \mu s_0$, where s is the observed signal yield and s_0 is the expected signal yield for a SM VH production cross section times a “benchmark” branching fraction $\mathcal{B}(H \rightarrow aa \rightarrow b\bar{b}b\bar{b}) = 1$.

For the ZH channel, there are also two SRs and two CRs, as indicated in the lower portion of Table 1, leading to 24 independent data regions in the fit as for the WH channel. The fitted parameters are the signal strength modifier, a global scale factor for $t\bar{t}+HF$ production, a global

Table 4: Signal-plus-background fit results for the 3b WH and ZH signal regions extracted with the $m_a = 60$ GeV signal hypothesis. The lepton flavor (e or μ) and BDT bin range (in square brackets) are indicated in the column headings. Signal yields corresponding to the expectation for SM VH production and $\mathcal{B}(H \rightarrow aa \rightarrow b\bar{b}b\bar{b}) = 1$ are shown for the $m_a = 20$ and 60 GeV hypotheses. The background uncertainties account for both systematic and statistical sources.

Process	e [1,3]	e [4,4]	e [5,5]	μ [1,3]	μ [4,4]	μ [5,5]
WH signal region, 3b						
Other bkg	2288 ± 97	32.8 ± 7.8	14.9 ± 1.7	3570 ± 160	50.4 ± 3.6	17.2 ± 2.4
Multijet	1370 ± 160	72 ± 15	48 ± 11	4400 ± 380	128 ± 18	43.4 ± 8.0
$Z \rightarrow \ell\ell$	476 ± 46	17.7 ± 6.4	4.7 ± 4.0	430 ± 54	19 ± 14	7.9 ± 1.2
$W \rightarrow \ell\nu$	2850 ± 180	110 ± 37	49 ± 12	3670 ± 150	250 ± 38	121 ± 23
$t\bar{t} + b\bar{b}$	5650 ± 280	58.9 ± 5.4	20.5 ± 2.4	6610 ± 400	74.8 ± 8.5	22.9 ± 5.1
$t\bar{t} + c\bar{c}$	$19\,080 \pm 260$	101 ± 12	38.4 ± 4.1	$30\,930 \pm 410$	162 ± 35	47.0 ± 6.2
$t\bar{t} + \text{LF}$	$11\,220 \pm 190$	98 ± 13	33.8 ± 4.1	$18\,010 \pm 310$	159.5 ± 6.7	48.1 ± 2.0
Total bkg	$42\,940 \pm 200$	490 ± 64	208 ± 17	$67\,630 \pm 280$	844 ± 52	308 ± 29
Data	42 934	510	230	67 688	874	326
Signal(20)	77.3 ± 1.4	30.2 ± 0.9	15.8 ± 0.7	110.1 ± 1.6	46.2 ± 1.1	23.5 ± 0.8
Signal(60)	117.5 ± 1.5	90.3 ± 1.6	60.7 ± 1.3	164.9 ± 1.7	125.5 ± 1.9	83.0 ± 1.5
ZH signal region, 3b						
Other bkg	72 ± 16	6.2 ± 1.7	1.2 ± 0.7	126 ± 24	13.2 ± 3.7	2.6 ± 0.9
$Z \rightarrow \ell\ell$	871 ± 40	98.1 ± 9.8	68 ± 12	1811 ± 58	237 ± 16	123 ± 16
$t\bar{t} + b\bar{b}$	288 ± 49	10.0 ± 2.4	2.9 ± 1.1	434 ± 57	11.8 ± 2.1	3.4 ± 5.5
$t\bar{t} + c\bar{c}$	128 ± 33	2.6 ± 2.9	2.2 ± 4.9	242 ± 51	5.2 ± 1.7	1.9 ± 5.3
$t\bar{t} + \text{LF}$	180 ± 11	4.2 ± 0.3	2.3 ± 0.6	346 ± 16	12.5 ± 0.8	2.4 ± 0.6
Total bkg	1539 ± 50	121 ± 11	77 ± 13	2959 ± 65	280 ± 17	134 ± 18
Data	1544	130	82	2962	292	144
Signal(20)	6.2 ± 0.6	9.9 ± 0.4	13.3 ± 0.4	13.1 ± 0.8	21.6 ± 0.5	24.9 ± 0.6
Signal(60)	7.6 ± 0.7	21.4 ± 0.5	43.4 ± 0.8	13.1 ± 0.8	42.8 ± 0.8	76.6 ± 1.0

scale factor for Z+jets production with three b-tagged jets, a global scale factor for Z+jets production with four b-tagged jets, and several nuisance parameters. We implement separate scale factors for Z+jets production with three and four b-tagged jets because the relative rates of Z boson production in association with two or more b quarks are not yet well established [67, 68]. For W+jets events, a common scale factor is used for the three and four b-tagged categories because the large statistical uncertainties do not allow discrimination between the two categories.

Systematic uncertainties in the signal and background normalizations are treated as log-normal distributions. The SR and CR distributions in data and the background estimates are used in the maximum likelihood fit to search for $H \rightarrow aa \rightarrow b\bar{b}b\bar{b}$ decays.

6 Results

No evidence is found for a significant excess of events above the SM background prediction. Model independent upper limits are placed, at 95% confidence level (CL), on the branching fraction $\mathcal{B}(H \rightarrow aa \rightarrow b\bar{b}b\bar{b})$ as a function of m_a . The results for the signal are normalized to the NNLO SM cross sections of the Higgs boson production $\sigma(\text{pp} \rightarrow \text{WH}) = 1.37$ pb and

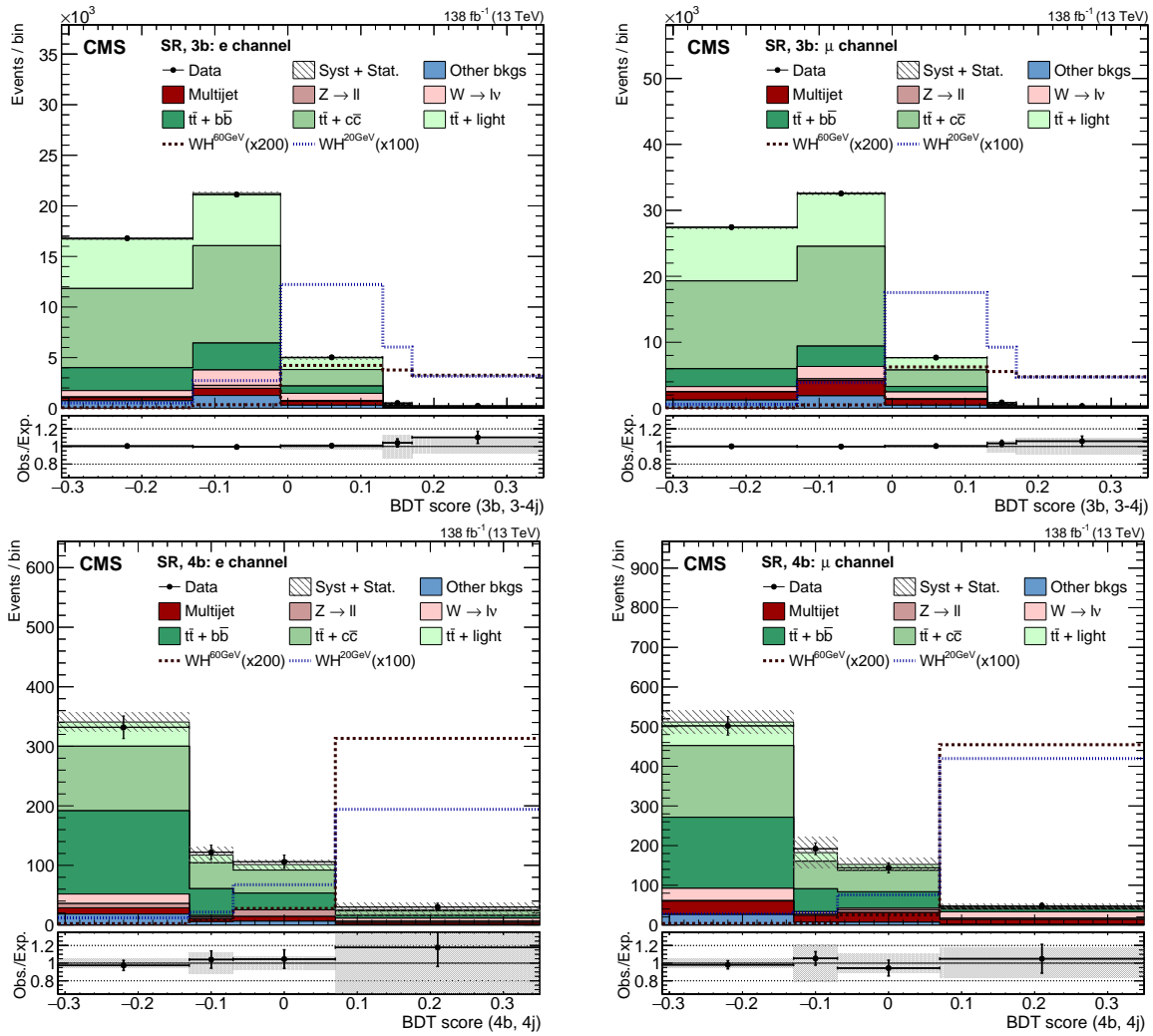


Figure 1: Post-fit BDT distributions in the WH channel extracted with the $m_a = 60$ GeV signal hypothesis. Signal regions for the 3b (upper) and 4b (lower) event categories are shown separately for the electron (left) and muon (right) channels. The dotted lines $WH^{20\text{GeV}}$, $WH^{60\text{GeV}}$, illustrate the shapes of the signal template normalised to the SM cross section times a branching fraction $\mathcal{B}(H \rightarrow aa \rightarrow b\bar{b}b\bar{b}) = 1$ and scaled by the factors indicated in the figure. The horizontal error bars indicate the bin width. The hatched band in each bin represents the uncertainty in the total background estimation.

$\sigma(pp \rightarrow ZH) = 0.86$ pb. The results are dominated by the statistical uncertainties. The dominant systematic uncertainties are associated with the b jet identification. For $m_a = 60$ GeV, the b-tagging uncertainties on the yield vary between 6 and 9% for the major background processes. For the signal process, this uncertainty is around 8%. Other uncertainties lie below 5%.

Figures 1 and 2 show the post-fit shapes of the BDT score variable for the WH and ZH channels, respectively, where “post-fit” means that the parameter values determined in the likelihood fit are used. The event yields for the various SM backgrounds are presented in Tables 4 and 5 for the 3b and 4b categories, respectively. The results are presented in the bins of the BDT variable shown in Figs. 1 and 2 (five bins for the 3b category and four bins for the 4b category). For purposes of illustration, signal yields corresponding to the expectation for SM VH production and

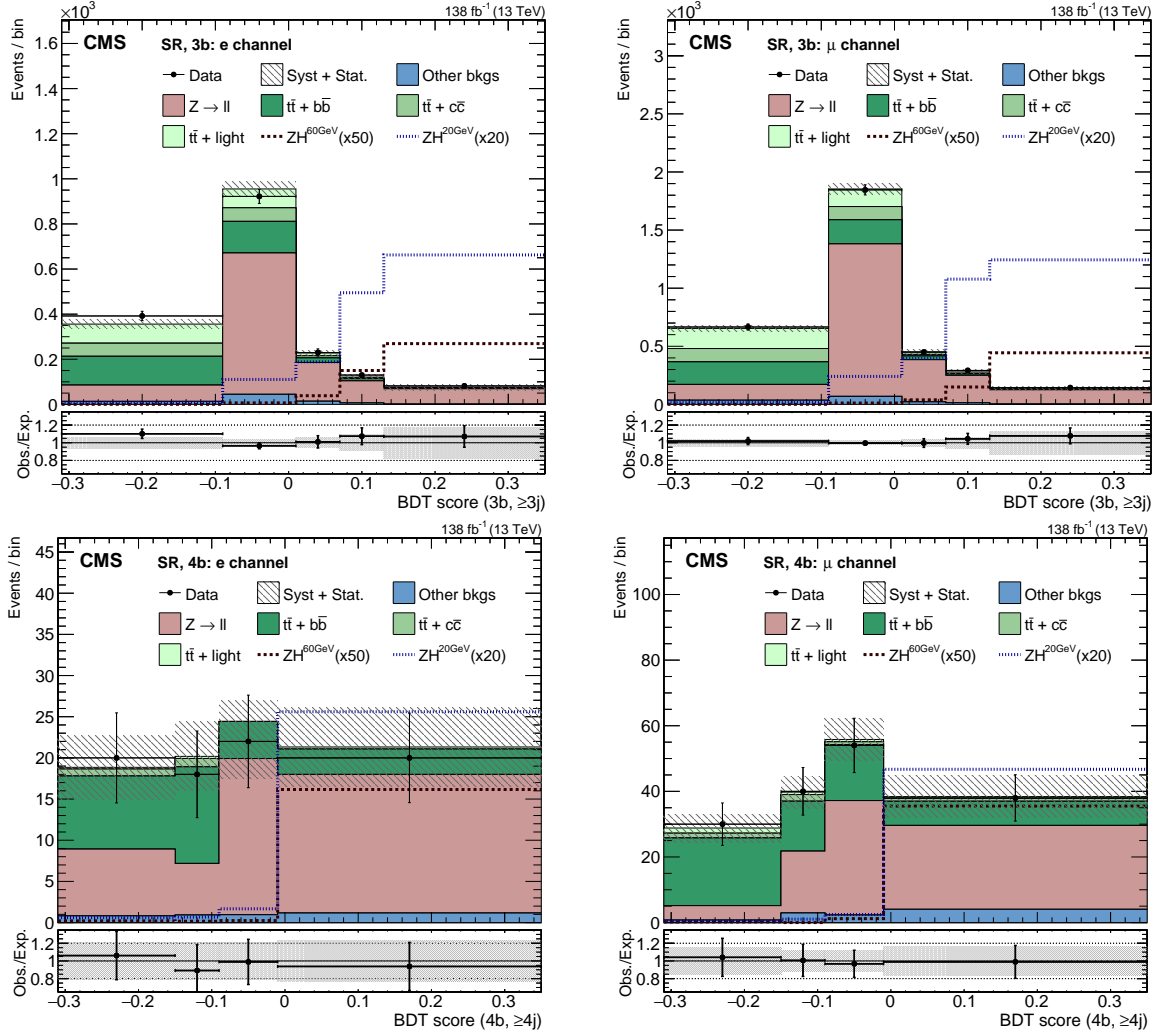


Figure 2: Post-fit BDT distributions in the ZH channel extracted with the $m_a = 60$ GeV signal hypothesis. Signal regions for the 3b (upper) and 4b (lower) event categories are shown separately for the electron (left) and muon (right) channels. The dotted lines $ZH^{20\text{GeV}}$ and $ZH^{60\text{GeV}}$, illustrate the shapes of the signal template normalised to the SM cross section times a branching fraction $\mathcal{B}(H \rightarrow aa \rightarrow b\bar{b}b\bar{b}) = 1$ and scaled by the factors indicated in the figure. The horizontal error bars indicate the bin width. The hatched band in each bin represents the uncertainty in the total background estimation.

$\mathcal{B}(H \rightarrow aa \rightarrow b\bar{b}b\bar{b}) = 1$, for $m_a = 20$ or 60 GeV are also shown. The background uncertainties account for both systematic and statistical sources. Figures 3 present model independent upper limits on the quantity $\sigma_{\text{VH}}\mathcal{B}(H \rightarrow aa \rightarrow b\bar{b}b\bar{b})/\sigma_{\text{SM}}$ as a function of m_a for the WH and ZH channels separately as well as their combination. The limits are obtained using the CL_s criterion and an asymptotic approximation to the distribution of the profiled likelihood ratio test statistic [81, 82], assuming SM predictions for the Higgs boson production cross section. The limit curves are plotted by interpolating smoothly across the mass points.

In the WH channel, the observed upper limit on the $\mathcal{B}(H \rightarrow aa \rightarrow b\bar{b}b\bar{b})$ is found to be 0.48 (1.59) for $m_a = 60$ (20) GeV, compared to an expected limit of 0.51 ± 0.16 (1.73 ± 0.56). In the ZH channel, the corresponding observed upper limit is 0.48 (1.40), with an expected result of 0.38 ± 0.13 (1.16 ± 0.38). Our search is optimized for m_a values between 20 and 60 GeV, with

Table 5: Signal-plus-background fit results for the 4b WH and ZH signal regions extracted with the $m_a = 60$ GeV signal hypothesis. The lepton flavor (e or μ) and BDT bin range (in square brackets) are indicated in the column headings. Signal yields corresponding to the expectation for SM VH production and $\mathcal{B}(H \rightarrow aa \rightarrow b\bar{b}b\bar{b}) = 1$ are shown for the $m_a = 20$ and 60 GeV hypotheses. The background uncertainties account for both systematic and statistical sources.

Process	e [1,3]	e [4,4]	μ [1,3]	μ [4,4]
WH signal region, 4b				
Other bkg	29.9 ± 1.9	0.4 ± 0.3	40.5 ± 2.0	1.4 ± 0.2
Multijet	23.2 ± 3.8	3.7 ± 1.3	74.5 ± 9.2	12.1 ± 3.0
$Z \rightarrow \ell\ell$	21 ± 11	2.5 ± 4.7	12.4 ± 1.9	3.2 ± 3.1
$W \rightarrow \ell\nu$	18.6 ± 5.3	5 ± 11	40 ± 14	16.4 ± 7.8
$t\bar{t} + b\bar{b}$	213 ± 15	4.6 ± 2.1	278 ± 15	6.7 ± 1.8
$t\bar{t} + c\bar{c}$	190.6 ± 7.0	7.9 ± 2.4	305 ± 14	2.1 ± 1.3
$t\bar{t} + \text{LF}$	63.0 ± 4.9	1.8 ± 1.1	96.0 ± 8.3	3.8 ± 1.3
Total bkg	559 ± 17	26 ± 11	846 ± 24	45.7 ± 7.8
Data	560	30	838	48
Signal(20)	1.0 ± 0.5	1.9 ± 0.2	1.4 ± 0.6	4.2 ± 0.7
Signal(60)	1.7 ± 0.6	13.9 ± 0.6	1.6 ± 0.5	18.8 ± 0.7
ZH signal region, 4b				
Other bkg	2.7 ± 2.8	1.2 ± 0.6	6.0 ± 1.4	4.0 ± 1.4
$Z \rightarrow \ell\ell$	33.3 ± 9.3	16.8 ± 4.7	58.2 ± 8.8	25.6 ± 6.0
$t\bar{t} + b\bar{b}$	25.1 ± 6.8	3.1 ± 1.1	52.9 ± 6.3	7.4 ± 1.3
$t\bar{t} + c\bar{c}$	-0.0 ± 3.1	-0.4 ± 4.5	4.4 ± 1.3	0.9 ± 0.4
$t\bar{t} + \text{LF}$	0.2 ± 1.2	0.7 ± 0.6	3.0 ± 0.7	0.6 ± 1.2
Total bkg	61.3 ± 8.2	21.3 ± 4.9	124 ± 10	38.4 ± 6.4
Data	60	20	124	38
Signal(20)	0.1 ± 0.3	1.3 ± 0.1	0.2 ± 0.3	2.3 ± 0.2
Signal(60)	0.2 ± 0.3	6.6 ± 0.3	0.3 ± 0.3	12.0 ± 0.4

signal sensitivity falling rapidly below 30 GeV. For $m_a \lesssim 30$ GeV, the sensitivity is degraded in both the WH and ZH channels because of the signal efficiency loss when reconstructing collimated b jet pairs from highly Lorentz-boosted pseudoscalar bosons.

The observed limit on $\mathcal{B}(H \rightarrow aa \rightarrow b\bar{b}b\bar{b})$ for the combined WH and ZH channels is 0.36 (1.10) for $m_a = 60$ (20) GeV, compared to an expected result of 0.31 ± 0.10 (0.96 ± 0.32). It is possible to extract model dependent limits on $\mathcal{B}(H \rightarrow aa)$ in the context of 2HDM+S models, predicting the branching fraction $\mathcal{B}(a \rightarrow b\bar{b})$, depending on the type and parameters of the model [7].

7 Summary

A search for exotic decays of the 125 GeV Higgs boson (H) to a pair of new light pseudoscalar bosons (a), followed by decay to four b quark jets, $H \rightarrow aa \rightarrow b\bar{b}b\bar{b}$, is presented, using data recorded with the CMS detector. The analysis is based on an integrated luminosity of 138 fb^{-1} collected at a center-of-mass energy of 13 TeV in 2016–2018. The search is performed in the context of the associated WH and ZH production in which the W or Z boson decays leptonically,

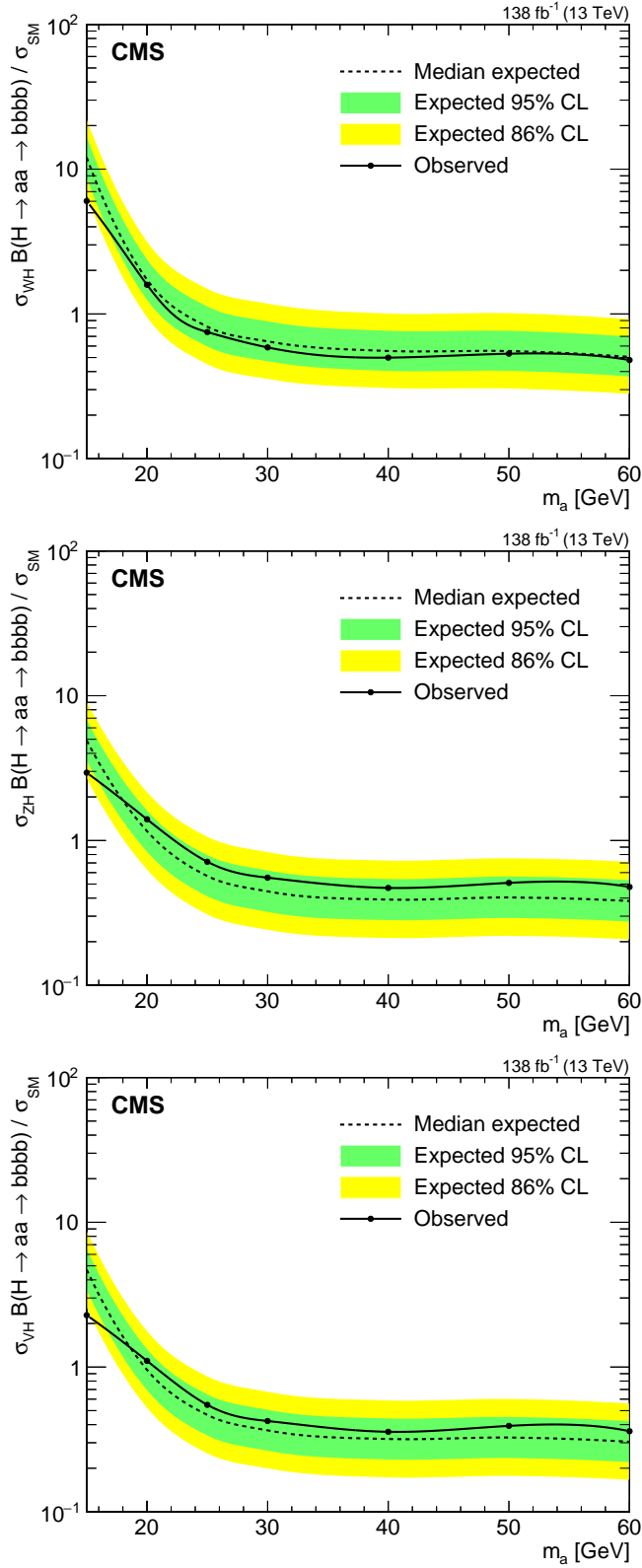


Figure 3: Model independent 95% CL upper limits on $\sigma_{\text{VH}} \mathcal{B}(H \rightarrow aa \rightarrow b\bar{b}b\bar{b}) / \sigma_{\text{SM}}$ for the WH channel (upper), the ZH channel (middle), and the combination of both channels (lower), where “a” is a new pseudoscalar particle decaying through $a \rightarrow b\bar{b}$, and σ_{SM} is the SM Higgs boson production cross section.

$W \rightarrow \ell\nu$ or $Z \rightarrow \ell^+\ell^-$, with ℓ an electron or muon. No evidence for the targeted decay mode is observed. The analysis obtains model independent upper limits at 95% confidence level on the branching fraction $\mathcal{B}(H \rightarrow aa \rightarrow b\bar{b}b\bar{b})$ of a SM-like Higgs boson. The combined result for the associated WH and ZH Higgs boson production excludes branching fractions as low as 0.36 in the mass range m_a between about 25 GeV and 60 GeV, assuming the SM WH and ZH cross-sections. These results provide enhanced sensitivity, in the mass range $m_a \gtrsim 20$ GeV, in complementary regions of the 2HDM+S model parameter space compared to CMS searches in the $\mu\mu\tau\tau$ and $b\bar{b}\ell\ell$ ($\ell = \mu, \tau$) final states.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid 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, RVTT3 and MoER TK202 (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); SRNSF (Georgia); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP 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 and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); 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, 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 Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science – EOS" – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010 and Fundamental Research Funds for the Central Universities (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), 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 124845, K 124850, K 128713, K 128786, K 129058, K 131991, K 133046, K 138136, K 143460, K 143477, 2020-2.2.1-ED-2021-00181, and TKP2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India; ICSC – National Research

Center for High Performance Computing, Big Data and Quantum Computing, funded by the EU NexGeneration 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 and 2021/43/B/ST2/01552 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MCIN/AEI/10.13039/501100011033, ERDF “a way of making Europe”, and the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, and the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B37G660013 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

- [1] ATLAS Collaboration, “Observation of a new particle in the search for the standard model Higgs boson with the ATLAS detector at the LHC”, *Phys. Lett. B* **716** (2012) 1, doi:10.1016/j.physletb.2012.08.020, arXiv:1207.7214.
- [2] CMS Collaboration, “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC”, *Phys. Lett. B* **716** (2012) 30, doi:10.1016/j.physletb.2012.08.021, arXiv:1207.7235.
- [3] CMS Collaboration, “Observation of a new boson with mass near 125 GeV in pp collisions at $\sqrt{s} = 7$ and 8 TeV”, *JHEP* **06** (2013) 081, doi:10.1007/JHEP06(2013)081, arXiv:1303.4571.
- [4] ATLAS Collaboration, “A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery”, *Nature* **607** (2022) 52, doi:10.1038/s41586-022-04893-w, arXiv:2207.00092. [Erratum: doi:https://doi.org/10.1038/s41586-022-05581-5].
- [5] CMS Collaboration, “A portrait of the Higgs boson by the CMS experiment ten years after the discovery.”, *Nature* **607** (2022) 60, doi:10.1038/s41586-022-04892-x, arXiv:2207.00043.
- [6] G. C. Branco et al., “Theory and phenomenology of two-Higgs-doublet models”, *Phys. Rept.* **516** (2012) 1, doi:10.1016/j.physrep.2012.02.002, arXiv:1106.0034.
- [7] D. Curtin et al., “Exotic decays of the 125 GeV Higgs boson”, *Phys. Rev. D* **90** (2014) 075004, doi:10.1103/PhysRevD.90.075004, arXiv:1312.4992.
- [8] U. Ellwanger, C. Hugonie, and A. M. Teixeira, “The next-to-minimal supersymmetric standard model”, *Phys. Rept.* **496** (2010) 1, doi:10.1016/j.physrep.2010.07.001, arXiv:0910.1785.
- [9] ATLAS Collaboration, “Search for the Higgs boson produced in association with a W boson and decaying to four b-quarks via two spin-zero particles in pp collisions at 13 TeV with the ATLAS detector”, *Eur. Phys. J. C* **76** (2016) 605, doi:10.1140/epjc/s10052-016-4418-9, arXiv:1606.08391.

- [10] ATLAS Collaboration, “Search for the Higgs boson produced in association with a vector boson and decaying into two spin-zero particles in the $H \rightarrow aa \rightarrow 4b$ channel in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *JHEP* **10** (2018) 031, doi:10.1007/JHEP10(2018)031, arXiv:1806.07355.
- [11] ATLAS Collaboration, “Search for Higgs boson decays into two new low-mass spin-0 particles in the $4b$ channel with the ATLAS detector using pp collisions at $\sqrt{s} = 13$ TeV”, *Phys. Rev. D* **102** (2020) 112006, doi:10.1103/PhysRevD.102.112006, arXiv:2005.12236.
- [12] ATLAS Collaboration, “Search for new light gauge bosons in Higgs boson decays to four-lepton final states in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector at the LHC”, *Phys. Rev. D* **92** (2015) 092001, doi:10.1103/PhysRevD.92.092001, arXiv:1505.07645.
- [13] CMS Collaboration, “Search for a non-standard-model Higgs boson decaying to a pair of new light bosons in four-muon final states”, *Phys. Lett. B* **726** (2013) 564, doi:10.1016/j.physletb.2013.09.009, arXiv:1210.7619.
- [14] CMS Collaboration, “A search for pair production of new light bosons decaying into muons”, *Phys. Lett. B* **752** (2016) 146, doi:10.1016/j.physletb.2015.10.067, arXiv:1506.00424.
- [15] CMS Collaboration, “Search for light bosons in decays of the 125 GeV Higgs boson in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *JHEP* **10** (2017) 076, doi:10.1007/JHEP10(2017)076, arXiv:1701.02032.
- [16] CMS Collaboration, “Search for a very light NMSSM Higgs boson produced in decays of the 125 GeV scalar boson and decaying into τ leptons in pp collisions at $\sqrt{s} = 8$ TeV”, *JHEP* **01** (2016) 079, doi:10.1007/JHEP01(2016)079, arXiv:1510.06534.
- [17] ATLAS Collaboration, “Search for new phenomena in events with at least three photons collected in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector”, *Eur. Phys. J. C* **76** (2016) 210, doi:10.1140/epjc/s10052-016-4034-8, arXiv:1509.05051.
- [18] ATLAS Collaboration, “Search for Higgs boson decays to beyond-the-standard-model light bosons in four-lepton events with the ATLAS detector at $\sqrt{s} = 13$ TeV”, *JHEP* **06** (2018) 166, doi:10.1007/JHEP06(2018)166, arXiv:1802.03388.
- [19] CMS Collaboration, “A search for pair production of new light bosons decaying into muons in proton-proton collisions at 13 TeV”, *Phys. Lett. B* **796** (2019) 131, doi:10.1016/j.physletb.2019.07.013, arXiv:1812.00380.
- [20] ATLAS Collaboration, “Search for Higgs bosons decaying to aa in the $\mu\mu\tau\tau$ final state in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS experiment”, *Phys. Rev. D* **92** (2015) 052002, doi:10.1103/PhysRevD.92.052002, arXiv:1505.01609.
- [21] CMS Collaboration, “Search for an exotic decay of the Higgs boson to a pair of light pseudoscalars in the final state of two muons and two τ leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **11** (2018) 018, doi:10.1007/JHEP11(2018)018, arXiv:1805.04865.
- [22] CMS Collaboration, “Search for a light pseudoscalar Higgs boson in the boosted $\mu\mu\tau\tau$ final state in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **08** (2020) 139, doi:10.1007/JHEP08(2020)139, arXiv:2005.08694.

- [23] CMS Collaboration, “Search for exotic Higgs boson decays $H \rightarrow \mathcal{A}\mathcal{A} \rightarrow 4\gamma$ with events containing two merged diphotons in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Rev. Lett.* **131** (2023) 101801, doi:10.1103/PhysRevLett.131.101801, arXiv:2209.06197.
- [24] CMS Collaboration, “Search for the exotic decay of the Higgs boson into two light pseudoscalars with four photons in the final state in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **07** (2023) 148, doi:10.1007/JHEP07(2023)148, arXiv:2208.01469.
- [25] ATLAS Collaboration, “Search for short- and long-lived axion-like particles in $H \rightarrow aa \rightarrow 4\gamma$ decays with the ATLAS experiment at the LHC”, 2023. arXiv:2312.03306. Submitted to *Eur. Phys. J. C*.
- [26] ATLAS Collaboration, “Search for Higgs boson decays into a pair of light bosons in the $bb\mu\mu$ final state in pp collision at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *Phys. Lett. B* **790** (2019) 1, doi:10.1016/j.physletb.2018.10.073, arXiv:1807.00539.
- [27] ATLAS Collaboration, “Search for Higgs boson decays into a pair of pseudoscalar particles in the $bb\mu\mu$ final state with the ATLAS detector in pp collisions at $\sqrt{s}=13$ TeV”, *Phys. Rev. D* **105** (2022) 012006, doi:10.1103/PhysRevD.105.012006, arXiv:2110.00313.
- [28] CMS Collaboration, “Search for exotic decays of the Higgs boson to a pair of pseudoscalars in the $\mu\mu bb$ and $\tau\tau bb$ final states”, 2024. arXiv:2402.13358. Submitted to *Eur. Phys. J. C*.
- [29] CMS Collaboration, “Search for an exotic decay of the Higgs boson to a pair of light pseudoscalars in the final state with two b quarks and two τ leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Lett. B* **785** (2018) 462, doi:10.1016/j.physletb.2018.08.057, arXiv:1805.10191.
- [30] ATLAS Collaboration, “Search for Higgs boson decays into pairs of light (pseudo)scalar particles in the $\gamma\gamma jj$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *Phys. Lett. B* **782** (2018) 750, doi:10.1016/j.physletb.2018.06.011, arXiv:1803.11145.
- [31] M. Cepeda, S. Gori, V. M. Outchoorn, and J. Shelton, “Exotic Higgs decays”, *Ann. Rev. Nucl. Part. Sci.* **72** (2022) 119, doi:10.1146/annurev-nucl-102319-024147, arXiv:2111.12751.
- [32] HEPData record for this analysis, 2024. doi:10.17182/hepdata.147309.
- [33] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [34] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
- [35] CMS Collaboration, “Performance of the CMS level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **15** (2020) P10017, doi:10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.
- [36] P. Nason, “A new method for combining NLO QCD with shower Monte Carlo algorithms”, *JHEP* **11** (2004) 040, doi:10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.

- [37] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with parton shower simulations: the POWHEG method”, *JHEP* **11** (2007) 070, doi:10.1088/1126-6708/2007/11/070, arXiv:0709.2092.
- [38] S. Alioli, P. Nason, C. Oleari, and E. Re, “A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX”, *JHEP* **06** (2010) 043, doi:10.1007/JHEP06(2010)043, arXiv:1002.2581.
- [39] CMS Collaboration, “Measurement of differential cross sections for top quark pair production using the lepton+jets final state in proton-proton collisions at 13 TeV”, *Phys. Rev. D* **95** (2017) 092001, doi:10.1103/PhysRevD.95.092001, arXiv:1610.04191.
- [40] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.
- [41] CMS Collaboration, “Observation of Higgs boson decay to bottom quarks”, *Phys. Rev. Lett.* **121** (2018) 121801, doi:10.1103/PhysRevLett.121.121801, arXiv:1808.08242.
- [42] J. Alwall et al., “Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions”, *Eur. Phys. J. C* **53** (2008) 473, doi:10.1140/epjc/s10052-007-0490-5, arXiv:0706.2569.
- [43] R. Frederix and S. Frixione, “Merging meets matching in MC@NLO”, *JHEP* **12** (2012) 061, doi:10.1007/JHEP12(2012)061, arXiv:1209.6215.
- [44] LHC Higgs Cross Section Working Group, “Handbook of LHC Higgs cross sections: 1. Inclusive observables”, CERN Report CERN-2011-002, 2011. doi:10.5170/CERN-2011-002, arXiv:1101.0593.
- [45] LHC Higgs Cross Section Working Group, “Handbook of LHC Higgs cross sections: 2. Differential distributions”, CERN Report CERN-2012-002, 2012. doi:10.5170/CERN-2012-002, arXiv:1201.3084.
- [46] LHC Higgs Cross Section Working Group, “Handbook of LHC Higgs cross sections: 3. Higgs properties”, CERN Report CERN-2013-004, 2013. doi:10.5170/CERN-2013-004, arXiv:1307.1347.
- [47] 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. doi:10.23731/CYRM-2017-002, arXiv:1610.07922.
- [48] NNPDF Collaboration, “Parton distributions from high-precision collider data”, *Eur. Phys. J. C* **77** (2017) 663, doi:10.1140/epjc/s10052-017-5199-5, arXiv:1706.00428.
- [49] P. Skands, S. Carrazza, and J. Rojo, “Tuning PYTHIA 8.1: the Monash 2013 Tune”, *Eur. Phys. J. C* **74** (2014) 3024, doi:10.1140/epjc/s10052-014-3024-y, arXiv:1404.5630.
- [50] CMS Collaboration, “Event generator tunes obtained from underlying event and multiparton scattering measurements”, *Eur. Phys. J. C* **76** (2016) 155, doi:10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.


- [51] CMS Collaboration, “Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements”, *Eur. Phys. J. C* **80** (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.
- [52] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [53] CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.
- [54] CMS Collaboration, “Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *JINST* **10** (2015) P06005, doi:10.1088/1748-0221/10/06/P06005, arXiv:1502.02701.
- [55] CMS Collaboration, “Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **13** (2018) P06015, doi:10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.
- [56] 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.
- [57] M. Cacciari and G. P. Salam, “Pileup subtraction using jet areas”, *Phys. Lett. B* **659** (2008) 119, doi:10.1016/j.physletb.2007.09.077, arXiv:0707.1378.
- [58] CMS Collaboration, “Measurement of the inclusive W and Z production cross sections in pp collisions at $\sqrt{s} = 7$ TeV”, *JHEP* **10** (2011) 132, doi:10.1007/JHEP10(2011)132, arXiv:1107.4789.
- [59] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- k_T jet clustering algorithm”, *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
- [60] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet user manual”, *Eur. Phys. J. C* **72** (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.
- [61] CMS Collaboration, “Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV”, *JINST* **12** (2017) P02014, doi:10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.
- [62] CMS Collaboration, “Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV”, *JINST* **13** (2018) P05011, doi:10.1088/1748-0221/13/05/P05011, arXiv:1712.07158.
- [63] CMS Collaboration, “Performance of missing transverse momentum reconstruction in proton-proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector”, *JINST* **14** (2019) P07004, doi:10.1088/1748-0221/14/07/P07004, arXiv:1903.06078.
- [64] UA1 Collaboration, “Experimental observation of isolated large transverse energy electrons with associated missing energy at $\sqrt{s} = 540$ GeV”, *Phys. Lett. B* **122** (1983) 103, doi:10.1016/0370-2693(83)91177-2.
- [65] H. Voss, A. Höcker, J. Stelzer, and F. Tegenfeldt, “TMVA, the toolkit for multivariate data analysis with ROOT”, in *XIth International Workshop on Advanced Computing and Analysis Techniques in Physics Research (ACAT)*, p. 40. 2007. arXiv:physics/0703039. [PoS(ACAT)040]. doi:10.22323/1.050.0040.

- [66] ATLAS Collaboration, “Measurement of the $b\bar{b}$ dijet cross section in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector”, *Eur. Phys. J. C* **76** (2016) 670, doi:10.1140/epjc/s10052-016-4521-y, arXiv:1607.08430.
- [67] ATLAS Collaboration, “Measurement of differential production cross-sections for a Z boson in association with b-jets in 7 TeV proton-proton collisions with the ATLAS detector”, *JHEP* **10** (2014) 141, doi:10.1007/JHEP10(2014)141, arXiv:1407.3643.
- [68] CMS Collaboration, “Measurement of the associated production of a Z boson with charm or bottom quark jets in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Rev. D* **102** (2020) 032007, doi:10.1103/PhysRevD.102.032007, arXiv:2001.06899.
- [69] 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** (2021) 800, doi:10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.
- [70] CMS Collaboration, “CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV”, CMS Physics Analysis Summary CMS-PAS-LUM-17-004, 2018.
- [71] CMS Collaboration, “CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV”, CMS Physics Analysis Summary CMS-PAS-LUM-18-002, 2019.
- [72] J. Butterworth et al., “PDF4LHC recommendations for LHC Run II”, *J. Phys. G* **43** (2016) 023001, doi:10.1088/0954-3899/43/2/023001, arXiv:1510.03865.
- [73] M. Czakon, P. Fiedler, and A. Mitov, “Total top-quark pair-production cross section at hadron colliders through $O(\alpha_s^4)$ ”, *Phys. Rev. Lett.* **110** (2013) 252004, doi:10.1103/PhysRevLett.110.252004, arXiv:1303.6254.
- [74] N. Kidonakis, “Two-loop soft anomalous dimensions for single top quark associated production with a W^- or H^- ”, *Phys. Rev. D* **82** (2010) 054018, doi:10.1103/PhysRevD.82.054018, arXiv:1005.4451.
- [75] N. Kidonakis, “Top quark production”, in *Helmholtz International Summer School on Physics of Heavy Quarks and Hadrons*, p. 139. 2014. arXiv:1311.0283. doi:10.3204/DESY-PROC-2013-03/Kidonakis.
- [76] T. Gehrmann et al., “ W^+W^- production at hadron colliders in next to next to leading order QCD”, *Phys. Rev. Lett.* **113** (2014) 212001, doi:10.1103/PhysRevLett.113.212001, arXiv:1408.5243.
- [77] F. Cascioli et al., “ZZ production at hadron colliders in NNLO QCD”, *Phys. Lett. B* **735** (2014) 311, doi:10.1016/j.physletb.2014.06.056, arXiv:1405.2219.
- [78] CMS Collaboration, “Measurement of the differential Drell-Yan cross section in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **12** (2019) 059, doi:10.1007/JHEP12(2019)059, arXiv:1812.10529.
- [79] CMS Collaboration, “Measurement of the inelastic proton-proton cross section at $\sqrt{s} = 13$ TeV”, *JHEP* **07** (2018) 161, doi:10.1007/JHEP07(2018)161, arXiv:1802.02613.
- [80] R. J. Barlow and C. Beeston, “Fitting using finite Monte Carlo samples”, *Comput. Phys. Commun.* **77** (1993) 219, doi:10.1016/0010-4655(93)90005-W.



















- [81] A. L. Read, "Presentation of search results: The CL_s technique", *J. Phys. G* **28** (2002) 2693, doi:10.1088/0954-3899/28/10/313.
- [82] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, "Asymptotic formulae for likelihood-based tests of new physics", *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727. [Erratum: doi:10.1140/epjc/s10052-013-2501-z].

A The CMS Collaboration




Yerevan Physics Institute, Yerevan, Armenia

A. Hayrapetyan, A. Tumasyan¹ 














Institut für Hochenergiephysik, Vienna, Austria

W. Adam , J.W. Andrejkovic, T. Bergauer , S. Chatterjee , K. Damanakis , M. Dragicevic , P.S. Hussain , M. Jeitler² , N. Krammer , A. Li , D. Liko , I. Mikulec , J. Schieck² , R. Schöfbeck , D. Schwarz , M. Sonawane , S. Templ , W. Waltenberger , C.-E. Wulz² 

















Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish³ , T. Janssen , P. Van Mechelen 











Vrije Universiteit Brussel, Brussel, Belgium

E.S. Bols , J. D'Hondt , S. Dansana , A. De Moor , M. Delcourt , S. Lowette , I. Makarenko , D. Müller , S. Tavernier , M. Tytgat⁴ , G.P. Van Onsem , S. Van Putte , D. Vannerom 













Université Libre de Bruxelles, Bruxelles, Belgium

B. Clerbaux , A.K. Das, G. De Lentdecker , H. Evard , L. Favart , P. Gianneios , D. Hohov , J. Jaramillo , A. Khalilzadeh, F.A. Khan , K. Lee , M. Mahdavihorrani , A. Malara , S. Paredes , L. Thomas , M. Vanden Bemden , C. Vander Velde , P. Vanlaer 







Ghent University, Ghent, Belgium

M. De Coen , D. Dobur , Y. Hong , J. Knolle , L. Lambrecht , G. Mestdach, K. Mota Amarilo , C. Rendón, A. Samalan, K. Skovpen , N. Van Den Bossche , J. van der Linden , L. Wezenbeek 



















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

A. Benecke , A. Bethani , G. Bruno , C. Caputo , C. Delaere , I.S. Donertas , A. Giammanco , Sa. Jain , V. Lemaitre, J. Lidrych , P. Mastrapasqua , T.T. Tran , S. Wertz 

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves , E. Coelho , C. Hensel , T. Menezes De Oliveira , A. Moraes , P. Rebello Teles , M. Soeiro

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
































W.L. Aldá Júnior , M. Alves Gallo Pereira , M. Barroso Ferreira Filho , H. Brandao Malbouisson , W. Carvalho , J. Chinellato⁵, E.M. Da Costa , G.G. Da Silveira⁶ , D. De Jesus Damiao , S. Fonseca De Souza , R. Gomes De Souza, J. Martins⁷ , C. Mora Herrera , L. Mundim , H. Nogima , J.P. Pinheiro , A. Santoro , A. Sznajder , M. Thiel , A. Vilela Pereira 

























































































Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil























































C.A. Bernardes⁶ , L. Calligaris , T.R. Fernandez Perez Tomei , E.M. Gregores , P.G. Mercadante , S.F. Novaes , B. Orzari , Sandra S. Padula 

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

A. Aleksandrov , G. Antchev , R. Hadjiiska , P. Iaydjiev , M. Misheva , M. Shopova , G. Sultanov 

University of Sofia, Sofia, BulgariaA. Dimitrov , L. Litov , B. Pavlov , P. Petkov , A. Petrov , E. Shumka **Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile**S. Keshri , S. Thakur **Beihang University, Beijing, China**T. Cheng , T. Javaid , L. Yuan **Department of Physics, Tsinghua University, Beijing, China**Z. Hu , J. Liu, K. Yi^{8,9} **Institute of High Energy Physics, Beijing, China**G.M. Chen¹⁰ , H.S. Chen¹⁰ , M. Chen¹⁰ , F. Iemmi , C.H. Jiang, A. Kapoor¹¹ , H. Liao , Z.-A. Liu¹² , R. Sharma¹³ , J.N. Song¹², J. Tao , C. Wang¹⁰, J. Wang , Z. Wang¹⁰, H. Zhang **State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China**A. Agapitos , Y. Ban , A. Levin , C. Li , Q. Li , Y. Mao, S.J. Qian , X. Sun , D. Wang , H. Yang, L. Zhang , C. Zhou **Sun Yat-Sen University, Guangzhou, China**Z. You **University of Science and Technology of China, Hefei, China**K. Jaffel , N. Lu **Nanjing Normal University, Nanjing, China**G. Bauer¹⁴**Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China**X. Gao¹⁵ **Zhejiang University, Hangzhou, Zhejiang, China**Z. Lin , C. Lu , M. Xiao **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**J. Mejia Guisao , F. Ramirez , M. Rodriguez , J.D. Ruiz Alvarez **University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia**D. Giljanovic , N. Godinovic , D. Lelas , A. Sculac **University of Split, Faculty of Science, Split, Croatia**M. Kovac , T. Sculac **Institute Rudjer Boskovic, Zagreb, Croatia**P. Bargassa , V. Brigljevic , B.K. Chitroda , D. Ferencek , K. Jakovcic, S. Mishra , A. Starodumov¹⁶ , T. Susa **University of Cyprus, Nicosia, Cyprus**A. Attikis , K. Christoforou , A. Hadjiagapiou, S. Konstantinou , J. Mousa , C. Nicolaou, F. Ptochos , P.A. Razis , H. Rykaczewski, H. Saka , A. Stepennov 

Charles University, Prague, Czech RepublicM. Finger , M. Finger Jr. , A. Kveton **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**S. Elgammal¹⁷, A. Ellithi Kamel¹⁸**Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt**M.A. Mahmoud , Y. Mohammed **National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**K. Ehataht , M. Kadastik, T. Lange , S. Nandan , C. Nielsen , J. Pata , M. Raidal , L. Tani , C. Veelken **Department of Physics, University of Helsinki, Helsinki, Finland**H. Kirschenmann , K. Osterberg , M. Voutilainen **Helsinki Institute of Physics, Helsinki, Finland**S. Bharthuar , E. Brücken , F. Garcia , K.T.S. Kallonen , R. Kinnunen, T. Lampén , K. Lassila-Perini , S. Lehti , T. Lindén , L. Martikainen , M. Myllymäki , M.m. Rantanen , H. Siikonen , E. Tuominen , J. Tuominiemi **Lappeenranta-Lahti University of Technology, Lappeenranta, Finland**P. Luukka , H. Petrow **IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France**M. Besancon , F. Couderc , M. Dejardin , D. Denegri, J.L. Faure, F. Ferri , S. Ganjour , P. Gras , G. Hamel de Monchenault , V. Lohezic , J. Malcles , F. Orlandi , L. Portales , J. Rander, A. Rosowsky , M.Ö. Sahin , A. Savoy-Navarro¹⁹ , P. Simkina , M. Titov , M. Tornago **Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France**F. Beaudette , A. Buchot Perraguin , P. Busson , A. Cappati , C. Charlot , M. Chiusi , F. Damas , O. Davignon , A. De Wit , I.T. Ehle , B.A. Fontana Santos Alves , S. Ghosh , A. Gilbert , R. Granier de Cassagnac , A. Hakimi , B. Harikrishnan , L. Kalipoliti , G. Liu , J. Motta , M. Nguyen , C. Ochando , R. Salerno , J.B. Sauvan , Y. Sirois , A. Tarabini , E. Vernazza , A. Zabi , A. Zghiche **Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France**J.-L. Agram²⁰ , J. Andrea , D. Apparuu , D. Bloch , J.-M. Brom , E.C. Chabert , C. Collard , S. Falke , U. Goerlach , C. Grimault, R. Haeberle , A.-C. Le Bihan , M. Meena , G. Saha , M.A. Sessini , P. Van Hove **Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France**S. Beauceron , B. Blancon , G. Boudoul , N. Chanon , D. Contardo , P. Depasse , C. Dozen²¹ , H. El Mamouni, J. Fay , S. Gascon , M. Gouzevitch , C. Greenberg, G. Grenier , B. Ille , I.B. Laktineh, M. Lethuillier , L. Mirabito, S. Perries, A. Purohit , M. Vander Donckt , P. Verdier , J. Xiao 

Georgian Technical University, Tbilisi, GeorgiaI. Bagaturia²² , I. Lomidze , Z. Tsamalaide¹⁶ **RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany**V. Botta , L. Feld , K. Klein , M. Lipinski , D. Meuser , A. Pauls , N. Rówert , M. Teroerde **RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany**S. Diekmann , A. Dodonova , N. Eich , D. Eliseev , F. Engelke , J. Erdmann, M. Erdmann , P. Fackeldey , B. Fischer , T. Hebbeker , K. Hoepfner , F. Ivone , A. Jung , M.y. Lee , F. Mausolf , M. Merschmeyer , A. Meyer , S. Mukherjee , D. Noll , F. Nowotny, A. Pozdnyakov , Y. Rath, W. Redjeb , F. Rehm, H. Reithler , U. Sarkar , V. Sarkisovi , A. Schmidt , A. Sharma , J.L. Spah , A. Stein , F. Torres Da Silva De Araujo²³ , S. Wiedenbeck , S. Zaleski**RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany**C. Dziwok , G. Flügge , W. Haj Ahmad²⁴ , T. Kress , A. Nowack , O. Pooth , A. Stahl , T. Ziemons , A. Zotz **Deutsches Elektronen-Synchrotron, Hamburg, Germany**H. Aarup Petersen , M. Aldaya Martin , J. Alimena , S. Amoroso, Y. An , S. Baxter , M. Bayatmakou , H. Becerril Gonzalez , O. Behnke , A. Belvedere , S. Bhattacharya , F. Blekman²⁵ , K. Borrás²⁶ , A. Campbell , A. Cardini , C. Cheng, F. Colombina , S. Consuegra Rodríguez , G. Correia Silva , M. De Silva , G. Eckerlin, D. Eckstein , L.I. Estevez Banos , O. Filatov , E. Gallo²⁵ , A. Geiser , A. Giraldi , V. Guglielmi , M. Guthoff , A. Hinzmann , A. Jafari²⁷ , L. Jeppe , N.Z. Jomhari , B. Kaech , M. Kasemann , C. Kleinwort , R. Kogler , M. Komm , D. Krücker , W. Lange, D. Leyva Pernia , K. Lipka²⁸ , W. Lohmann²⁹ , F. Lorkowski , R. Mankel , I.-A. Melzer-Pellmann , M. Mendizabal Morentin , A.B. Meyer , G. Milella , A. Mussgiller , L.P. Nair , A. Nürnberg , Y. Otariid, J. Park , D. Pérez Adán , E. Ranken , A. Raspereza , D. Rastorguev , B. Ribeiro Lopes , J. Rübenach, A. Saggio , M. Scham^{30,26} , S. Schnake²⁶ , P. Schütze , C. Schwanenberger²⁵ , D. Selivanova , K. Sharko , M. Shchedrolosiev , R.E. Sosa Ricardo , D. Stafford, F. Vazzoler , A. Ventura Barroso , R. Walsh , Q. Wang , Y. Wen , K. Wichmann, L. Wiens²⁶ , C. Wissing , Y. Yang , A. Zimmermann Castro Santos **University of Hamburg, Hamburg, Germany**A. Albrecht , S. Albrecht , M. Antonello , S. Bein , L. Benato , S. Bollweg, M. Bonanomi , P. Connor , K. El Morabit , Y. Fischer , E. Garutti , A. Grohsjean , J. Haller , H.R. Jabusch , G. Kasieczka , P. Keicher, R. Klanner , W. Korcari , T. Kramer , V. Kutzner , F. Labe , J. Lange , A. Lobanov , C. Matthies , L. Moureaux , M. Mrowietz, A. Nigamova , Y. Nissan, A. Paasch , K.J. Pena Rodriguez , T. Quadfasel , B. Raciti , M. Rieger , D. Savoio , J. Schindler , P. Schleper , M. Schröder , J. Schwandt , M. Sommerhalder , H. Stadie , G. Steinbrück , A. Tews, M. Wolf **Karlsruher Institut fuer Technologie, Karlsruhe, Germany**S. Brommer , M. Burkart, E. Butz , T. Chwalek , A. Dierlamm , A. Droll, N. Faltermann , M. Giffels , A. Gottmann , F. Hartmann³¹ , R. Hofsaess , M. Horzela , U. Husemann , J. Kieseler , M. Klute , R. Koppenhöfer , J.M. Lawhorn , M. Link, A. Lintuluoto , B. Maier , S. Maier , S. Mitra , M. Mormile , Th. Müller , M. Neukum, M. Oh , E. Pfeffer , M. Presilla , G. Quast , K. Rabbertz , B. Regnery , N. Shadskiy

I. Shvetsov , H.J. Simonis , M. Toms , N. Trevisani , R.F. Von Cube , M. Wassmer ,
S. Wieland , F. Wittig, R. Wolf , X. Zuo 




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

G. Anagnostou, G. Daskalakis , A. Kyriakis, A. Papadopoulos³¹, A. Stakia 

National and Kapodistrian University of Athens, Athens, Greece

P. Kontaxakis , G. Melachroinos, Z. Painesis , A. Panagiotou, I. Papavergou ,
I. Paraskevas , N. Saoulidou , K. Theofilatos , E. Tziaferi , K. Vellidis , I. Zisopoulos 




National Technical University of Athens, Athens, Greece

G. Bakas , T. Chatzistavrou, G. Karapostoli , K. Kousouris , I. Papakrivopoulos ,
E. Siamarkou, G. Tsiopolitis, A. Zacharopoulou

University of Ioánnina, Ioánnina, Greece

K. Adamidis, I. Bestintzanos, I. Evangelou , C. Foudas, C. Kamtsikis, P. Katsoulis,
P. Kokkas , P.G. Kosmoglou Kioseoglou , N. Manthos , I. Papadopoulos , J. Strologas 


HUN-REN Wigner Research Centre for Physics, Budapest, Hungary

M. Bartók³² , C. Hajdu , D. Horvath^{33,34} , K. Márton, A.J. Rádl³⁵ , F. Sikler ,
V. Veszpremi 

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

M. Csanád , K. Farkas , M.M.A. Gadallah³⁶ , Á. Kadlecik , P. Major , K. Mandal ,
G. Pásztor , G.I. Veres 




Faculty of Informatics, University of Debrecen, Debrecen, Hungary

P. Raics, B. Ujvari , G. Zilizi 















Institute of Nuclear Research ATOMKI, Debrecen, Hungary

G. Bencze, S. Czellar, J. Molnar, Z. Szillasi

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary

T. Csorgo³⁷ , F. Nemes³⁷ , T. Novak 





Panjab University, Chandigarh, India

J. Babbar , S. Bansal , S.B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan ,
N. Dhingra³⁸ , A. Kaur , A. Kaur , H. Kaur , M. Kaur , S. Kumar , K. Sandeep ,
T. Sheokand, J.B. Singh , A. Singla 














University of Delhi, Delhi, India

A. Ahmed , A. Bhardwaj , A. Chhetri , B.C. Choudhary , A. Kumar , A. Kumar ,
M. Naimuddin , K. Ranjan , S. Saumya 



Saha Institute of Nuclear Physics, HBNI, Kolkata, India

S. Baradia , S. Barman³⁹ , S. Bhattacharya , S. Dutta , S. Dutta, S. Sarkar










Indian Institute of Technology Madras, Madras, India

M.M. Ameen , P.K. Behera , S.C. Behera , S. Chatterjee , P. Jana , P. Kalbhor ,
J.R. Komaragiri⁴⁰ , D. Kumar⁴⁰ , P.R. Pujahari , N.R. Saha , A. Sharma , A.K. Sikdar ,
S. Verma 












Tata Institute of Fundamental Research-A, Mumbai, India

S. Dugad, M. Kumar , G.B. Mohanty , P. Suryadevara










Tata Institute of Fundamental Research-B, Mumbai, India

A. Bala , S. Banerjee , R.M. Chatterjee, R.K. Dewanjee⁴¹ , M. Guchait , Sh. Jain ,
A. Jaiswal, S. Kumar , G. Majumder , K. Mazumdar , S. Parolia , A. Thachayath 

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India

S. Bahinipati⁴² , C. Kar , D. Maity⁴³ , P. Mal , T. Mishra , V.K. Muraleedharan Nair Bindhu⁴³ , K. Naskar⁴³ , A. Nayak⁴³ , P. Sadangi, S.K. Swain , S. Varghese⁴³ ,
D. Vats⁴³ 

Indian Institute of Science Education and Research (IISER), Pune, India

S. Acharya⁴⁴ , A. Alpana , S. Dube , B. Gomber⁴⁴ , P. Hazarika , B. Kansal ,
A. Laha , B. Sahu⁴⁴ , S. Sharma , K.Y. Vaish


Isfahan University of Technology, Isfahan, Iran

H. Bakhshiansohi⁴⁵ , E. Khazaie⁴⁶ , M. Zeinali⁴⁷ 
































Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

S. Chenarani⁴⁸ , S.M. Etesami , M. Khakzad , M. Mohammadi Najafabadi 




























University College Dublin, Dublin, Ireland

M. Grunewald 

INFN Sezione di Bari^a, Università di Bari^b, Politecnico di Bari^c, Bari, Italy

M. Abbrescia^{a,b} , R. Aly^{a,c,49} , A. Colaleo^{a,b} , D. Creanza^{a,c} , B. D'Anzi^{a,b} ,
N. De Filippis^{a,c} , M. De Palma^{a,b} , A. Di Florio^{a,c} , W. Elmetenawee^{a,b,49} ,
L. Fiore^a , G. Iaselli^{a,c} , M. Louka^{a,b}, G. Maggi^{a,c} , M. Maggi^a , I. Margjeka^{a,b} ,
V. Mastrapasqua^{a,b} , S. My^{a,b} , S. Nuzzo^{a,b} , A. Pellicchia^{a,b} , A. Pompili^{a,b} ,
G. Pugliese^{a,c} , R. Radogna^a , G. Ramirez-Sanchez^{a,c} , D. Ramos^a , A. Ranieri^a ,
L. Silvestris^a , F.M. Simone^{a,b} , Ü. Sözbilir^a , A. Stamerra^a , R. Venditti^a ,
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} , L. Borgonovi^a , R. Campanini^{a,b} ,
P. Capiluppi^{a,b} , A. Castro^{a,b} , F.R. Cavallo^a , M. Cuffiani^{a,b} , G.M. Dallavalle^a ,
T. Diotallevi^{a,b} , F. Fabbri^a , A. Fanfani^{a,b} , D. Fasanella^{a,b} , P. Giacomelli^a ,
L. Giommi^{a,b} , C. Grandi^a , S. Lo Meo^{a,50} , L. Lunerti^{a,b} , S. Marcellini^a ,
G. Masetti^a , F.L. Navarria^{a,b} , A. Perrotta^a , F. Primavera^{a,b} , A.M. Rossi^{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,51} , A. Di Mattia^a , R. Potenza^{a,b}, A. Tricomi^{a,b,51} , C. Tuve^{a,b} 

INFN Sezione di Firenze^a, Università di Firenze^b, Firenze, Italy

P. Assiouras^a , G. Barbagli^a , G. Bardelli^{a,b} , B. Camaiani^{a,b} , A. Cassese^a ,
R. Ceccarelli^a , V. Ciulli^{a,b} , C. Civinini^a , R. D'Alessandro^{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. Meola⁵² , D. Piccolo 










INFN Sezione di Genova^a, Università di Genova^b, Genova, Italy

P. Chatagnon^a , F. Ferro^a , E. Robutti^a , S. Tosi^{a,b} 













INFN Sezione di Milano-Bicocca^a, Università di Milano-Bicocca^b, Milano, Italy

A. Benaglia^a , G. Boldrini^{a,b} , F. Brivio^a , F. Cetorelli^a , 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.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 , B.S. Pinolini^a, G. Pizzati^{a,b}, S. Ragazzi^{a,b} , T. Tabarelli de Fatis^{a,b} , D. Zuolo^a












INFN Sezione di Napoli^a, Università di Napoli 'Federico II'^b, Napoli, Italy; Università della Basilicata^c, Potenza, Italy; Scuola Superiore Meridionale (SSM)^d, Napoli, Italy

S. Buontempo^a , A. Cagnotta^{a,b} , F. Carnevali^{a,b}, N. Cavallo^{a,c} , F. Fabozzi^{a,c} , A.O.M. Iorio^{a,b} , L. Lista^{a,b,53} , P. Paolucci^{a,31} , B. Rossi^a , C. Sciacca^{a,b} 









INFN Sezione di Padova^a, Università di Padova^b, Padova, Italy; Università di Trento^c, Trento, Italy

R. Ardino^a , P. Azzi^a , N. Bacchetta^{a,54} , M. Bellato^a , D. Bisello^{a,b} , P. Bortignon^a , G. Bortolato^{a,b}, A. Bragagnolo^{a,b} , A.C.M. Bulla^a , R. Carlin^{a,b} , P. Checchia^a , T. Dorigo^a , F. Gasparini^{a,b} , E. Lusiani^a , M. Margoni^{a,b} , F. Marini^a , A.T. Meneguzzo^{a,b} , M. Migliorini^{a,b} , J. Pazzini^{a,b} , P. Ronchese^{a,b} , R. Rossin^{a,b} , F. Simonetto^{a,b} , G. Strong^a , M. Tosi^{a,b} , A. Triossi^{a,b} , S. Ventura^a , H. Yarar^{a,b}, M. Zanetti^{a,b} , P. Zotto^{a,b} , A. Zucchetta^{a,b} , G. Zumerle^{a,b}








INFN Sezione di Pavia^a, Università di Pavia^b, Pavia, Italy

S. Abu Zeid^{a,55} , C. Aimè^{a,b} , A. Braghieri^a , S. Calzaferri^a , D. Fiorina^a , P. Montagna^{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} , G.M. Bilei^a , D. Ciangottini^{a,b} , L. Fanò^{a,b} , M. Magherini^{a,b} , V. Mariani^{a,b} , M. Menichelli^a , F. Moscatelli^{a,56} , 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



















P. Asenov^{a,b} , P. Azzurri^a , G. Bagliesi^a , R. Bhattacharya^a , L. Bianchini^{a,b} , T. Boccali^a , E. Bossini^a , D. Bruschini^{a,c} , R. Castaldi^a , M.A. Ciocci^{a,b} , M. Cipriani^{a,b} , V. D'Amante^{a,d} , R. Dell'Orso^a , S. Donato^a , A. Giassi^a , F. Ligabue^{a,c} , D. Matos Figueiredo^a , A. Messineo^{a,b} , M. Musich^{a,b} , F. Palla^a , A. Rizzi^{a,b} , G. Rolandi^{a,c} , S. Roy Chowdhury^a , T. Sarkar^a , A. Scribano^a , P. Spagnolo^a , 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, Roma, Italy







C. Baldenegro Barrera^{a,b} , P. Barria^a , C. Basile^{a,b} , M. Campana^{a,b} , F. Cavallari^a , L. Cunqueiro Mendez^{a,b} , D. Del Re^{a,b} , E. Di Marco^a , M. Diemoz^a , F. Errico^{a,b} , E. Longo^{a,b} , P. Meridiani^a , J. Mijuskovic^{a,b} , G. Organtini^{a,b} , F. Pandolfi^a , R. Paramatti^{a,b} , C. Quaranta^{a,b} , S. Rahatlou^{a,b} , C. Rovelli^a , F. Santanastasio^{a,b} , L. Soffi^a

INFN Sezione di Torino^a, Università di Torino^b, Torino, Italy; Università del Piemonte Orientale^c, Novara, Italy










N. Amapane^{a,b} , R. Arcidiacono^{a,c} , S. Argiro^{a,b} , M. Arneodo^{a,c} , N. Bartosik^a , R. Bellan^{a,b} , 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} , F. Legger^a , F. Luongo^{a,b} , C. Mariotti^a , L. Markovic^{a,b} , S. Maselli^a , A. Mecca^{a,b}

E. Migliore^{a,b} , M. Monteno^a , R. Mulargia^a , M.M. Obertino^{a,b} , G. Ortona^a ,
L. Pacher^{a,b} , N. Pastrone^a , M. Pelliccioni^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 

INFN Sezione di Trieste^a, Università di Trieste^b, Trieste, Italy

S. Belforte^a , V. Candelise^{a,b} , M. Casarsa^a , F. Cossutti^a , K. De Leo^a ,
G. Della Ricca^{a,b} 

Kyungpook National University, Daegu, Korea

S. Dogra , J. Hong , C. Huh , B. Kim , D.H. Kim , J. Kim, H. Lee, S.W. Lee ,
C.S. Moon , Y.D. Oh , M.S. Ryu , S. Sekmen , Y.C. Yang 





Department of Mathematics and Physics - GWNNU, 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 

Hanyang University, Seoul, Korea

E. Asilar , J. Choi , D. Kim , T.J. Kim , J.A. Merlin

Korea University, Seoul, Korea

S. Choi , S. Han, B. Hong , K. Lee, K.S. Lee , S. Lee , J. Park, S.K. Park, J. Yoo 





Kyung Hee University, Department of Physics, Seoul, Korea

J. Goh , S. Yang 








Sejong University, Seoul, Korea

H. S. Kim , Y. Kim, S. Lee



Seoul National University, Seoul, Korea

J. Almond, J.H. Bhyun, J. Choi , W. Jun , J. Kim , S. Ko , H. Kwon , H. Lee , J. Lee ,
J. Lee , B.H. Oh , S.B. Oh , H. Seo , U.K. Yang, I. Yoon

University of Seoul, Seoul, Korea

W. Jang , D.Y. Kang, Y. Kang , S. Kim , B. Ko, J.S.H. Lee , Y. Lee , I.C. Park , Y. Roh,
I.J. Watson 

Yonsei University, Department of Physics, Seoul, Korea

S. Ha , H.D. Yoo 





Sungkyunkwan University, Suwon, Korea

M. Choi , M.R. Kim , H. Lee, Y. Lee , I. Yu 


**College of Engineering and Technology, American University of the Middle East (AUM),
Dasman, Kuwait**

T. Beyrouthy

Riga Technical University, Riga, Latvia

K. Dreimanis , A. Gaile , G. Pikurs, A. Potrebko , M. Seidel 

University of Latvia (LU), Riga, Latvia

N.R. Strautnieks 







Vilnius University, Vilnius, Lithuania

M. Ambrozias , A. Juodagalvis , A. Rinkevicius , G. Tamulaitis 







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

N. Bin Norjoharuddeen , I. Yusuff⁵⁷ , Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico

J.F. Benitez , A. Castaneda Hernandez , H.A. Encinas Acosta, L.G. Gallegos Maríñez, M. León Coello , J.A. Murillo Quijada , A. Sehwat , L. Valencia Palomo 





Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

G. Ayala , H. Castilla-Valdez , H. Crotte Ledesma, E. De La Cruz-Burelo , I. Heredia-De La Cruz⁵⁸ , R. Lopez-Fernandez , C.A. Mondragon Herrera, A. Sánchez Hernández 


Universidad Iberoamericana, Mexico City, Mexico

C. Oropeza Barrera , M. Ramírez García 

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

I. Bautista , 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, H.R. Hoorani , W.A. Khan 







AGH University of Krakow, Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland

V. Avati, L. Grzanka , M. Malawski 

National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska , M. Bluj , B. Boimska , M. Górski , M. Kazana , M. Szeper , 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

K. Pozniak , W. Zabolotny 

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

M. Araujo , D. Bastos , C. Beirão Da Cruz E Silva , A. Boletti , M. Bozzo , T. Camporesi , G. Da Molin , P. Faccioli , M. Gallinaro , J. Hollar , N. Leonardo , T. Niknejad , A. Petrilli , M. Pisano , J. Seixas , J. Varela , J.W. Wulff

Faculty of Physics, University of Belgrade, Belgrade, Serbia


























P. Adzic , P. Milenovic 

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

M. Dordevic , J. Milosevic , V. Rekovic

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















M. Aguilar-Benitez, J. Alcaraz Maestre , Cristina F. Bedoya , 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 , O. Gonzalez Lopez , S. Goy Lopez , J.M. Hernandez , M.I. Josa , D. Moran , C. M. Morcillo Perez , Á. Navarro Tobar , C. Perez Dengra , A. Pérez-Calero Yzquierdo , J. Puerta Pelayo , I. Redondo , D.D. Redondo Ferrero , L. Romero, S. Sánchez Navas , L. Urda Gómez , J. Vazquez Escobar , C. Willmott



















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. Cuevas , J. Fernandez Menendez , S. Folgueras , I. Gonzalez Caballero , J.R. González Fernández , P. Leguina , E. Palencia Cortezon , C. Ramón Álvarez , V. Rodríguez Bouza , A. Soto Rodríguez , A. Trapote , C. Vico Villalba , P. Vischia 




Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

S. Bhowmik , S. Blanco Fernández , J.A. Brochero Cifuentes , 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 , L. Scodellaro , I. Vila , J.M. Vizan Garcia 
































































University of Colombo, Colombo, Sri Lanka

M.K. Jayananda , B. Kailasapathy⁵⁹ , D.U.J. Sonnadara , D.D.C. Wickramarathna 

University of Ruhuna, Department of Physics, Matara, Sri Lanka

W.G.D. Dharmaratna⁶⁰ , K. Liyanage , N. Perera , N. Wickramage 





CERN, European Organization for Nuclear Research, Geneva, Switzerland

















D. Abbaneo , C. Amendola , E. Auffray , G. Auzinger , J. Baechler, D. Barney , A. Bermúdez Martínez , M. Bianco , B. Bilin , A.A. Bin Anuar , A. Bocci , C. Botta , E. Brondolin , C. Caillol , G. Cerminara , N. Chernyavskaya , D. d'Enterria , A. Dabrowski , A. David , A. De Roeck , M.M. Defranchis , M. Deile , M. Dobson , L. Forthomme , G. Franzoni , W. Funk , S. Giani, D. Gigi, K. Gill , F. Glege , L. Gouskos , M. Haranko , J. Hegeman , B. Huber, V. Innocente , T. James , P. Janot , O. Kaluzinska , S. Laurila , P. Lecoq , E. Leutgeb , C. Lourenço , L. Malgeri , M. Mannelli , A.C. Marini , M. Matthewman, A. Mehta , F. Meijers , S. Mersi , E. Meschi , V. Milosevic , F. Monti , F. Moortgat , M. Mulders , I. Neutelings , S. Orfanelli, F. Pantaleo , G. Petrucciani , A. Pfeiffer , M. Pierini , D. Piparo , H. Qu , D. Rabadý , M. Rovere , H. Sakulin , S. Scarfi , C. Schwick, M. Selvaggi , A. Sharma , K. Shchelina , P. Silva , P. Sphicas⁶¹ , A.G. Stahl Leitner , A. Steen , S. Summers , D. Treille , P. Tropea , A. Tsiros, D. Walter , J. Wanczyk⁶² , J. Wang, S. Wuchterl , P. Zehetner , P. Zejdl , W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland









T. Bevilacqua⁶³ , L. Caminada⁶³ , A. Ebrahimi , W. Erdmann , R. Horisberger , Q. Ingram , H.C. Kaestli , D. Kotlinski , C. Lange , M. Missiroli⁶³ , L. Noehte⁶³ , T. Rohe 

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland








T.K. Aarrestad , K. Androsov⁶² , M. Backhaus , G. Bonomelli, A. Calandri , C. Caz-

zaniga , K. Datta , A. De Cosa , G. Dissertori , M. Dittmar , M. Donegà , F. Eble , M. Galli , K. Gedia , F. Glessgen , C. Grab , N. Härringer , T.G. Harte , D. Hits , W. Lustermann , A.-M. Lyon , R.A. Manzoni , M. Marchegiani , L. Marchese , C. Martin Perez , A. Mascellani⁶² , F. Nessi-Tedaldi , F. Pauss , V. Perovic , S. Pigazzini , C. Reissel , T. Reitspiess , B. Ristic , F. Riti , R. Seidita , J. Steggemann⁶² , D. Valsecchi , R. Wallny









Universität Zürich, Zurich, Switzerland

C. Amsler⁶⁴ , P. Bäertschi , M.F. Canelli , K. Cormier , J.K. Heikkilä , M. Huwiler , W. Jin , A. Jofrehei , B. Kilminster , S. Leontsinis , S.P. Liechti , A. Macchiolo , P. Meiring , U. Molinatti , A. Reimers , P. Robmann , S. Sanchez Cruz , M. Senger , E. Shokr , F. Stäger , Y. Takahashi , R. Tramontano

National Central University, Chung-Li, Taiwan

C. Adloff⁶⁵ , D. Bhowmik , C.M. Kuo , W. Lin , P.K. Rout , P.C. Tiwari⁴⁰ , S.S. Yu 









National Taiwan University (NTU), Taipei, Taiwan

L. Ceard , Y. Chao , K.F. Chen , P.s. Chen , Z.g. Chen , A. De Iorio , W.-S. Hou , T.h. Hsu , Y.w. Kao , S. Karmakar , R. Khurana , G. Kole , Y.y. Li , R.-S. Lu , E. Paganis , X.f. Su , J. Thomas-Wilsker , L.s. Tsai , H.y. Wu , E. Yazgan

High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand

C. Asawatangtrakuldee , N. Srimanobhas , V. Wachirapusanand 

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey

D. Agyel , F. Boran , Z.S. Demiroglu , F. Dolek , I. Dumanoglu⁶⁶ , E. Eskut , Y. Guler⁶⁷ , E. Gurpinar Guler⁶⁷ , C. Isik , O. Kara , A. Kayis Topaksu , U. Kiminsu , G. Onengut , K. Ozdemir⁶⁸ , A. Polatoz , B. Tali⁶⁹ , U.G. Tok , S. Turkcapar , E. Uslan , I.S. Zorbakir

Middle East Technical University, Physics Department, Ankara, Turkey

G. Sokmen , M. Yalvac⁷⁰ 

Bogazici University, Istanbul, Turkey

B. Akgun , I.O. Atakisi , E. Gülmez , M. Kaya⁷¹ , O. Kaya⁷² , S. Tekten⁷³ 

Istanbul Technical University, Istanbul, Turkey

A. Cakir , K. Cankocak^{66,74} , G.G. Dincer , Y. Komurcu , S. Sen⁷⁵ 

Istanbul University, Istanbul, Turkey

O. Aydilek²⁴ , S. Cerci⁶⁹ , V. Epshteyn , B. Haciasahinoglu , I. Hos⁷⁶ , B. Kaynak , S. Ozkorucuklu , O. Potok , H. Sert , C. Simsek , C. Zorbilmez

Yildiz Technical University, Istanbul, Turkey

B. Isildak⁷⁷ , D. Sunar Cerci⁶⁹ 

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine

A. Boyaryntsev , B. Grynyov 

National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine


















L. Levchuk 

University of Bristol, Bristol, United Kingdom


































D. Anthony , J.J. Brooke , A. Bundock , F. Bury , E. Clement , D. Cussans 

H. Flacher , M. Glowacki, J. Goldstein , H.F. Heath , M.-L. Holmberg , L. Kreczko , S. Paramesvaran , L. Robertshaw, S. Seif El Nasr-Storey, V.J. Smith , N. Stylianou⁷⁸ , K. Walkingshaw Pass




Rutherford Appleton Laboratory, Didcot, United Kingdom

A.H. Ball, K.W. Bell , A. Belyaev⁷⁹ , C. Brew , R.M. Brown , D.J.A. Cockerill , C. Cooke , K.V. Ellis, K. Harder , S. Harper , J. Linacre , K. Manolopoulos, D.M. Newbold , E. Olaiya, D. Petyt , T. Reis , A.R. Sahasransu , G. Salvi , T. Schuh, C.H. Shepherd-Themistocleous , I.R. Tomalin , T. Williams 

Imperial College, London, United Kingdom

R. Bainbridge , P. Bloch , C.E. Brown , O. Buchmuller, V. Cacchio, C.A. Carrillo Montoya , G.S. Chahal⁸⁰ , D. Colling , J.S. Dancu, I. Das , P. Dauncey , G. Davies , J. Davies, M. Della Negra , S. Fayer, G. Fedi , G. Hall , M.H. Hassanshahi , A. Howard, G. Iles , M. Knight , J. Langford , J. León Holgado , L. Lyons , A.-M. Magnan , S. Malik, M. Mieskolainen , J. Nash⁸¹ , M. Pesaresi , B.C. Radburn-Smith , A. Richards, A. Rose , K. Savva, C. Seez , R. Shukla , A. Tapper , K. Uchida , G.P. Uttley , L.H. Vage, T. Virdee³¹ , M. Vojinovic , N. Wardle , D. Winterbottom 






Brunel University, Uxbridge, United Kingdom

K. Coldham, J.E. Cole , A. Khan, P. Kyberd , I.D. Reid 

Baylor University, Waco, Texas, USA

S. Abdullin , A. Brinkerhoff , B. Caraway , E. Collins , J. Dittmann , K. Hatakeyama , J. Hiltbrand , B. McMaster , M. Saunders , S. Sawant , C. Sutantawibul , J. Wilson 





















Catholic University of America, Washington, DC, USA

R. Bartek , A. Dominguez , C. Huerta Escamilla, A.E. Simsek , R. Uniyal , A.M. Vargas Hernandez 


















The University of Alabama, Tuscaloosa, Alabama, USA

B. Bam , R. Chudasama , S.I. Cooper , S.V. Gleyzer , C.U. Perez , P. Rumerio⁸² , E. Usai , R. Yi 




















Boston University, Boston, Massachusetts, USA

A. Akpinar , D. Arcaro , C. Cosby , Z. Demiragli , C. Erice , C. Fangmeier , C. Fernandez Madrazo , E. Fontanesi , D. Gastler , F. Golf , S. Jeon , I. Reed , J. Rohlf , K. Salyer , D. Sperka , D. Spitzbart , I. Suarez , A. Tsatsos , S. Yuan , A.G. Zecchinelli 











Brown University, Providence, Rhode Island, USA

G. Benelli , X. Coubez²⁶, D. Cutts , M. Hadley , U. Heintz , J.M. Hogan⁸³ , T. Kwon , G. Landsberg , K.T. Lau , D. Li , J. Luo , S. Mondal , M. Narain[†] , N. Pervan , S. Sagir⁸⁴ , F. Simpson , M. Stamenkovic , N. Venkatasubramanian, X. Yan , W. Zhang







University of California, Davis, Davis, California, USA

S. Abbott , J. Bonilla , C. Brainerd , R. Breedon , H. Cai , M. Calderon De La Barca Sanchez , M. Chertok , M. Citron , J. Conway , P.T. Cox , R. Erbacher , F. Jensen , O. Kukral , G. Mocellin , M. Mulhearn , D. Pellett , W. Wei , Y. Yao , F. Zhang 










University of California, Los Angeles, California, USA

M. Bachtis , R. Cousins , A. Datta , G. Flores Avila, J. Hauser , M. Ignatenko , M.A. Iqbal , T. Lam , E. Manca , A. Nunez Del Prado, D. Saltzberg , V. Valuev 

University of California, Riverside, Riverside, California, USA

R. Clare , J.W. Gary , M. Gordon, G. Hanson , O.R. Long , W. Si , S. Wimpenny[†] 

University of California, San Diego, La Jolla, California, USA

J.G. Branson , S. Cittolin , S. Cooperstein , D. Diaz , J. Duarte , L. Giannini , J. Guiang , R. Kansal , V. Krutelyov , R. Lee , J. Letts , M. Masciovecchio , F. Mokhtar , S. Mukherjee , M. Pieri , M. Quinnan , B.V. Sathia Narayanan , V. Sharma , M. Tadel , E. Vourliotis , F. Würthwein , Y. Xiang , A. Yagil










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

A. Barzdukas , L. Brennan , C. Campagnari , J. Incandela , J. Kim , A.J. Li , P. Masterson , H. Mei , J. Richman , U. Sarica , R. Schmitz , F. Setti , J. Sheplock , D. Stuart , T.Á. Vami , S. Wang










California Institute of Technology, Pasadena, California, USA

A. Bornheim , O. Cerri, A. Latorre, J. Mao , H.B. Newman , G. Reales Gutiérrez, M. Spiropulu , J.R. Vlimant , C. Wang , S. Xie , R.Y. Zhu










Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

J. Alison , S. An , M.B. Andrews , P. Bryant , M. Cremonesi, V. Dutta , T. Ferguson , A. Harilal , C. Liu , T. Mudholkar , S. Murthy , P. Palit , M. Paulini , A. Roberts , A. Sanchez , W. Terrill










University of Colorado Boulder, Boulder, Colorado, USA

J.P. Cumalat , W.T. Ford , A. Hart , A. Hassani , G. Karathanasis , N. Manganelli , A. Perloff , C. Savard , N. Schonbeck , K. Stenson , K.A. Ulmer , S.R. Wagner , N. Zipper










Cornell University, Ithaca, New York, USA

J. Alexander , S. Bright-Thonney , X. Chen , D.J. Cranshaw , J. Fan , X. Fan , S. Hogan , P. Kotamnives, J. Monroy , M. Oshiro , J.R. Patterson , J. Reichert , M. Reid , A. Ryd , J. Thom , P. Wittich , R. Zou














Fermi National Accelerator Laboratory, Batavia, Illinois, 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 , G. Cummings , J. Dickinson , I. Dutta , V.D. Elvira , Y. Feng , J. Freeman , A. Gandrakota , Z. Gecse , L. Gray , D. Green, A. Grummer , S. Grünendahl , D. Guerrero , O. Gutsche , R.M. Harris , R. Heller , T.C. Herwig , J. Hirschauer , L. Horyn , B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , T. Klijnsma , B. Klima , K.H.M. Kwok , S. Lammel , D. Lincoln , R. Lipton , T. Liu , C. Madrid , K. Maeshima , C. Mantilla , D. Mason , P. McBride , P. Merkel , S. Mrenna , S. Nahn , J. Ngadiuba , D. Noonan , V. Papadimitriou , N. Pastika , K. Pedro , C. Pena⁸⁵ , F. Ravera , A. Reinsvold Hall⁸⁶ , L. Ristori , E. Sexton-Kennedy , N. Smith , A. Soha , L. Spiegel , S. Stoynev , J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger , E.W. Vaandering , A. Whitbeck , I. Zoi







University of Florida, Gainesville, Florida, USA

C. Aruta , P. Avery , D. Bourilkov , L. Cadamuro , P. Chang , V. Cherepanov , R.D. Field, E. Koenig , M. Kolosova , J. Konigsberg , A. Korytov , K. Matchev , N. Menendez , G. Mitselmakher , K. Mohrman , A. Muthirakalayil Madhu , N. Rawal , D. Rosenzweig , S. Rosenzweig , J. Wang
























Florida State University, Tallahassee, Florida, USA

T. Adams , A. Al Kadhim , A. Askew , S. Bower , R. Habibullah , V. Hagopian , R. Hashmi , R.S. Kim , S. Kim , T. Kolberg , G. Martinez, H. Prosper , P.R. Prova, M. Wulansatiti , R. Yohay , J. Zhang












Florida Institute of Technology, Melbourne, Florida, USA

B. Alsufyani, M.M. Baarmand , S. Butalla , S. Das , T. Elkafrawy⁵⁵ , M. Hohlmann , R. Kumar Verma , M. Rahmani, E. Yanes












University of Illinois Chicago, Chicago, USA, Chicago, USA

M.R. Adams , A. Baty , C. Bennett, R. Cavanaugh , R. Escobar Franco , O. Evdokimov , C.E. Gerber , M. Hawksworth, A. Hingrajiya, D.J. Hofman , J.h. Lee , D. S. Lemos , A.H. Merrit , C. Mills , S. Nanda , G. Oh , B. Ozek , D. Pilipovic , R. Pradhan , E. Prifti, T. Roy , S. Rudrabhatla , M.B. Tonjes , N. Varelas , M.A. Wadud , Z. Ye , J. Yoo 

























The University of Iowa, Iowa City, Iowa, USA

M. Alhusseini , D. Blend, K. Dilsiz⁸⁷ , L. Emediato , G. Karaman , O.K. Köseyan , J.-P. Merlo, A. Mestvirishvili⁸⁸ , J. Nachtman , O. Neogi, H. Ogul⁸⁹ , Y. Onel , A. Penzo , C. Snyder, E. Tiras⁹⁰ 










Johns Hopkins University, Baltimore, Maryland, USA

B. Blumenfeld , L. Corcodilos , J. Davis , A.V. Gritsan , L. Kang , S. Kyriacou , P. Maksimovic , M. Roguljic , J. Roskes , S. Sekhar , M. Swartz 

The University of Kansas, Lawrence, Kansas, USA

A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , P. Baringer , A. Bean , Z. Flowers , D. Grove , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu , J. Marquez , N. Minafra , M. Murray , M. Nickel , M. Pitt , S. Popescu⁹¹ , C. Rogan , C. Royon , R. Salvatico , S. Sanders , C. Smith , Q. Wang , G. Wilson 
















Kansas State University, Manhattan, Kansas, USA

B. Allmond , R. Gujju Gurunadha , A. Ivanov , K. Kaadze , A. Kalogeropoulos , D. Kim, Y. Maravin , J. Natoli , D. Roy , G. Sorrentino 






















Lawrence Livermore National Laboratory, Livermore, California, USA

F. Rebassoo , D. Wright 














University of Maryland, College Park, Maryland, USA

A. Baden , A. Belloni , Y.M. Chen , S.C. Eno , N.J. Hadley , S. Jabeen , R.G. Kellogg , T. Koeth , Y. Lai , S. Lascio , A.C. Mignerey , S. Nabili , C. Palmer , C. Papageorgakis , M.M. Paranipe, L. Wang 

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

J. Bendavid , I.A. Cali , M. D'Alfonso , J. Eysermans , C. Freer , G. Gomez-Ceballos , M. Goncharov, G. Grosso, P. Harris, D. Hoang, D. Kovalskiy , J. Krupa , L. Lavezzo , Y.-J. Lee , K. Long , A. Novak , C. Paus , D. Rankin , C. Roland , G. Roland , S. Rothman , G.S.F. Stephans , Z. Wang , B. Wyslouch , T. J. Yang 













University of Minnesota, Minneapolis, Minnesota, USA

B. Crossman , B.M. Joshi , C. Kapsiak , M. Krohn , D. Mahon , J. Mans , B. Marzocchi , S. Pandey , M. Revering , R. Rusack , R. Saradhy , N. Schroeder , N. Strobbe 

University of Mississippi, Oxford, Mississippi, USA

L.M. Cremaldi 

















University of Nebraska-Lincoln, Lincoln, Nebraska, USA

K. Bloom , D.R. Claes , G. Haza , J. Hossain , C. Joo , I. Kravchenko , J.E. Siado ,
W. Tabb , A. Vagnerini , A. Wightman , F. Yan , D. Yu 










State University of New York at Buffalo, Buffalo, New York, USA

H. Bandyopadhyay , L. Hay , I. Iashvili , A. Kharchilava , M. Morris , D. Nguyen ,
S. Rappoccio , H. Rejeb Sfar, A. Williams 



























Northeastern University, Boston, Massachusetts, USA

G. Alverson , E. Barberis , J. Dervan, Y. Haddad , Y. Han , A. Krishna , J. Li ,
M. Lu , G. Madigan , R. Mccarthy , D.M. Morse , V. Nguyen , T. Orimoto ,
A. Parker , L. Skinnari , B. Wang , D. Wood 









Northwestern University, Evanston, Illinois, USA

S. Bhattacharya , J. Bueghly, Z. Chen , S. Dittmer , K.A. Hahn , Y. Liu , Y. Miao ,
D.G. Monk , M.H. Schmitt , A. Taliercio , M. Velasco



















University of Notre Dame, Notre Dame, Indiana, USA

G. Agarwal , R. Band , R. Bucci, S. Castells , A. Das , R. Goldouzian , M. Hildreth ,
K.W. Ho , K. Hurtado Anampa , T. Ivanov , C. Jessop , K. Lannon , J. Lawrence ,
N. Loukas , L. Lutton , J. Mariano, N. Marinelli, I. Mcalister, T. McCauley , C. Mcgrady ,
C. Moore , Y. Musienko¹⁶ , H. Nelson , M. Osherson , A. Piccinelli , R. Ruchti ,
A. Townsend , Y. Wan, M. Wayne , H. Yockey, M. Zarucki , L. Zygalá 

The Ohio State University, Columbus, Ohio, USA

A. Basnet , B. Bylsma, M. Carrigan , L.S. Durkin , C. Hill , M. Joyce , M. Nunez Ornelas ,
K. Wei, B.L. Winer , B. R. Yates 




















Princeton University, Princeton, New Jersey, USA

F.M. Addesa , H. Bouchamaoui , P. Das , G. Dezoort , P. Elmer , A. Frankenthal ,
B. Greenberg , N. Haubrich , G. Kopp , S. Kwan , D. Lange , A. Loeliger ,
D. Marlow , I. Ojalvo , J. Olsen , A. Shevelev , D. Stickland , C. Tully 




University of Puerto Rico, Mayaguez, Puerto Rico, USA

S. Malik 












Purdue University, West Lafayette, Indiana, USA

A.S. Bakshi , V.E. Barnes , S. Chandra , R. Chawla , A. Gu , L. Gutay, M. Jones ,
A.W. Jung , D. Kondratyev , A.M. Koshy, M. Liu , G. Negro , N. Neumeister ,
G. Paspalaki , S. Piperov , V. Scheurer, J.F. Schulte , M. Stojanovic , J. Thieman ,
A. K. Viridi , F. Wang , W. Xie 

Purdue University Northwest, Hammond, Indiana, USA
















































J. Dolen , N. Parashar , A. Pathak 

Rice University, Houston, Texas, USA

D. Acosta , T. Carnahan , K.M. Ecklund , P.J. Fernández Manteca , S. Freed, P. Gardner,
E.J.M. Geurts , W. Li , O. Miguel Colin , B.P. Padley , R. Redjimi, J. Rotter ,
E. Yigitbasi , Y. Zhang 

University of Rochester, Rochester, New York, USA

A. Bodek , P. de Barbaro , R. Demina , J.L. Dulemba , A. Garcia-Bellido ,
O. Hindrichs , A. Khukhunaishvili , N. Parmar, P. Parygin⁹² , E. Popova⁹² , R. Taus 

The Rockefeller University, New York, New York, USAK. Goulianos **Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA**B. Chiarito, J.P. Chou , S.V. Clark , D. Gadkari , Y. Gershtein , E. Halkiadakis , M. Heindl , C. Houghton , D. Jaroslowski , O. Karacheban²⁹ , I. Laflotte , A. Lath , R. Montalvo, K. Nash, H. Routray , P. Saha , S. Salur , S. Schnetzer, S. Somalwar , R. Stone , S.A. Thayil , S. Thomas, J. Vora , H. Wang **University of Tennessee, Knoxville, Tennessee, USA**H. Acharya, D. Ally , A.G. Delannoy , S. Fiorendi , S. Higginbotham , T. Holmes , A.R. Kanuganti , N. Karunarathna , L. Lee , E. Nibigira , S. Spanier **Texas A&M University, College Station, Texas, USA**D. Aebi , M. Ahmad , O. Bouhali⁹³ , R. Eusebi , J. Gilmore , T. Huang , T. Kamon⁹⁴ , H. Kim , S. Luo , R. Mueller , D. Overton , D. Rathjens , A. Safonov **Texas Tech University, Lubbock, Texas, USA**N. Akchurin , J. Damgov , V. Hegde , A. Hussain , Y. Kazhykarim, K. Lamichhane , S.W. Lee , A. Mankel , T. Peltola , I. Volobouev **Vanderbilt University, Nashville, Tennessee, USA**E. Appelt , Y. Chen , S. Greene, A. Gurrola , W. Johns , R. Kunnawalkam Elayavalli , A. Melo , F. Romeo , P. Sheldon , S. Tuo , J. Velkovska , J. Viinikainen **University of Virginia, Charlottesville, Virginia, USA**B. Cardwell , B. Cox , J. Hakala , R. Hirosky , A. Ledovskoy , C. Neu , C.E. Perez Lara **Wayne State University, Detroit, Michigan, USA**P.E. Karchin **University of Wisconsin - Madison, Madison, Wisconsin, USA**A. Aravind, S. Banerjee , K. Black , T. Bose , S. Dasu , I. De Bruyn , P. Everaerts , C. Galloni, H. He , M. Herndon , A. Herve , C.K. Koraka , A. Lanaro, R. Loveless , J. Madhusudanan Sreekala , A. Mallampalli , A. Mohammadi , S. Mondal, G. Parida , L. Pétré , D. Pinna, A. Savin, V. Shang , V. Sharma , W.H. Smith , D. Teague, H.F. Tsoi , W. Vetens , A. Warden **Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN**S. Afanasiev , V. Andreev , Yu. Andreev , T. Aushev , M. Azarkin , I. Azhgirey , A. Babaev , A. Belyaev , V. Blinov⁹⁵, E. Boos , V. Borshch , D. Budkouski , V. Bunichev , V. Chekhovsky, R. Chistov⁹⁵ , M. Danilov⁹⁵ , A. Dermenev , T. Dimova⁹⁵ , D. Druzhkin⁹⁶ , M. Dubinin⁸⁵ , L. Dudko , G. Gavrilo , V. Gavrilo , S. Gninenko , V. Golovtsov , N. Golubev , I. Golutvin , I. Gorbunov , A. Gribushin , Y. Ivanov , V. Kachanov , V. Karjavine , A. Karneyeu , V. Kim⁹⁵ , M. Kirakosyan, D. Kirpichnikov , M. Kirsanov , V. Klyukhin , O. Kodolova⁹⁷ , D. Konstantinov , V. Korenkov , A. Kozyrev⁹⁵ , N. Krasnikov , A. Lanev , P. Levchenko⁹⁸ , N. Lychkovskaya , V. Makarenko , A. Malakhov , V. Matveev⁹⁵ , V. Murzin , A. Nikitenko^{99,97} , S. Obraztsov , V. Oreshkin , V. Palichik , V. Perelygin , M. Perfilov, S. Petrushanko , S. Polikarpov⁹⁵ , V. Popov , O. Radchenko⁹⁵ , R. Ryutin, M. Savina , V. Savrin , V. Shalaev , S. Shmatov , S. Shulha , Y. Skovpen⁹⁵ , S. Slabospitskii , V. Smirnov , D. Sosnov , V. Sulimov , E. Tcherniaev , A. Terkulov , O. Teryaev

I. Tlisova , A. Toropin , L. Uvarov , A. Uzunian , A. Vorobyev[†], G. Vorotnikov ,
N. Voytishin , B.S. Yuldashev¹⁰⁰, A. Zarubin , I. Zhizhin , A. Zhokin 

†: Deceased

¹Also at Yerevan State University, Yerevan, Armenia

²Also at TU Wien, Vienna, Austria

³Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt

⁴Also at Ghent University, Ghent, Belgium

⁵Also at Universidade Estadual de Campinas, Campinas, Brazil

⁶Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

⁷Also at UFMS, Nova Andradina, Brazil

⁸Also at Nanjing Normal University, Nanjing, China

⁹Now at The University of Iowa, Iowa City, Iowa, USA

¹⁰Also at University of Chinese Academy of Sciences, Beijing, China

¹¹Also at China Center of Advanced Science and Technology, Beijing, China

¹²Also at University of Chinese Academy of Sciences, Beijing, China

¹³Also at China Spallation Neutron Source, Guangdong, China

¹⁴Now at Henan Normal University, Xinxiang, China

¹⁵Also at Université Libre de Bruxelles, Bruxelles, Belgium

¹⁶Also at an institute or an international laboratory covered by a cooperation agreement with CERN

¹⁷Now at British University in Egypt, Cairo, Egypt

¹⁸Now at Cairo University, Cairo, Egypt

¹⁹Also at Purdue University, West Lafayette, Indiana, USA

²⁰Also at Université de Haute Alsace, Mulhouse, France

²¹Also at Department of Physics, Tsinghua University, Beijing, China

²²Also at Ilia State University, Tbilisi, Georgia

²³Also at The University of the State of Amazonas, Manaus, Brazil

²⁴Also at Erzincan Binali Yildirim University, Erzincan, Turkey

²⁵Also at University of Hamburg, Hamburg, Germany

²⁶Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

²⁷Also at Isfahan University of Technology, Isfahan, Iran

²⁸Also at Bergische University Wuppertal (BUW), Wuppertal, Germany

²⁹Also at Brandenburg University of Technology, Cottbus, Germany

³⁰Also at Forschungszentrum Jülich, Juelich, Germany

³¹Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

³²Also at Institute of Physics, University of Debrecen, Debrecen, Hungary

³³Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary

³⁴Now at Universitatea Babeş-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania

³⁵Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

³⁶Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt

³⁷Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary

³⁸Also at Punjab Agricultural University, Ludhiana, India

³⁹Also at University of Visva-Bharati, Santiniketan, India

⁴⁰Also at Indian Institute of Science (IISc), Bangalore, India

⁴¹Also at Birla Institute of Technology, Mesra, Mesra, India

⁴²Also at IIT Bhubaneswar, Bhubaneswar, India

⁴³Also at Institute of Physics, Bhubaneswar, India

- ⁴⁴Also at University of Hyderabad, Hyderabad, India
- ⁴⁵Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- ⁴⁶Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran
- ⁴⁷Also at Sharif University of Technology, Tehran, Iran
- ⁴⁸Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- ⁴⁹Also at Helwan University, Cairo, Egypt
- ⁵⁰Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- ⁵¹Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- ⁵²Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- ⁵³Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
- ⁵⁴Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
- ⁵⁵Also at Ain Shams University, Cairo, Egypt
- ⁵⁶Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- ⁵⁷Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
- ⁵⁸Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- ⁵⁹Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- ⁶⁰Also at Saegis Campus, Nugegoda, Sri Lanka
- ⁶¹Also at National and Kapodistrian University of Athens, Athens, Greece
- ⁶²Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- ⁶³Also at Universität Zürich, Zurich, Switzerland
- ⁶⁴Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- ⁶⁵Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- ⁶⁶Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
- ⁶⁷Also at Konya Technical University, Konya, Turkey
- ⁶⁸Also at Izmir Bakircay University, Izmir, Turkey
- ⁶⁹Also at Adiyaman University, Adiyaman, Turkey
- ⁷⁰Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey
- ⁷¹Also at Marmara University, Istanbul, Turkey
- ⁷²Also at Milli Savunma University, Istanbul, Turkey
- ⁷³Also at Kafkas University, Kars, Turkey
- ⁷⁴Now at Istanbul Okan University, Istanbul, Turkey
- ⁷⁵Also at Hacettepe University, Ankara, Turkey
- ⁷⁶Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
- ⁷⁷Also at Yildiz Technical University, Istanbul, Turkey
- ⁷⁸Also at Vrije Universiteit Brussel, Brussel, Belgium
- ⁷⁹Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- ⁸⁰Also at IPPP Durham University, Durham, United Kingdom
- ⁸¹Also at Monash University, Faculty of Science, Clayton, Australia
- ⁸²Also at Università di Torino, Torino, Italy
- ⁸³Also at Bethel University, St. Paul, Minnesota, USA
- ⁸⁴Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- ⁸⁵Also at California Institute of Technology, Pasadena, California, USA
- ⁸⁶Also at United States Naval Academy, Annapolis, Maryland, USA

⁸⁷Also at Bingol University, Bingol, Turkey

⁸⁸Also at Georgian Technical University, Tbilisi, Georgia

⁸⁹Also at Sinop University, Sinop, Turkey

⁹⁰Also at Erciyes University, Kayseri, Turkey

⁹¹Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania

⁹²Now at an institute or an international laboratory covered by a cooperation agreement with CERN

⁹³Also at Texas A&M University at Qatar, Doha, Qatar

⁹⁴Also at Kyungpook National University, Daegu, Korea

⁹⁵Also at another institute or international laboratory covered by a cooperation agreement with CERN

⁹⁶Also at Universiteit Antwerpen, Antwerpen, Belgium

⁹⁷Also at Yerevan Physics Institute, Yerevan, Armenia

⁹⁸Also at Northeastern University, Boston, Massachusetts, USA

⁹⁹Also at Imperial College, London, United Kingdom

¹⁰⁰Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan