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Search for charged Higgs bosons produced in vector boson fusion processes and decaying into vector boson pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

A search for charged Higgs bosons produced in vector boson fusion processes and decaying into vector bosons, using proton-proton collisions at $\sqrt{s} = 13$ TeV at the LHC, is reported. The data sample corresponds to an integrated luminosity of 137 fb^{-1} collected with the CMS detector. Events are selected by requiring two or three electrons or muons, moderate missing transverse momentum, and two jets with a large rapidity separation and a large dijet mass. No excess of events with respect to the standard model background predictions is observed. Model independent upper limits at 95% confidence level are reported on the product of the cross section and branching fraction for vector boson fusion production of charged Higgs bosons as a function of mass, from 200 to 3000 GeV. The results are interpreted in the context of the Georgi-Machacek model.

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1 Introduction

The discovery [1–3] of a Higgs boson [4–9] at the CERN LHC marks an important milestone in the exploration of the electroweak (EW) sector of the standard model (SM) of particle physics. Measurements of vector boson scattering (VBS) processes at the LHC may reveal hints for extensions of the SM. In particular, extended Higgs sectors with additional $SU(2)$ doublets [10–13] or triplets [14–19] introduce couplings of gauge bosons to heavy neutral or charged Higgs bosons with specific signatures like singly or doubly charged Higgs boson decays to WZ boson pairs or same-sign W^+W^+ boson pairs, respectively.

At the LHC, interactions from VBS are characterized by the presence of two gauge bosons in association with two forward jets with a large pseudorapidity separation ($\Delta\eta_{jj}$) and a large dijet invariant mass (m_{jj}). An excess of events with respect to the SM predictions could indicate the presence of new resonances, such as singly or doubly charged Higgs bosons. Extended Higgs sectors with additional $SU(2)$ isotriplet scalars give rise to charged Higgs bosons with couplings to W and Z bosons at the tree-level [19]. Specifically, the Georgi–Machacek (GM) model [18, 20], with both real and complex triplets, preserves a global symmetry $SU(2)_L \times SU(2)_R$, which is broken by the Higgs vacuum expectation value to the diagonal subgroup $SU(2)_{L+R}$. Thus, the tree-level ratio of the W and Z boson masses is protected against large radiative corrections. In this model, singly (doubly) charged Higgs bosons that decay to W and Z bosons (same-sign W boson pairs) are produced via vector boson fusion (VBF).

The charged Higgs bosons H^\pm and $H^{\pm\pm}$ in the GM model are degenerate in mass (denoted as m_{H_5}) at tree level and transform as a quintuplet under the $SU(2)_{L+R}$ symmetry. The H^\pm and $H^{\pm\pm}$ bosons are also collectively referred to as H_5 in the context of the GM model. Production and decays of the H_5 states depend on the two parameters m_{H_5} and s_H , where s_H^2 characterizes the fraction of the W boson mass squared generated by the vacuum expectation value of the triplet fields. The H_5 states are fermiophobic and are assumed to decay to vector boson pairs with branching fraction of 100% [21]. Figure 1 shows representative Feynman diagrams for the production and decay of the charged Higgs bosons. There are additional charged Higgs bosons H^\pm predicted in the GM model that transform as a triplet under the $SU(2)_{L+R}$ symmetry. These H^\pm bosons have only fermionic couplings and are not considered here.

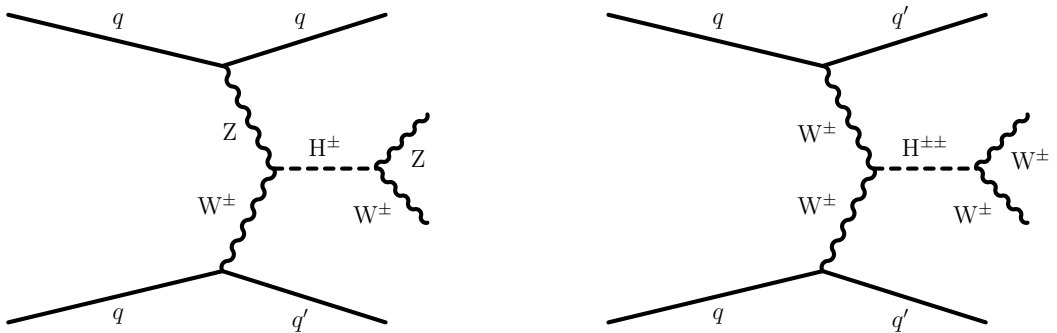


Figure 1: Examples of Feynman diagrams showing the production of singly (left) and doubly (right) charged Higgs bosons via VBF.

This paper presents a search for H^\pm and $H^{\pm\pm}$ that are produced via VBF and decay to WZ and W^+W^+ boson pairs, respectively, using proton-proton (pp) collisions at $\sqrt{s} = 13$ TeV. The data sample corresponds to an integrated luminosity of 137.2 fb^{-1} [22–24], collected with the CMS detector [25] in three separate LHC operating periods during 2016, 2017, and 2018. The three data sets are analyzed independently, with appropriate calibrations and corrections, to account

for the various LHC running conditions and the performance of the CMS detector.

The W^+W^- and WZ channels are simultaneously studied by performing a binned maximum-likelihood fit of distributions sensitive to these processes, following the methods described in Ref. [26]. The searches for H^\pm and H^0 are performed in the leptonic decay modes $W^\pm Z$ and $W^\pm W^\pm$, where $l = e, \mu$. Candidate events contain either two identified leptons of the same charge or three identified charged leptons with the total charge of ± 1 , moderate missing transverse momentum (p_T^{miss}), and two jets with large values of p_T and m_{jj} .

Model independent upper limits at 95% confidence level (CL) are reported on the product of the cross section and branching fraction for vector boson fusion production of the H^\pm and H^0 bosons individually. The results are also interpreted in the context of the GM model including the simultaneous contributions of the H^\pm and H^0 bosons. Searches for charged Higgs bosons in these topologies have been performed by the CMS Collaboration at 13 TeV using the data sample collected during 2016 [27–29]. The ATLAS and CMS Collaborations have also set constraints on the GM model by performing searches for charged Higgs bosons in semileptonic final states at 8 TeV [30] and 13 TeV [31], respectively.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead-tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the coverage provided by the barrel and endcap detectors up to $|\eta| = 5$. Muons are detected in gas-ionization chambers embedded in the steel magnetic flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system and the relevant kinematic variables, is reported in Ref. [25]. Events of interest are selected using a two-tiered trigger system [32]. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of 4 μ s. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage.

3 Signal and background simulation

Processes characterized by the presence of two gauge bosons in association with two forward jets are an important background contribution. The processes contributing to diboson plus two jets production that proceeds via the EW interaction are referred to as EW-induced diboson production, leading to tree-level contributions at $\mathcal{O}(\alpha^4)$, where α is the EW coupling. Figure 2 shows representative Feynman diagrams of EW-induced diboson production involving quartic vertices. An additional contribution to the diboson plus two jets production arises via quantum chromodynamics (QCD) radiation, leading to tree-level contributions at $\mathcal{O}(\alpha^2 \alpha_s^2)$, where α_s is the strong coupling. This class of processes is referred to as QCD-induced diboson production. Figure 3 shows representative Feynman diagrams of the QCD-induced production. The associated production of a Z boson and a single top quark, referred to as tZq production, is also an important background contribution. Additional background contributions arise from

the $t\bar{t}$, tW , $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}$, triple vector boson (VVV, $V = W, Z$), and double parton scattering processes.

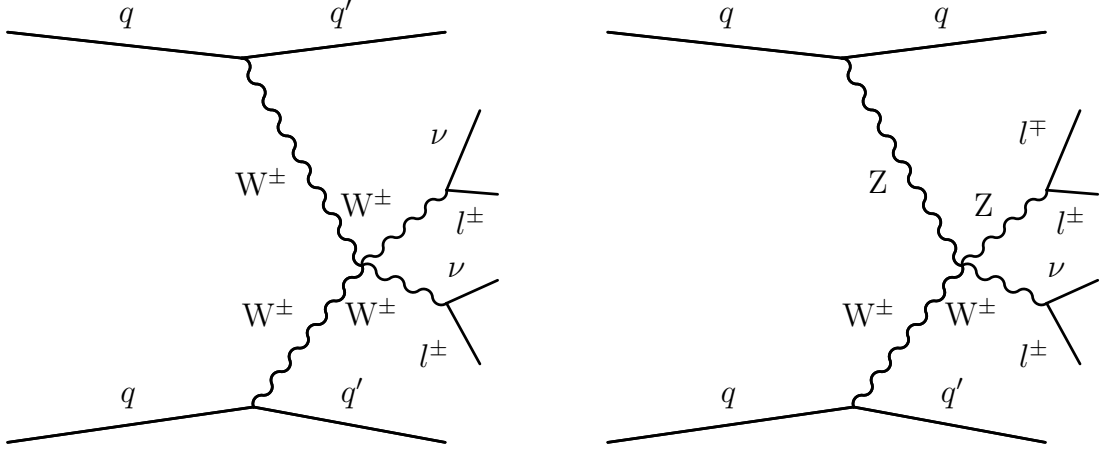


Figure 2: Representative Feynman diagrams of a VBS process contributing to the EW-induced production of events containing $W W$ (left) and WZ (right) boson pairs decaying to leptons, and two forward jets.

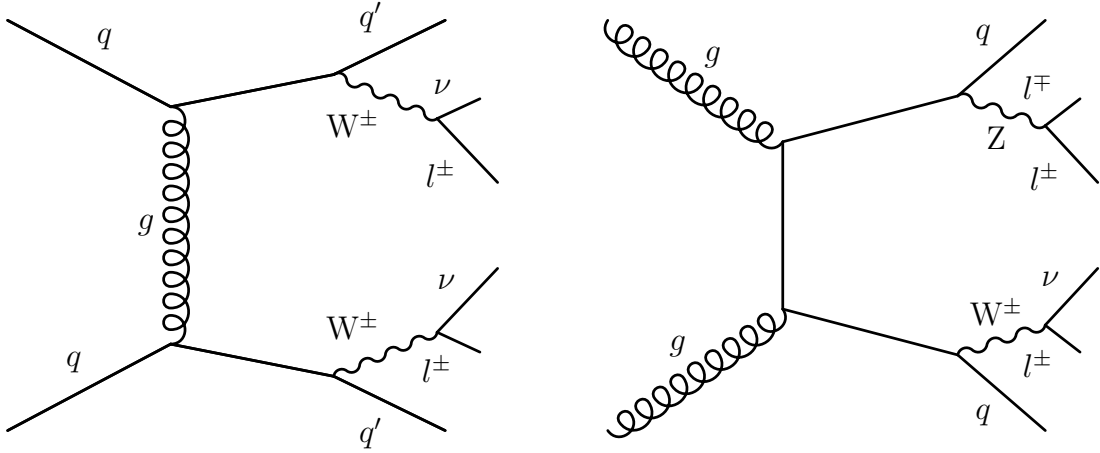


Figure 3: Representative Feynman diagrams of the QCD-induced production of $W W$ (left) and WZ (right) boson pairs decaying to leptons, and two jets.

Multiple Monte Carlo (MC) event generators are used to simulate the signal and background contributions. The signal and background processes are produced with on-shell particles. Three sets of simulated events for each process are needed to match the data taking conditions in the three years. The charged Higgs boson signal samples are simulated using MADGRAPH5_aMC@NLO 2.4.2 [33, 34] at leading order (LO) accuracy. The predicted signal cross sections are taken at next-to-next-to-LO (NNLO) accuracy from the GM model [21].

The SM EW $W W$ and WZ processes, where both bosons decay leptonically, are simulated using MADGRAPH5_aMC@NLO at LO accuracy with six EW (\mathcal{O}^6) and zero QCD vertices. The same generator is also used to simulate the QCD-induced $W W$ process with four EW and two QCD vertices. Contributions with an initial-state b quark are excluded from the EW WZ simulation because they are considered part of the tZq background process. Triboson processes, where the WZ boson pair is accompanied by a third vector boson that decays into

jets, are included in the EW WZ simulation. The QCD-induced WZ process is simulated at LO with up to three additional partons in the matrix element calculations using the MADGRAPH5_aMC@NLO generator with at least one QCD vertex at tree level. The different jet multiplicities are merged using the MLM scheme [35] to match matrix element and parton shower jets, and the inclusive contribution is normalized to NNLO predictions [36]. The interference between the EW and QCD diagrams is also accounted for with MADGRAPH5_aMC@NLO.

A complete set of NLO QCD and EW corrections for the leptonic W^+W^- scattering process has been computed [37, 38] and they reduce the LO cross section of the EW W^+W^- process by 10–15%, with the correction increasing in magnitude with increasing dilepton and dijet invariant masses. Similarly, the NLO QCD and EW corrections for the leptonic WZ scattering process have been computed at the orders of \mathcal{O}_s^{-6} and \mathcal{O}_s^{-7} [39], reducing the cross sections for the EW WZ process by 10%. The SM EW W^+W^- and WZ processes are normalized by applying these \mathcal{O}_s^{-6} and \mathcal{O}_s^{-7} corrections to MADGRAPH5_aMC@NLO LO cross sections.

The POWHEG v2 [40–44] generator is used to simulate the $t\bar{t}$, tW , ZZ , and W^+W^- processes at NLO accuracy in QCD. Production of $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}\gamma$, and VVV events is simulated at NLO accuracy in QCD using the MADGRAPH5_aMC@NLO 2.2.2 (2.4.2) generator for the 2016 (2017 and 2018) samples. The tZq process is simulated in the four-flavor scheme using MADGRAPH5_aMC@NLO 2.3.3 at next-to-LO (NLO). Events in which two hard parton-parton interactions occur within a single pp collision, referred to as double parton scattering W^+W^- production, are generated at LO using PYTHIA 8.226 (8.230) [45] for the 2016 (2017 and 2018) samples.

The NNPDF 2.3 LO [46] (NNPDF 3.1 NNLO [47]) PDFs are used for generating 2016 (2017 and 2018) signal samples. The NNPDF 3.0- NLO [48] (NNPDF 3.1 NNLO) PDFs are used for generating all 2016 (2017 and 2018) background samples. For all processes, the parton showering and hadronization are simulated using PYTHIA 8.226 (8.230) for 2016 (2017 and 2018). The modeling of the underlying event is done using the CUETP8M1 [49, 50] (CP5 [51]) tune for simulated samples corresponding to the 2016 (2017 and 2018) data.

All MC generated events are processed through a simulation of the CMS detector based on GEANT4 [52] and are reconstructed with the same algorithms used for data. The simulated samples include additional interactions in the same and neighboring bunch crossings, referred to as pileup. The additional inelastic events are generated using PYTHIA with the same underlying event tune as the main interaction and superimposed on the hard-scattering events. The distribution of the number of pileup interactions in the simulation is adjusted to match the one observed in the data. The average number of interactions per bunch crossing was 23 (32) in 2016 (2017 and 2018) corresponding to an inelastic pp cross-section of 69.2 mb.

4 Event reconstruction

The primary vertex (PV) is defined as the vertex with the largest value of summed physics-object p_T^2 . The physics objects are the jets, clustered using the jet finding algorithm [53, 54] with the tracks assigned to candidate vertices as inputs, and the associated missing transverse momentum, taken as the negative vector sum of the p_T of those jets.

The CMS particle-flow (PF) algorithm [55] is used to combine the information from the tracker, calorimeters, and muon systems to reconstruct and identify charged and neutral hadrons, photons, muons, and electrons (PF candidates). The missing transverse momentum vector p_T^{miss} is defined as the projection onto the plane perpendicular to the beam axis of the negative vector

momentum sum of all reconstructed PF candidates in an event. Its magnitude is referred to as p_T^{miss} .

Jets are reconstructed by clustering PF candidates using the anti- k_T algorithm [53] with a distance parameter of 0.4. Additional proton-proton interactions within the same or nearby bunch crossings can contribute additional tracks and calorimetric energy depositions, increasing the apparent jet momentum. To mitigate this effect, tracks identified to be originating from pileup vertices are discarded and an offset correction is applied to correct for remaining contributions [56]. Jet energy corrections are derived from simulation studies so that the average measured energy of jets becomes identical to that of particle level jets. In situ measurements of the momentum balance in dijet, photon+jet, Z+jet, and multijet events are used to determine any residual differences between the jet energy scale in data and in simulation, and appropriate corrections are made [57]. Corrections to jet energies to account for the detector response are propagated to p_T^{miss} [58]. Jets with transverse momentum $p_T \geq 30$ GeV and $\Delta R \geq 4.7$ are included in the analysis.

Events with at least one jet with $p_T \geq 20$ GeV and $\Delta R \geq 2.4$ that is consistent with the fragmentation of a bottom quark are rejected to reduce the number of top quark background events. The DEEPCSV b tagging algorithm [59] is used for this selection. For the chosen working point, the efficiency of the algorithm to select b quark jets is about 72% and the rate for incorrectly tagging jets originating from the hadronization of gluons or u, d, s quarks is about 1%. The rate for incorrectly tagging jets originating from the hadronization of c quarks is about 10%.

Events with at least one reconstructed hadronic decay of a lepton, denoted as ℓ_h , with $p_T \geq 18$ GeV and $\Delta R \geq 2.3$, are rejected to reduce the contribution of diboson processes with ℓ_h decays. The ℓ_h decays are reconstructed using the hadrons-plus-strips algorithm [60].

Electrons and muons are reconstructed by associating a track reconstructed in the tracking detectors with either a cluster of energy deposits in the ECAL [61, 62] or a track in the muon system [63]. Electrons (muons) must pass loose identification criteria with $p_T \geq 10$ GeV and $\Delta R \geq 2.5$ (2.4) to be selected for the analysis. At the final stage of the lepton selection, tight working points, following the definitions provided in Refs. [61–63], are chosen for the identification criteria, including requirements on the impact parameter of the candidates with respect to the PV and their isolation with respect to other particles in the event [64]. For electrons, the background contribution arising from charge misidentification is not negligible. The sign mismeasurement is evaluated using three observables that measure the electron curvature applying different methods as discussed in Ref. [61]. Requiring all three charge evaluations to agree reduces this background contribution by a factor of four (six) with an efficiency of about 97 (90)% in the barrel (endcap) region. The sign mismeasurement is negligible for muons [65, 66].

5 Event selection

Collision events are collected using single-electron and single-muon triggers that require the presence of an isolated lepton with $p_T \geq 27$ and 24 GeV, respectively [67]. In addition, a set of dilepton triggers with lower p_T thresholds is used, ensuring a trigger efficiency above 99% for events that satisfy the subsequent offline selection [67].

Several selection requirements are used to isolate the W^+W^- and WZ topologies defining the signal regions (SRs), while reducing the contributions from background processes [26]. Candidate events must contain exactly two isolated same-sign charged leptons or exactly three isolated charged leptons with $p_T \geq 10$ GeV, and at least two jets with $\Delta R \geq 4.7$ and the leading

jet $p_T^j \geq 50$ GeV. To exclude the selected electrons and muons from the jet sample, the jets are required to be separated from the identified leptons by $R = \frac{\Delta R}{\sqrt{\Delta R^2 + \Delta \eta^2}} \geq 0.4$, where ΔR is the azimuthal angle in radians.

For the WZ candidate events, one of the oppositely charged same-flavor leptons from the Z boson candidate is required to have $p_T \geq 25$ GeV and the other $p_T \geq 10$ GeV with the invariant mass of the dilepton pair m_{ll} satisfying $m_{ll} > m_Z = 91.1876$ GeV. For candidate events with three same-flavor leptons, the oppositely charged lepton pair with the invariant mass closest to the world-average Z boson mass m_Z [68] is selected as the Z boson candidate. The third lepton associated with the W boson is required to have $p_T \geq 20$ GeV. In addition, the trilepton invariant mass m_{3l} is required to exceed 100 GeV to exclude a region where production of Z bosons with final-state photon radiation is expected to contribute.

One of the leptons in the same-sign W^+W^+ candidate events is required to have $p_T \geq 25$ GeV and the other $p_T \geq 20$ GeV. The value of m_{ll} must be greater than 20 GeV. Candidate events in the dielectron final state with $m_{ll} > m_Z = 91.1876$ GeV are rejected to reduce the number of Z boson background events where the sign of one of the electron candidates is misidentified.

The VBF topology is targeted by requiring the two highest p_T jets to have a mass $m_{jj} \geq 500$ GeV and a pseudorapidity separation $|\eta_{jj}| \geq 2.5$. The W and Z bosons in the VBF topologies are mostly produced in the central rapidity region with respect to the two selected jets. The candidate W^+W^+ (WZ) events are required to satisfy $\max(z_1, z_2) \leq 1.0$, where $z_i = \frac{|\eta_{l_i}|}{|\eta_{jj}|}$ is the Zeppenfeld variable [69] for one of the selected leptons. Here $|\eta_{l_i}|$ is the pseudorapidity of the lepton, and $|\eta_{j_1}|$ and $|\eta_{j_2}|$ are the pseudorapidities of the two candidates VBF jets.

The p_T^{miss} is required to exceed 30 GeV for both SRs. The selection requirements used to define the same-sign W^+W^+ and WZ SRs are summarized in Table 1.

Table 1: Summary of the selection requirements defining the W^+W^+ and WZ SRs. The looser lepton p_T requirement in the WZ selection refers to the trailing lepton from the Z boson decays. The $m_{ll} > m_Z$ requirement is applied only to the dielectron final state in the W^+W^+ SR.

Variable	W^+W^+	WZ
Leptons	2 leptons, $p_T \geq 25/20$ GeV	3 leptons, $p_T \geq 25/10/20$ GeV
p_T^j	50/30 GeV	50/30 GeV
$m_{ll} > m_Z$	15 GeV (ee)	15 GeV
m_{ll}	20 GeV	—
m_{3l}	—	100 GeV
p_T^{miss}	30 GeV	30 GeV
b jet veto	Required	Required
h veto	Required	Required
$\max(z_1, z_2)$	0.75	1.0
m_{jj}	500 GeV	500 GeV
$ \eta_{jj} $	2.5	2.5

6 Background estimation

A combination of methods based on simulation and on control regions (CRs) in data is used to estimate background contributions. By inverting some of the requirements in Table 1 we select background-enriched CRs. Uncertainties related to the theoretical and experimental pre-

dictions are estimated as described in Section 8.

The nonprompt lepton backgrounds originating from leptonic decays of heavy quarks, hadrons misidentified as leptons, and electrons from photon conversions are suppressed by the identification and isolation requirements imposed on leptons. The remaining contribution from the nonprompt lepton background is dominant in the $W W$ SR and is estimated directly from data following the technique described in Ref. [70], using events selected by the final selection criteria, except for one of the leptons, which is requested to pass a looser criterion having failed the nominal selection. The yield in this sample is extrapolated to the signal region using the efficiencies for such loosely identified leptons to pass the standard lepton selection criteria. This efficiency is calculated in a sample of events dominated by dijet production. An uncertainty of 20% is assigned for the nonprompt lepton background normalization to include possible differences in the composition of jets between the data sample used to derive these efficiencies and the data samples in the $W W$ and WZ SRs [64].

The background contribution from the electron sign mismeasurement is estimated from the simulation by applying a data-to-simulation efficiency correction due to electrons with sign mismeasurement. These corrections are determined using $Z \rightarrow ee$ events in the Z boson peak region that were recorded with independent triggers. These corrections amount to 40% for data collected in 2017 and 2018, while they are negligible for 2016 data. The electron sign mismeasurement rate is about 0.01 (0.3)% in the barrel (endcap) region [61, 62].

Three CRs are used to select nonprompt lepton, tZq , and ZZ background-enriched events to further estimate the normalization of these background processes from data. The nonprompt lepton CR is defined by requiring the same selection as for the $W W$ SR, but with the b jet veto requirement inverted. The selected events are enriched in the nonprompt lepton background coming mostly from semileptonic $t\bar{t}$ events. Similarly, the tZq CR is defined by requiring the same selection as for the WZ SR, but with the b jet veto requirement inverted. The selected events are dominated by the tZq background process. Finally, the ZZ CR selects events with two opposite-sign same-flavor lepton pairs with the same VBS-like requirements. The three CRs are used together with the SRs to constrain the normalization of the nonprompt lepton, tZq , and ZZ background processes from data. All other background processes are estimated from simulation after applying corrections to account for the small differences between data and simulation. The shapes of the tZq and ZZ background processes are estimated from simulation as well.

The prediction for the QCD WZ background process is validated in a CR defined by requiring the same selection as for the WZ SR, but with a requirement of $200 < m_{jj} < 500$ GeV. The predicted yields are shown with their best fit normalizations from the simultaneous fit (described in Section 7) for the background-only hypothesis i.e., assuming no contributions from the H and H processes. Good agreement between the data and post-fit predicted yields is observed in this CR as can be seen in Fig. 4.

7 Signal extraction

A binned maximum-likelihood fit is performed using the $W W$ and WZ SRs, and the nonprompt lepton, tZq , and ZZ CRs to discriminate between the signal and the remaining backgrounds. Signal contributions with electrons and muons produced in the decay of a lepton are included. The normalization factors for the tZq and ZZ background processes, affecting both the SRs and CRs, are included as free parameters in the maximum-likelihood fit together with the signal strength. The SM $W W$ (WZ) contribution is obtained from the sum of the

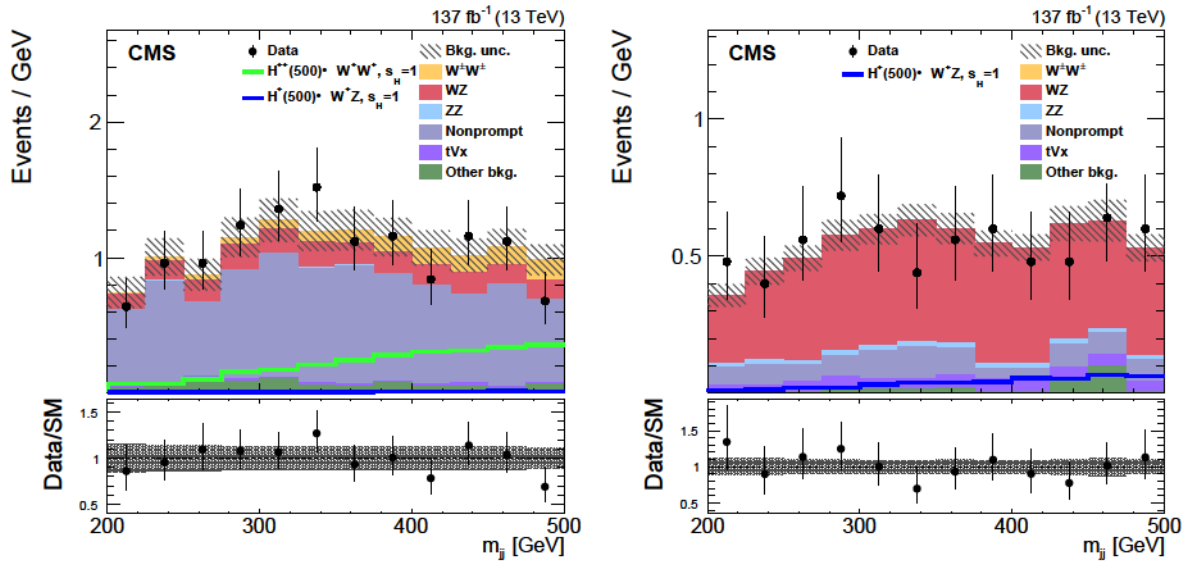


Figure 4: The m_{jj} distributions after requiring the same selection as for the WW (left) and WZ (right) SRs, but with a requirement of $200 < m_{jj} < 500$ GeV. The predicted yields are shown with their best fit normalizations from the simultaneous fit (described in Section 7) for the background-only hypothesis i.e., assuming no contributions from the H^\pm and $H^{\pm\pm}$ processes. Vertical bars on data points represent the statistical uncertainty in the data. The histograms for tVx backgrounds include the contributions from $t\bar{t}V$ and tZq processes. The histograms for other backgrounds include the contributions from double parton scattering, VVV, and from oppositely charged dilepton final states from $t\bar{t}$, tW , W^+W^- , and Drell–Yan processes. The overflow is included in the last bin. The lower panels show the ratio of the number of events observed in data to that of the total SM prediction. The hatched gray bands represent the uncertainties in the predicted yields. The solid lines show the signal predictions for values of $s_H = 1.0$ and $m_{H_5} = 500$ GeV in the GM model.

EW $W W$ (WZ), QCD $W W$ (WZ), and the interference contributions according to the SM predictions [26] and allowed to vary within the uncertainties.

The diboson transverse mass (m_T^{VV}) is constructed from the four-momentum of the selected charged leptons and the p_T^{miss} . The four-momentum of the neutrino system is defined using the p_T^{miss} , assuming that the values of the longitudinal component of the momentum and the mass are zero. The value of m_T^{VV} , defined as

$$m_T^{VV} = \sqrt{\sum_i E_i^2 - \sum_i p_{z,i}^2}, \quad (1)$$

where E_i and $p_{z,i}$ are the energies and longitudinal components of the momenta of the leptons and neutrino system from the decay of the gauge bosons in the event, is effective in discriminating between the resonant signal and nonresonant background processes. The value of m_{jj} is effective in discriminating between all non-VBS processes and the signal (plus EW VV) processes because VBF and VBS topologies typically exhibit large values for the dijet mass. A two-dimensional distribution is used in the fit for the $W W$ SR with 8 bins in m_T^{VV} ([0, 250, 350, 450, 550, 650, 850, 1050,] GeV) and 4 bins in m_{jj} ([500, 800, 1200, 1800,] GeV). Similarly, a two-dimensional distribution is used in the fit for the WZ SR with 7 bins in m_T^{VV} ([0, 325, 450, 550, 650, 850, 1350,] GeV) and 2 bins in m_{jj} ([500, 1500,] GeV). The m_{jj} distribution is used for the CRs in the fit with 4 bins ([500, 800, 1200, 1800,] GeV).

A profile likelihood technique is used where systematic uncertainties are represented by nuisance parameters [71]. For each individual bin, a Poisson likelihood term describes the fluctuation of the data around the expected central value, which is given by the sum of the contributions from signal and background processes. The systematic uncertainties are treated as nuisance parameters and are profiled with the shape and normalization of each distribution varying within the respective uncertainties in the fit. The normalization uncertainties are treated as log-normal nuisance parameters. Correlation across bins is taken into account. The uncertainties affecting the shapes of the distributions are modeled in the fit as nuisance parameters with external Gaussian constraints. The dominant nuisance parameters are not significantly constrained by the data, i.e., the normalized nuisance parameter uncertainties are close to unity.

8 Systematic uncertainties

Several sources of systematic uncertainty are taken into account in the signal extraction procedure. For each source of uncertainty, the effects on the signal and background distributions are considered to be correlated.

The total Run 2 (2016–2018) integrated luminosity has an uncertainty of 1.8%, the improvement in precision relative to Refs. [22–24] reflecting the (uncorrelated) time evolution of some systematic effects.

The simulation of pileup events assumes an inelastic pp cross section of 69.2 mb, with an associated uncertainty of 5% [72], which has an impact on the expected signal and background yields of about 1%.

Discrepancies in the lepton reconstruction and identification efficiencies between data and simulation are corrected by applying scale factors to all simulation samples. These scale factors, which depend on the p_T and η for both electrons and muons, are determined using Z

events in the Z boson peak region that were recorded with independent triggers [61, 63, 73]. The uncertainty in the determination of the trigger efficiency leads to an uncertainty smaller than 1% in the expected signal yield. The trigger efficiency in the simulation is corrected to account for the effect of a gradual time shifts in the forward region in the ECAL endcaps for the 2016 and 2017 data [74]. The uncertainty in this correction is included in the trigger efficiency uncertainty. The lepton momentum scale uncertainty is computed by varying the lepton momenta in simulation with their uncertainties, and repeating the analysis selection. The resulting uncertainties in the yields are 1% for both electrons and muons. These uncertainties are assumed to be correlated across the three data sets.

The uncertainty in the calibration of the jet energy scale (JES) directly affects the acceptance of the jet multiplicity requirement and the p_T^{miss} measurement. These effects are estimated by shifting the JES in the simulated samples up and down by one standard deviation. The uncertainty in the jet energy resolution (JER) smearing applied to simulated samples to match the p_T resolution measured in data causes both a change in the normalization and in the shape of the distributions. The overall uncertainty in the JES and JER is 2–5%, depending on p_T and η [57, 75], and its impact on the expected signal and background yields is about 3%.

The b tagging efficiency in the simulation is corrected using scale factors determined from data [59]. These values are estimated separately for correctly and incorrectly tagged jets. Each set of values results in uncertainties in the b tagging efficiency of about 1–4% depending on p_T and η , and the impact on the expected signal and background yields is about 1%. The uncertainties in the JER, JES and b tagging are treated as uncorrelated across the three data taking years, since the detector conditions have changed among the three years.

The theoretical uncertainties associated with the choice of the renormalization and factorization scales are estimated by varying these scales independently up and down by a factor of two from their nominal values. The envelope of the resulting distributions, excluding the two extreme variations where one scale is varied up and the other one down, is taken as the uncertainty [76, 77]. The variations of the PDF set and α_s are used to estimate the corresponding uncertainties in the yields of the signal and background processes, following Refs. [48, 78]. The uncertainty in the yields due to missing higher-order EW corrections in the GM model is estimated to be 7% [21]. These theoretical uncertainties may affect both the estimated signal and background rates. The statistical uncertainties that are associated with the limited number of simulated events and data events used to estimate the nonprompt lepton background are also considered as systematic uncertainties.

A summary of the impact of the systematic uncertainties on the signal strength, μ , defined as the ratio of the observed charged Higgs signal yield to the expected yield, is shown in Table 2 for the case of a background-only simulated data set, i.e., assuming no contributions from the H and H_{CP} processes. Table 2 also shows systematic uncertainties including a charged Higgs boson signal for values of $s_H = 1.0$ and $m_{H_5} = 500 \text{ GeV}$ in the GM model. The impacts shown in Table 2 result from a fit to two simulated samples: background-only (first column, expected $\mu = 0$) and signal-plus-background (second column, expected $\mu = 1$). They differ from the impacts in percent on the expected signal and background yields given above, which are estimated before the fit. The total systematic uncertainty is smaller for the background-only simulated data set because the uncertainties partially cancel out between the SRs and the CRs for the background processes.

Table 2: Summary of the impact of the systematic uncertainties on the extracted signal strength; for the case of a background-only simulated data set, i.e., assuming no contributions from the $H \rightarrow W W$ and $H \rightarrow W Z$ processes, and including a charged Higgs boson signal for values of $s_H = 1.0$ and $m_{H_5} = 500$ GeV in the GM model. The impacts shown result from a fit to two simulated samples: background-only (first column, expected $\mu = 0$) and signal-plus-background (second column, expected $\mu = 1$).

Source of uncertainty	background-only	$s_H = 1.0$ and $m_{H_5} = 500$ GeV
Integrated luminosity	0.002	0.019
Pileup	0.001	0.001
Lepton measurement	0.003	0.033
Trigger	0.001	0.007
JES and JER	0.003	0.006
b tagging	0.001	0.006
Nonprompt rate	0.002	0.002
W \rightarrow WZ rate	0.014	0.015
Other prompt background rate	0.002	0.015
Signal rate	—	0.064
Limited sample size	0.005	0.005
Total systematic uncertainty	0.016	0.078
Statistical uncertainty	0.021	0.044
Total uncertainty	0.027	0.090

9 Results

The distributions of m_{jj} and m_T^{VV} in the WW and WZ SRs are shown in Fig. 5. The m_{jj} distributions in the WW and WZ SRs are shown with finer binning compared to the binning used in the two-dimensional distribution in the fit. Distributions for signal, backgrounds, and data for the bins used in the simultaneous fit are shown in Fig. 6. The data yields, together with the background expectations with the best fit normalizations for the background-only hypothesis, i.e., assuming no contributions from the $H \rightarrow W W$ and $H \rightarrow W Z$ processes, are shown in Table 3. The product of kinematic acceptance and selection efficiency within the fiducial region for the $H \rightarrow W W$ and $H \rightarrow W Z$ processes, as a function of m_{H_5} , is shown in Fig. 7. The drop of selection efficiency for the $H \rightarrow W Z$ process for masses above 1000 GeV is coming from the lepton isolation requirement as the leptons from high-momentum Z boson decay are produced with a small angular separation.

No significant excess of events above the expectation from the SM background predictions is found. The 95% CL upper limits on the charged Higgs production cross sections are calculated using the modified frequentist approach with the CL_s criterion [79, 80] and asymptotic method for the test statistic [71, 81].

Constraints on resonant charged Higgs boson production are derived. The exclusion limits on the product of the doubly charged Higgs boson cross section and branching fraction $\sigma_{\text{VBF}}(H^{\pm\pm}) \mathcal{B}(H^{\pm\pm} \rightarrow W W)$ at 95% CL as a function of m_H are shown in Fig. 8 (upper left). The exclusion limits on the product of the charged Higgs boson cross section and branching fraction $\sigma_{\text{VBF}}(H^\pm) \mathcal{B}(H^\pm \rightarrow W Z)$ at 95% CL as a function of m_H are shown in Fig. 8 (upper right). The contributions of the H and H^\pm boson signals are set to zero for the derivation of the individual exclusion limits on $\sigma_{\text{VBF}}(H^{\pm\pm}) \mathcal{B}(H^{\pm\pm} \rightarrow W W)$ and

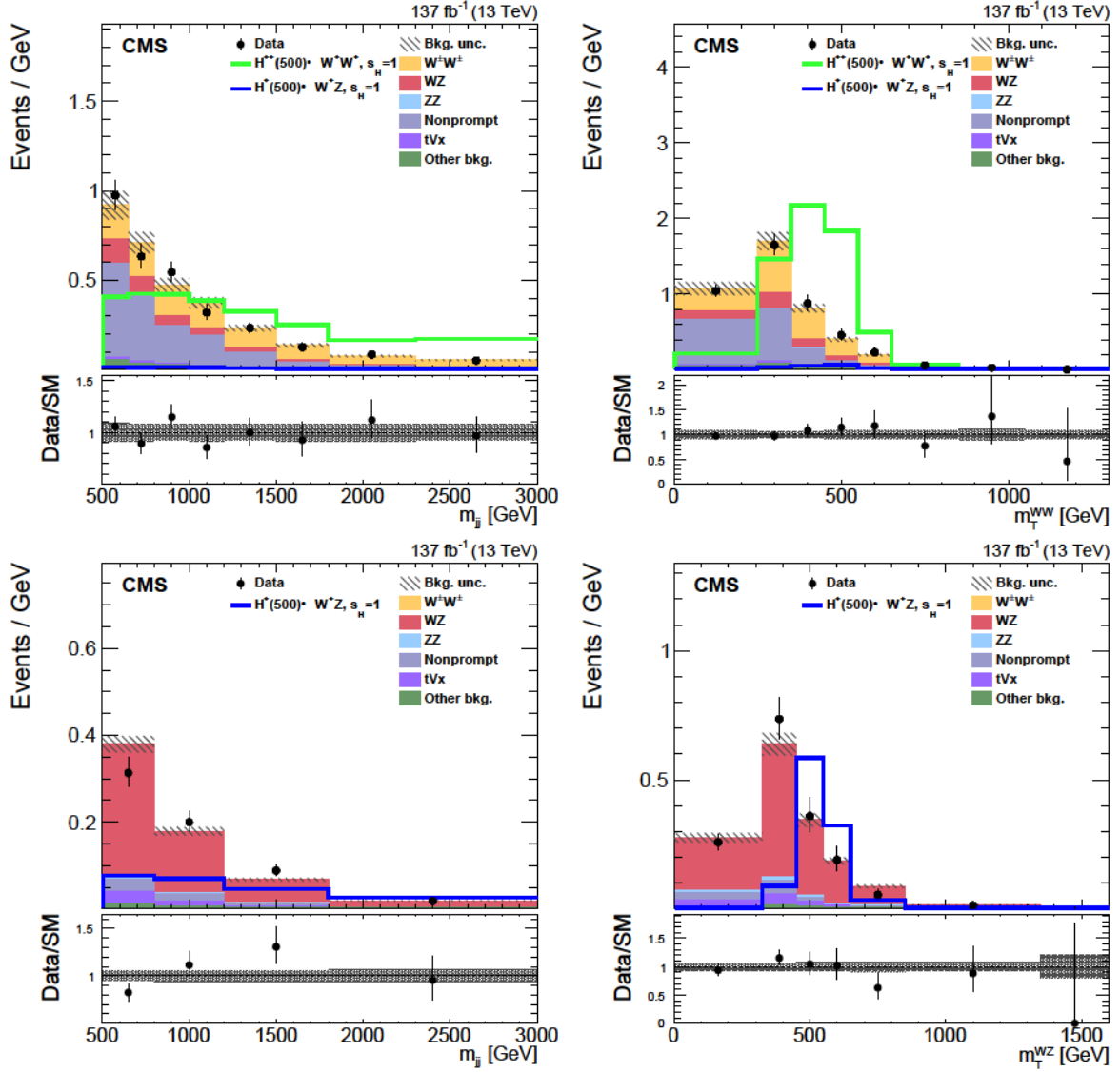


Figure 5: The m_{jj} (upper left) and m_T^{WW} (upper right) distributions in the WW SR, and the m_{jj} (lower left) and m_T^{WZ} (lower right) distributions in the WZ SR for signal, backgrounds, and data. The predicted yields are shown with their best fit normalizations from the simultaneous fit for the background-only hypothesis, i.e., assuming no contributions from the H^\pm and $H^{\pm\pm}$ processes. Vertical bars on data points represent the statistical uncertainty in the data. The histograms for tVx backgrounds include the contributions from $t\bar{t}V$ and tZq processes. The histograms for other backgrounds include the contributions from double parton scattering, VVV, and from oppositely charged dilepton final states from $t\bar{t}$, tW , W^+W^- , and Drell–Yan processes. The overflow is included in the last bin. The lower panels show the ratio of the number of events observed in data to that of the total SM prediction. The hatched gray bands represent the uncertainties in the predicted yields. The solid lines show the signal predictions for values of $s_H = 1.0$ and $m_{H_5} = 500$ GeV in the GM model.

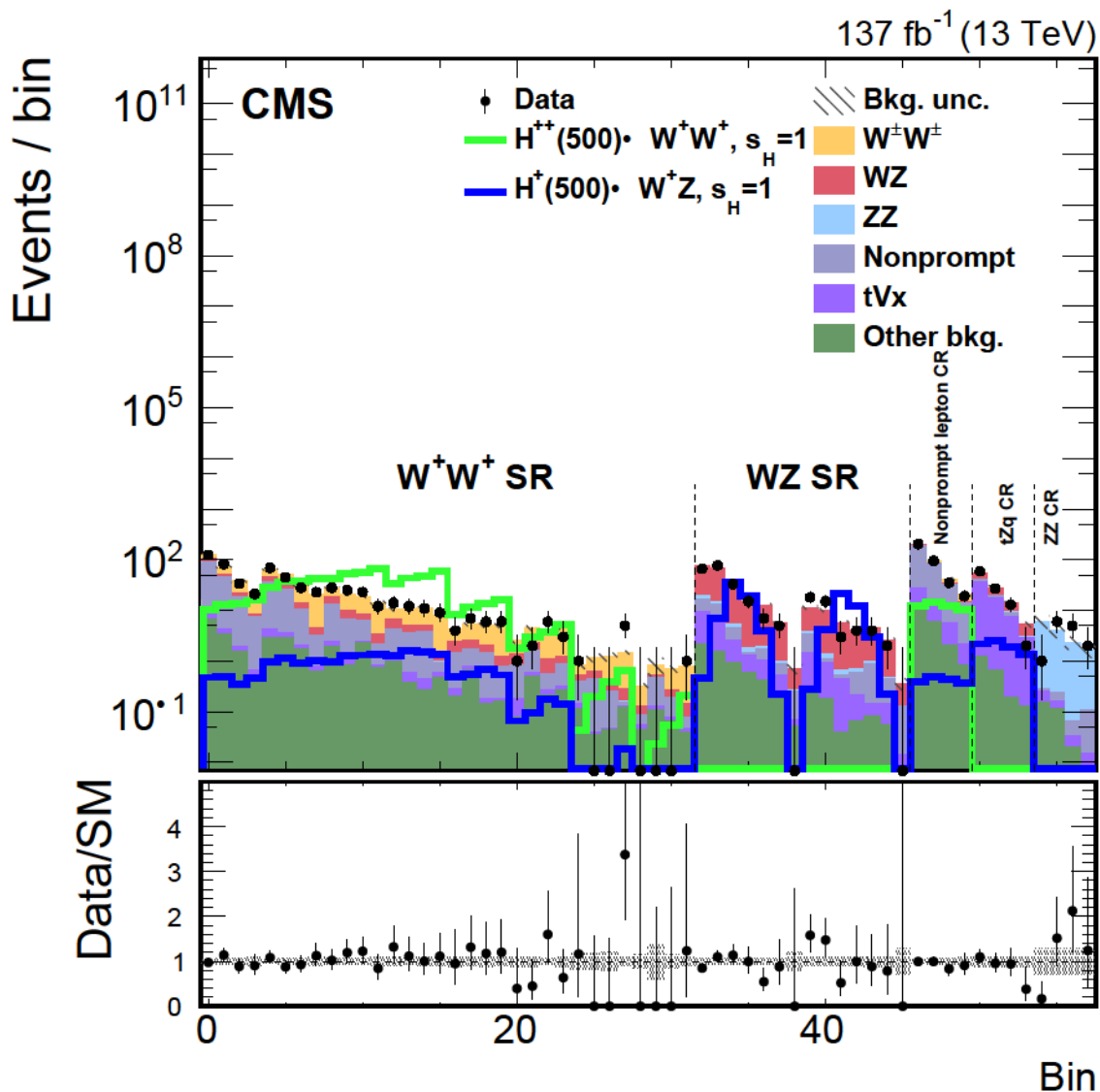


Figure 6: Distributions for signal, backgrounds, and data for the bins used in the simultaneous fit. The bins 1–32 (4×8) show the events in the WW SR ($m_{jj} \times m_T$), the bins 33–46 (2×7) show the events in the WZ SR ($m_{jj} \times m_T$), the 4 bins 47–50 show the events in the nonprompt lepton CR (m_{jj}), the 4 bins 51–54 show the events in the tZq CR (m_{jj}), and the 4 bins 55–58 show the events in the ZZ CR (m_{jj}). The predicted yields are shown with their best fit normalizations from the simultaneous fit for the background-only hypothesis, i.e., assuming no contributions from the H^\pm and $H^{\pm\pm}$ processes. Vertical bars on data points represent the statistical uncertainty in the data. The histograms for tVx backgrounds include the contributions from $t\bar{t}V$ and tZq processes. The histograms for other backgrounds include the contributions from double parton scattering, VVV , and from oppositely charged dilepton final states from $t\bar{t}$, tW , W^+W^- , and Drell–Yan processes. The overflow is included in the last bin in each corresponding region. The lower panels show the ratio of the number of events observed in data to that of the total SM prediction. The hatched gray bands represent the uncertainties in the predicted yields. The solid lines show the signal predictions for values of $s_H = 1.0$ and $m_{H_5} = 500$ GeV in the GM model.

Table 3: Expected signal and background yields from various SM processes and observed data events in all regions used in the analysis. The expected background yields are shown with their normalizations from the simultaneous fit for the background-only hypothesis, i.e., assuming no contributions from the H^\pm and $H^{\pm\pm}$ processes. The expected signal yields are shown for $s_H = 1.0$ in the GM model. The combination of the statistical and systematic uncertainties is shown.

Process	WW SR	WZ SR	Nonprompt CR	tZq CR	ZZ CR
$H^{\pm\pm}(500) \rightarrow W^\pm W^\pm$	666 ± 68	—	48.9 ± 5.1	—	—
$H^\pm(500) \rightarrow WZ$	19.2 ± 2.4	107 ± 11	1.7 ± 0.2	8.0 ± 0.9	—
$W^\pm W^\pm$	230 ± 16	—	28.2 ± 1.8	—	—
WZ	67.8 ± 5.8	196 ± 15	10.3 ± 1.0	27.2 ± 2.4	—
ZZ	0.7 ± 0.2	6.4 ± 2.0	0.1 ± 0.1	1.1 ± 0.3	13.3 ± 4.0
Nonprompt	262 ± 36	22.3 ± 7.7	263 ± 21	8.4 ± 3.1	0.2 ± 0.2
tVx	8.4 ± 1.9	17.7 ± 3.3	28.8 ± 5.6	62 ± 11	0.2 ± 0.1
Other background	31.1 ± 7.3	6.8 ± 1.4	21.1 ± 4.2	2.2 ± 0.4	0.3 ± 0.1
Total background	600 ± 40	249 ± 18	352 ± 22	101 ± 12	14.0 ± 4.0
Data	602	249	352	101	14

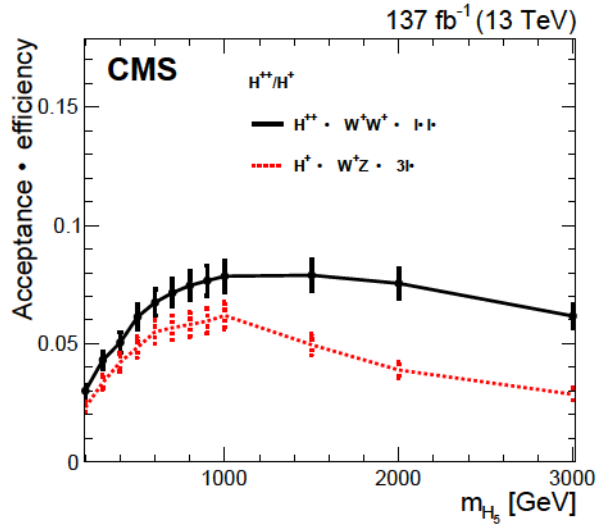


Figure 7: The product of acceptance and selection efficiency within the fiducial region for the VBF $H^{\pm\pm} \rightarrow W^\pm W^\pm \rightarrow 2\ell 2\nu$ and $H^\pm \rightarrow WZ \rightarrow 3\ell\nu$ processes, as a function of m_{H_5} . The combination of the statistical and systematic uncertainties is shown. The theoretical uncertainties in the acceptance are also included.

$\sigma_{\text{VBF}} \text{H} \rightarrow \beta \text{H} \rightarrow \text{WZ}$, respectively. The results assume that the intrinsic width of the H (H_5) boson is $\Gamma_{\text{H}_5} = 0.05m_{\text{H}_5}$ ($0.05m_{\text{H}_5}$), which is below the experimental resolution in the phase space considered. The results are also interpreted in the context of the GM model including the simultaneous contributions of the H and H_5 bosons. The predicted cross sections of the H and H_5 bosons at NNLO accuracy in the GM model [21] are used for given GM parameter values of s_{H} and m_{H_5} . The excluded s_{H} values as a function of m_{H_5} are shown in Fig. 8 (lower). The blue shaded region shows the parameter space for which the H_5 total width exceeds 10% of m_{H_5} , where the model is not applicable because of perturbativity and vacuum stability requirements [21]. For the probed parameter space and m_{T}^{VV} distribution used for signal extraction, the varying width as a function of s_{H} is assumed to have negligible effect on the result. The observed limit excludes s_{H} values greater than 0.20–0.35 for the m_{H_5} range from 200 to 1500 GeV. The limit improves the sensitivity of the previous CMS results at 13 TeV, where s_{H} values greater than about 0.4 and 0.5 are excluded using the leptonic decay mode of the $\sigma_{\text{VBF}} \text{H} \rightarrow \beta \text{H} \rightarrow \text{W} \text{W}$ [28] and $\sigma_{\text{VBF}} \text{H} \rightarrow \beta \text{H} \rightarrow \text{WZ}$ [29] processes, respectively, for the m_{H_5} range from 200 to 1000 GeV. Tabulated results are available in the HepData database [82].

10 Summary

A search for charged Higgs bosons produced in vector boson fusion processes and decaying into vector bosons, using proton-proton collisions at $\sqrt{s} = 13$ TeV at the LHC, is reported. The data sample corresponds to an integrated luminosity of 137 fb^{-1} , collected with the CMS detector between 2016 and 2018. The search is performed in the leptonic decay modes $\text{W} \rightarrow \text{W} \rightarrow \ell \ell$ and $\text{W} \rightarrow \text{Z} \rightarrow \ell \ell$, where $\ell = e, \mu$. The $\text{W} \rightarrow \text{W}$ and WZ channels are simultaneously studied by performing a binned maximum-likelihood fit using the transverse mass m_{T} and dijet invariant mass m_{jj} distributions. No excess of events with respect to the standard model background predictions is observed. Model independent upper limits at 95% confidence level are reported on the product of the cross section and branching fraction for vector boson fusion production of charged Higgs bosons decaying into vector bosons as a function of mass from 200 to 3000 GeV. The results are interpreted in the Georgi–Machacek (GM) model for which the most stringent limits to date are derived. The observed 95% confidence level limits exclude GM s_{H} parameter values greater than 0.20–0.35 for the mass range from 200 to 1500 GeV.

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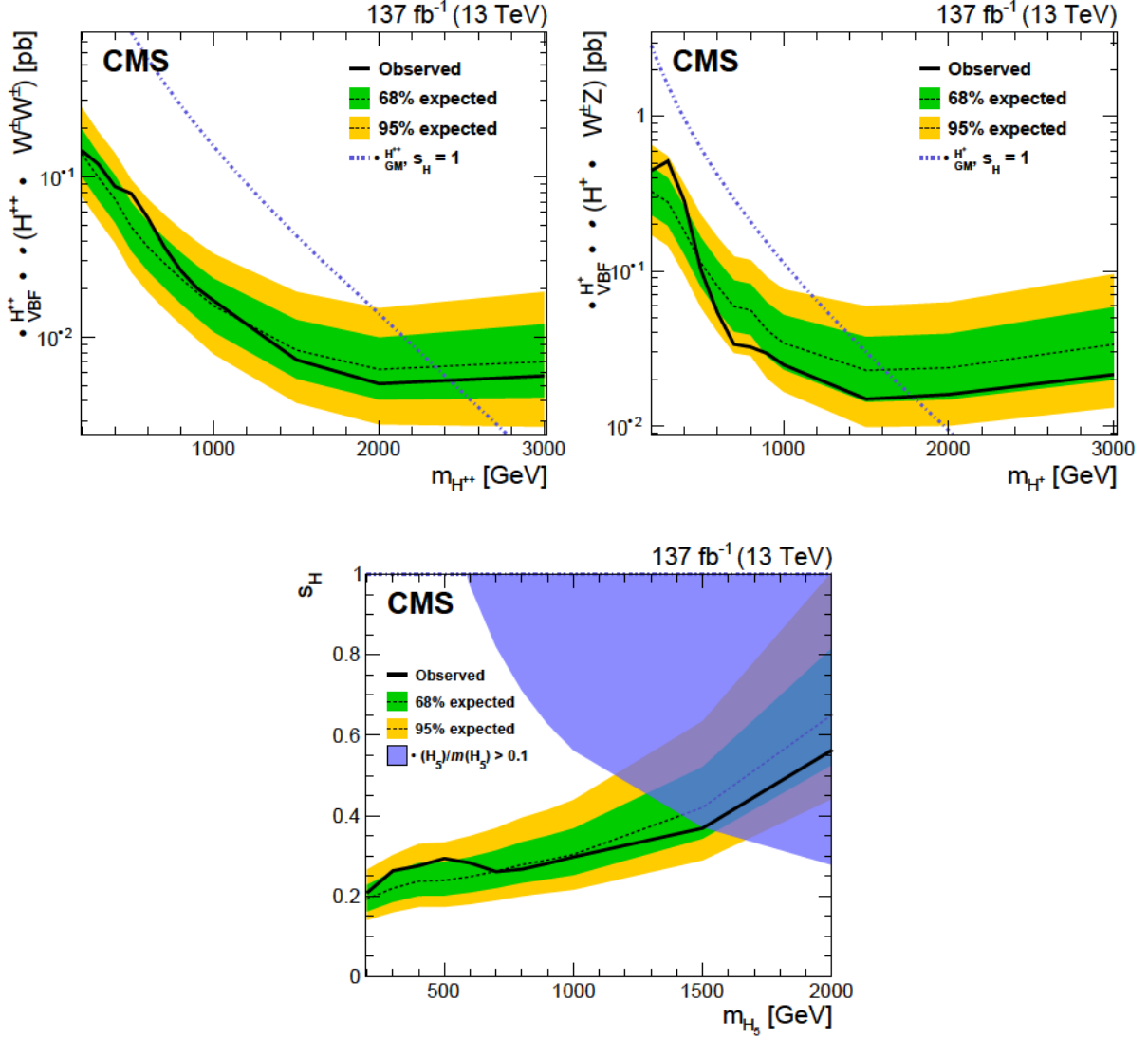


Figure 8: Expected and observed exclusion limits at 95% CL for $\sigma_{\text{VBF}}(H^{\pm\pm}) \mathcal{B}(H^{\pm\pm} \rightarrow W^{\pm}W^{\pm})$ as functions of $m_{H^{\pm\pm}}$ (upper left), for $\sigma_{\text{VBF}}(H^{\pm}) \mathcal{B}(H^{\pm} \rightarrow WZ)$ as functions of $m_{H^{\pm}}$ (upper right), and for s_H as functions of m_{H_5} in the GM model (lower). The contribution of the H^{\pm} ($H^{\pm\pm}$) boson signal is set to zero for the derivation of the exclusion limits on the $\sigma_{\text{VBF}}(H^{\pm\pm}) \mathcal{B}(H^{\pm\pm} \rightarrow W^{\pm}W^{\pm})$ ($\sigma_{\text{VBF}}(H^{\pm}) \mathcal{B}(H^{\pm} \rightarrow WZ)$). The exclusion limits for s_H are shown up to $m_{H_5} = 2000$ GeV, given the low sensitivity in the GM model for values above that mass. Values above the curves are excluded.

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A.M. Sirunyan[†], A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria

W. Adam, J.W. Andrejkovic, T. Bergauer, S. Chatterjee, M. Dragicevic, A. Escalante Del Valle, R. Frühwirth¹, M. Jeitler¹, N. Krammer, L. Lechner, D. Liko, I. Mikulec, P. Paulitsch, F.M. Pitters, J. Schieck¹, R. Schöfbeck, M. Spanring, S. Templ, W. Waltenberger, C.-E. Wulz¹

Institute for Nuclear Problems, Minsk, Belarus

V. Chekhovsky, A. Litomin, V. Makarenko

Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish², E.A. De Wolf, X. Janssen, T. Kello³, A. Lelek, H. Rejeb Sfar, P. Van Mechelen, S. Van Putte, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium

F. Blekman, E.S. Bols, J. D'Hondt, J. De Clercq, M. Delcourt, H. El Faham, S. Lowette, S. Moortgat, A. Morton, D. Müller, A.R. Sahasransu, S. Tavernier, W. Van Doninck, P. Van Mulders

Université Libre de Bruxelles, Bruxelles, Belgium

D. Beghin, B. Bilin, B. Clerbaux, G. De Lentdecker, L. Favart, A. Grebenyuk, A.K. Kalsi, K. Lee, M. Mahdavihorrami, I. Makarenko, L. Moureaux, L. Pétré, A. Popov, N. Postiau, E. Starling, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer, D. Vannerom, L. Wezenbeek

Ghent University, Ghent, Belgium

T. Cornelis, D. Dobur, J. Knolle, L. Lambrecht, G. Mestdach, M. Niedziela, C. Roskas, A. Samalan, K. Skovpen, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit

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

A. Bethani, G. Bruno, F. Bury, C. Caputo, P. David, C. Delaere, I.S. Donertas, A. Giammanco, K. Jaffel, Sa. Jain, V. Lemaître, K. Mondal, J. Prisciandaro, A. Taliencio, M. Teklishyn, T.T. Tran, P. Vischia, S. Wertz, S. Wuyckens

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

G.A. Alves, C. Hensel, A. Moraes

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. Chinellato⁴, E.M. Da Costa, G.G. Da Silveira⁵, D. De Jesus Damiao, S. Fonseca De Souza, D. Matos Figueiredo, C. Mora Herrera, K. Mota Amarilo, L. Mundim, H. Nogima, P. Rebello Teles, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista ^a, Universidade Federal do ABC ^b, São Paulo, Brazil

C.A. Bernardes^{a,5}, L. Calligaris^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^{a,b}, D.S. Lemos^a, P.G. Mercadante^{a,b}, S.F. Novaes^a, Sandra S. Padula^a

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

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

University of Sofia, Sofia, Bulgaria

A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov

Beihang University, Beijing, China

T. Cheng, W. Fang³, Q. Guo, T. Javaid⁶, M. Mittal, H. Wang, L. Yuan

Department of Physics, Tsinghua University, Beijing, China

M. Ahmad, G. Bauer, C. Dozen⁷, Z. Hu, J. Martins⁸, Y. Wang, K. Yi^{9,10}

Institute of High Energy Physics, Beijing, China

E. Chapon, G.M. Chen⁶, H.S. Chen⁶, M. Chen, F. Iemmi, A. Kapoor, D. Leggat, H. Liao, Z.-A. LIU⁶, V. Milosevic, F. Monti, R. Sharma, J. Tao, J. Thomas-wilsker, J. Wang, H. Zhang, S. Zhang⁶, J. Zhao

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

A. Agapitos, Y. Ban, C. Chen, Q. Huang, A. Levin, Q. Li, X. Lyu, Y. Mao, S.J. Qian, D. Wang, Q. Wang, J. Xiao

Sun Yat-Sen University, Guangzhou, China

M. Lu, Z. You

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China

X. Gao³, H. Okawa

Zhejiang University, Hangzhou, China

Z. Lin, M. Xiao

Universidad de Los Andes, Bogota, Colombia

C. Avila, A. Cabrera, C. Florez, J. Fraga, A. Sarkar, M.A. Segura Delgado

Universidad de Antioquia, Medellin, Colombia

J. Mejia Guisao, F. Ramirez, J.D. Ruiz Alvarez, C.A. Salazar González

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia

D. Giljanovic, N. Godinovic, D. Lelas, I. Puljak

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac, T. Sculac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, D. Ferencek, D. Majumder, M. Roguljic, A. Starodumov¹¹, T. Susa

University of Cyprus, Nicosia, Cyprus

A. Attikis, K. Christoforou, E. Erodotou, A. Ioannou, G. Kole, M. Kolosova, S. Konstantinou, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka

Charles University, Prague, Czech Republic

M. Finger¹², M. Finger Jr.¹², 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

H. Abdalla¹³, A.A. Abdelalim^{14,15}

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt

A. Lotfy, M.A. Mahmoud

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, S. Nandan, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, L. Forthomme, H. Kirschenmann, K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

S. Bharthuar, E. Brücken, F. Garcia, J. Havukainen, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, M. Lotti, L. Martikainen, M. Myllymäki, J. Ott, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland

P. Luukka, H. Petrow, T. Tuuva

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

C. Amendola, M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, B. Lenzi, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro¹⁶, M. Titov, G.B. Yu

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France

S. Ahuja, F. Beaudette, M. Bonanomi, A. Buchot Perraguin, P. Busson, A. Cappati, C. Charlot, O. Davignon, B. Diab, G. Falmagne, S. Ghosh, R. Granier de Cassagnac, A. Hakimi, I. Kucher, M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France

J.-L. Agram¹⁷, J. Andrea, D. Apparau, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, D. Darej, J.-C. Fontaine¹⁷, U. Goerlach, C. Grimault, A.-C. Le Bihan, E. Nibigira, P. Van Hove

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France

E. Asilar, S. Beauceron, C. Bernet, G. Boudoul, C. Camen, A. Carle, N. Chanon, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Guzevitch, B. Ille, I.B. Laktineh, H. Lattaud, A. Lesauvage, M. Lethuillier, L. Mirabito, S. Perries, K. Shchablo, V. Sordini, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia

A. Khvedelidze¹², I. Lomidze, Z. Tsamalaidze¹²

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

L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M.P. Rauch, N. Röwert, J. Schulz, M. Teroerde

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

A. Dodonova, D. Eliseev, M. Erdmann, P. Fackeldey, B. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, F. Ivone, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, G. Mocellin,

S. Mondal, S. Mukherjee, D. Noll, A. Novak, T. Pook, A. Pozdnyakov, Y. Rath, H. Reithler, J. Roemer, A. Schmidt, S.C. Schuler, A. Sharma, L. Vigilante, S. Wiedenbeck, S. Zaleski

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

C. Dziwok, G. Flügge, W. Haj Ahmad¹⁸, O. Hlushchenko, T. Kress, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl¹⁹, T. Ziemons

Deutsches Elektronen-Synchrotron, Hamburg, Germany

H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, I. Babounikau, S. Baxter, O. Behnke, A. Bermúdez Martínez, S. Bhattacharya, A.A. Bin Anuar, K. Borras²⁰, V. Botta, D. Brunner, A. Campbell, A. Cardini, C. Cheng, F. Colombina, S. Consuegra Rodríguez, G. Correia Silva, V. Danilov, L. Didukh, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, O. Filatov, E. Gallo²¹, A. Geiser, A. Giraldi, A. Grohsjean, M. Guthoff, A. Jafari²², N.Z. Jomhari, H. Jung, A. Kasem²⁰, M. Kasemann, H. Kaveh, C. Kleinwort, D. Krücker, W. Lange, J. Lidrych, K. Lipka, W. Lohmann²³, R. Mankel, I.-A. Melzer-Pellmann, J. Metwally, A.B. Meyer, M. Meyer, J. Mnich, A. Mussgiller, Y. Otariid, D. Pérez Adán, D. Pitzl, A. Raspereza, B. Ribeiro Lopes, J. Rübenach, A. Saggio, A. Saibel, M. Savitskyi, M. Scham, V. Scheurer, C. Schwanenberger²¹, A. Singh, R.E. Sosa Ricardo, D. Stafford, N. Tonon, O. Turkot, M. Van De Klundert, R. Walsh, D. Walter, Y. Wen, K. Wichmann, L. Wiens, C. Wissing, S. Wuchterl

University of Hamburg, Hamburg, Germany

R. Aggleton, S. Albrecht, S. Bein, L. Benato, A. Benecke, P. Connor, K. De Leo, M. Eich, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, P. Gunnellini, J. Haller, A. Hinzmann, G. Kasieczka, R. Klanner, R. Kogler, T. Kramer, V. Kutzner, J. Lange, T. Lange, A. Lobanov, A. Malara, A. Nigamova, K.J. Pena Rodriguez, O. Rieger, P. Schleper, M. Schröder, J. Schwandt, D. Schwarz, J. Sonneveld, H. Stadie, G. Steinbrück, A. Tews, B. Vormwald, I. Zoi

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

J. Bechtel, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer[†], A. Dierlamm, A. Droll, K. El Morabit, N. Faltermann, M. Giffels, J.o. Gosewisch, A. Gottmann, F. Hartmann¹⁹, C. Heidecker, U. Husemann, I. Katkov²⁴, P. Keicher, R. Koppenhöfer, S. Maier, M. Metzler, S. Mitra, Th. Müller, M. Neukum, A. Nürnberg, G. Quast, K. Rabbertz, J. Rauser, D. Savoii, M. Schnepf, D. Seith, I. Shvetsov, H.J. Simonis, R. Ulrich, J. Van Der Linden, R.F. Von Cube, M. Wassmer, M. Weber, S. Wieland, R. Wolf, S. Wozniewski, S. Wunsch

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

G. Anagnostou, P. Asenov, G. Daskalakis, T. Gerasis, A. Kyriakis, D. Loukas, A. Stakia

National and Kapodistrian University of Athens, Athens, Greece

M. Diamantopoulou, D. Karasavvas, G. Karathanasis, P. Kontaxakis, C.K. Koraka, A. Manousakis-katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, E. Vourliotis

National Technical University of Athens, Athens, Greece

G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis, A. Zacharopoulou

University of Ioánnina, Ioánnina, Greece

I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, N. Manthos, I. Papadopoulos, J. Strologas

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

Budapest, Hungary

M. Csanad, K. Farkas, M.M.A. Gadallah²⁵, S. Lökös²⁶, P. Major, K. Mandal, A. Mehta, G. Pasztor, A.J. Rádl, O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary

M. Bartók²⁷, G. Bencze, C. Hajdu, D. Horvath²⁸, F. Sikler, V. Veszpremi, G. Vesztergombi[†]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

S. Czellar, J. Karancsi²⁷, J. Molnar, Z. Szillasi, D. Teyssier

Institute of Physics, University of Debrecen, Debrecen, Hungary

P. Raics, Z.L. Trocsanyi²⁹, B. Ujvari

Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary

T. Csorgo³⁰, F. Nemes³⁰, T. Novak

Indian Institute of Science (IISc), Bangalore, India

J.R. Komaragiri, D. Kumar, L. Panwar, P.C. Tiwari

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

S. Bahinipati³¹, D. Dash, C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu³², A. Nayak³², P. Saha, N. Sur, S.K. Swain, D. Vats³²

Panjab University, Chandigarh, India

S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra³³, R. Gupta, A. Kaur, M. Kaur, S. Kaur, P. Kumari, M. Meena, K. Sandeep, J.B. Singh, A.K. Viridi

University of Delhi, Delhi, India

A. Ahmed, A. Bhardwaj, B.C. Choudhary, M. Gola, S. Keshri, A. Kumar, M. Naimuddin, P. Priyanka, K. Ranjan, A. Shah

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

M. Bharti³⁴, R. Bhattacharya, S. Bhattacharya, D. Bhowmik, S. Dutta, S. Dutta, B. Gomber³⁵, M. Maity³⁶, P. Palit, P.K. Rout, G. Saha, B. Sahu, S. Sarkar, M. Sharan, B. Singh³⁴, S. Thakur³⁴

Indian Institute of Technology Madras, Madras, India

P.K. Behera, S.C. Behera, P. Kalbhor, A. Muhammad, R. Pradhan, P.R. Pujahari, A. Sharma, A.K. Sikdar

Bhabha Atomic Research Centre, Mumbai, India

D. Dutta, V. Jha, V. Kumar, D.K. Mishra, K. Naskar³⁷, P.K. Netrakanti, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research-A, Mumbai, India

T. Aziz, S. Dugad, M. Kumar, U. Sarkar

Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee, R. Chudasama, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee

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

K. Alpana, S. Dube, B. Kansal, A. Laha, S. Pandey, A. Rane, A. Rastogi, S. Sharma

Department of Physics, Isfahan University of Technology, Isfahan, Iran

H. Bakhshiansohi³⁸, M. Zeinali³⁹

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

S. Chenarani⁴⁰, 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,b,41}, C. Aruta^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, N. De Filippis^{a,c}, M. De Palma^{a,b}, A. Di Florio^{a,b}, A. Di Pilato^{a,b}, W. Elmetenawee^{a,b}, L. Fiore^a, A. Gelmi^{a,b}, M. Gul^a, G. Iaselli^{a,c}, M. Ince^{a,b}, S. Lezki^{a,b}, G. Maggi^{a,c}, M. Maggi^a, I. Margjeka^{a,b}, V. Mastrapasqua^{a,b}, J.A. Merlin^a, S. My^{a,b}, S. Nuzzo^{a,b}, A. Pellecchia^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, A. Ranieri^a, G. Selvaggi^{a,b}, L. Silvestris^a, F.M. Simone^{a,b}, R. Venditti^a, P. Verwilligen^a

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, L. Brigliadori^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. Fabbrì^a, A. Fanfani^{a,b}, P. Giacomelli^a, L. Giommi^{a,b}, C. Grandi^a, L. Guiducci^{a,b}, S. Lo Meo^{a,42}, L. Lunerti^{a,b}, S. Marcellini^a, G. Masetti^a, F.L. Navarra^{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. Albergo^{a,b,43}, S. Costa^{a,b,43}, A. Di Mattia^a, R. Potenza^{a,b}, A. Tricomi^{a,b,43}, C. Tuve^{a,b}

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

G. Barbagli^a, A. Cassese^a, R. Ceccarelli^{a,b}, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, G. Latino^{a,b}, P. Lenzi^{a,b}, M. Lizzo^{a,b}, M. Meschini^a, S. Paoletti^a, R. Seidita^{a,b}, G. Sguazzoni^a, L. Viliani^a

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, D. Piccolo

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

M. Bozzo^{a,b}, F. Ferro^a, R. Mulargia^{a,b}, E. Robutti^a, S. Tosi^{a,b}

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

A. Benaglia^a, F. Brivio^{a,b}, F. Cetorelli^{a,b}, V. Ciriolo^{a,b,19}, F. De Guio^{a,b}, M.E. Dinardo^{a,b}, P. Dini^a, S. Gennai^a, A. Ghezzi^{a,b}, P. Govoni^{a,b}, L. Guzzi^{a,b}, M. Malberti^a, S. Malvezzi^a, A. Massironi^a, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, N. Redaelli^a, T. Tabarelli de Fatis^{a,b}, D. Valsecchi^{a,b,19}, D. Zuolo^{a,b}

INFN Sezione di Napoli ^a, Università di Napoli 'Federico II' ^b, Napoli, Italy, Università della Basilicata ^c, Potenza, Italy, Università G. Marconi ^d, Roma, Italy

S. Buontempo^a, F. Carnevali^{a,b}, N. Cavallo^{a,c}, A. De Iorio^{a,b}, F. Fabozzi^{a,c}, A.O.M. Iorio^{a,b}, L. Lista^{a,b}, S. Meola^{a,d,19}, P. Paolucci^{a,19}, B. Rossi^a, C. Sciacca^{a,b}

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

P. Azzi^a, N. Bacchetta^a, D. Bisello^{a,b}, P. Bortignon^a, A. Bragagnolo^{a,b}, R. Carlin^{a,b}, P. Checchia^a, T. Dorigo^a, U. Dosselli^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, S.Y. Hoh^{a,b}, L. Layer^{a,44}, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, J. Pazzini^{a,b}, M. Presilla^{a,b}, P. Ronchese^{a,b}, R. Rossin^{a,b}, F. Simonetto^{a,b}, G. Strong^a, M. Tosi^{a,b}, 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

C. Aime^{a,b}, A. Braghieri^a, S. Calzaferri^{a,b}, D. Fiorina^{a,b}, P. Montagna^{a,b}, S.P. Ratti^{a,b}, V. Re^a, C. Riccardi^{a,b}, P. Salvini^a, I. Vai^a, P. Vitulo^{a,b}

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

G.M. Bilei^a, D. Ciangottini^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b}, M. Magherini^b, G. Mantovani^{a,b}, V. Mariani^{a,b}, M. Menichelli^a, F. Moscatelli^a, A. Piccinelli^{a,b}, 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. Azzurri^a, G. Bagliesi^a, V. Bertacchi^{a,c}, L. Bianchini^a, T. Boccali^a, E. Bossini^{a,b}, R. Castaldi^a, M.A. Ciocci^{a,b}, V. D'Amante^{a,d}, R. Dell'Orso^a, M.R. Di Domenico^{a,d}, S. Donato^a, A. Giassi^a, M.T. Grippo^a, F. Ligabue^{a,c}, E. Manca^{a,c}, G. Mandorli^{a,c}, A. Messineo^{a,b}, F. Palla^a, S. Parolia^{a,b}, G. Ramirez-Sanchez^{a,c}, A. Rizzi^{a,b}, G. Rolandi^{a,c}, S. Roy Chowdhury^{a,c}, A. Scribano^a, N. Shafiei^{a,b}, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b}, N. Turini^{a,d}, A. Venturi^a, P.G. Verdini^a

INFN Sezione di Roma ^a, Sapienza Università di Roma ^b, Rome, Italy

M. Campana^{a,b}, F. Cavallari^a, M. Cipriani^{a,b}, D. Del Re^{a,b}, E. Di Marco^a, M. Diemoz^a, E. Longo^{a,b}, P. Meridiani^a, 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, R. Tramontano^{a,b}

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

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, N. Bartosik^a, R. Bellan^{a,b}, A. Bellora^{a,b}, J. Berenguer Antequera^{a,b}, C. Biino^a, N. Cartiglia^a, S. Cometti^a, M. Costa^{a,b}, R. Covarelli^{a,b}, N. Demaria^a, B. Kiani^{a,b}, F. Legger^a, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, E. Monteil^{a,b}, M. Monteno^a, M.M. Obertino^{a,b}, G. Ortona^a, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G.L. Pinna Angioni^{a,b}, M. Ruspa^{a,c}, K. Shchelina^{a,b}, F. Siviero^{a,b}, V. Sola^a, A. Solano^{a,b}, D. Soldi^{a,b}, A. Staiano^a, M. Tornago^{a,b}, D. Trocino^{a,b}, A. Vagnerini

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

S. Belforte^a, V. Candelise^{a,b}, M. Casarsa^a, F. Cossutti^a, A. Da Rold^{a,b}, G. Della Ricca^{a,b}, G. Sorrentino^{a,b}, F. Vazzoler^{a,b}

Kyungpook National University, Daegu, Korea

S. Dogra, C. Huh, B. Kim, D.H. Kim, G.N. Kim, J. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, B.C. Radburn-Smith, S. Sekmen, Y.C. Yang

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea

H. Kim, D.H. Moon

Hanyang University, Seoul, Korea

B. Francois, T.J. Kim, J. Park

Korea University, Seoul, Korea

S. Cho, S. Choi, Y. Go, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, J. Yoo

Kyung Hee University, Department of Physics, Seoul, Republic of Korea

J. Goh, A. Gurtu

Sejong University, Seoul, Korea

H.S. Kim, Y. Kim

Seoul National University, Seoul, Korea

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

University of Seoul, Seoul, Korea

W. Jang, D. Jeon, D.Y. Kang, Y. Kang, J.H. Kim, S. Kim, B. Ko, J.S.H. Lee, Y. Lee, I.C. Park, Y. Roh, M.S. Ryu, D. Song, I.J. Watson, S. Yang

Yonsei University, Department of Physics, Seoul, Korea

S. Ha, H.D. Yoo

Sungkyunkwan University, Suwon, Korea

M. Choi, Y. Jeong, H. Lee, Y. Lee, I. Yu

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

T. Beyrouthy, Y. Maghrbi

Riga Technical University, Riga, Latvia

V. Veckalns⁴⁵

Vilnius University, Vilnius, Lithuania

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

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

N. Bin Norjoharuddeen, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico

J.F. Benitez, A. Castaneda Hernandez, M. León Coello, J.A. Murillo Quijada, A. Sehwawat, L. Valencia Palomo

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

G. Ayala, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz⁴⁶, R. Lopez-Fernandez, C.A. Mondragon Herrera, D.A. Perez Navarro, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

University of Montenegro, Podgorica, Montenegro

J. Mijuskovic⁴⁷, N. Raicevic

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

S. Bheesette, P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

AGH University of Science and Technology 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. Szleper, P. Zalewski

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

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, P. Bargassa, D. Bastos, A. Boletti, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, M. Pisano, J. Seixas, O. Toldaiev, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, D. Budkouski, I. Golutvin, I. Gorbunov, V. Karjavine, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev^{48,49}, V. Palichik, V. Perelygin, M. Savina, D. Seitova, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, B.S. Yuldashev⁵⁰, A. Zarubin, I. Zhizhin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
G. Gavrillov, V. Golovtsov, Y. Ivanov, V. Kim⁵¹, E. Kuznetsova⁵², V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Volkov, A. Vorobyev

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

Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia
V. Epshteyn, V. Gavrillov, N. Lychkovskaya, A. Nikitenko⁵³, V. Popov, A. Spiridonov, A. Stepenov, M. Toms, E. Vlasov, A. Zhokin

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

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
M. Chadeeva⁵⁴, A. Oskin, P. Parygin, E. Popova, E. Zhemchugov⁵⁵

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

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, V. Bunichev, M. Dubinin⁵⁶, L. Dudko, A. Ershov, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, M. Perfilov, S. Petrushanko, V. Savrin

Novosibirsk State University (NSU), Novosibirsk, Russia
V. Blinov⁵⁷, T. Dimova⁵⁷, L. Kardapoltsev⁵⁷, A. Kozyrev⁵⁷, I. Ovtin⁵⁷, Y. Skovpen⁵⁷

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia
I. Azhgirey, I. Bayshev, D. Elumakhov, V. Kachanov, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

National Research Tomsk Polytechnic University, Tomsk, Russia
A. Babaev, V. Okhotnikov

Tomsk State University, Tomsk, Russia
V. Borshch, V. Ivanchenko, E. Tcherniaev

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Belgrade, Serbia

P. Adzic⁵⁸, M. Dordevic, P. Milenovic, J. Milosevic

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

M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, Cristina F. Bedoya, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. León Holgado, D. Moran, Á. Navarro Tobar, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, L. Urda Gómez, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain

J.F. de Trocóniz, R. Reyes-Almanza

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain

B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, C. Ramón Álvarez, J. Ripoll Sau, V. Rodríguez Bouza, A. Trapote, N. Trevisani

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

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, C. Fernandez Madrazo, P.J. Fernández Manteca, A. García Alonso, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka

MK Jayananda, B. Kailasapathy⁵⁹, D.U.J. Sonnadara, DDC Wickramarathna

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

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

CERN, European Organization for Nuclear Research, Geneva, Switzerland

T.K. Aarrestad, D. Abbaneo, J. Alimena, E. Auffray, G. Auzinger, J. Baechler, P. Baillon[†], D. Barney, J. Bendavid, M. Bianco, A. Bocci, T. Camporesi, M. Capeans Garrido, G. Cerminara, S.S. Chhibra, L. Cristella, D. d'Enterria, A. Dabrowski, N. Daci, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita⁶⁰, D. Fasanella, S. Fiorendi, A. Florent, G. Franzoni, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Haranko, J. Hegeman, Y. Iiyama, V. Innocente, T. James, P. Janot, J. Kaspar, J. Kieseler, M. Komm, N. Kratochwil, C. Lange, S. Laurila, P. Lecoq, K. Long, C. Lourenço, L. Malgeri, S. Mallios, M. Mannelli, A.C. Marini, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, S. Orfanelli, L. Orsini, F. Pantaleo, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Piparo, M. Pitt, H. Qu, T. Quast, D. Rabady, A. Racz, G. Reales Gutiérrez, M. Rieger, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas⁶¹, S. Summers, V.R. Tavolaro, D. Treille, A. Tsiros, G.P. Van Onsem, M. Verzetti, J. Wanczyk⁶², K.A. Wozniak, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

L. Caminada⁶³, A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, M. Missiroli, T. Rohe

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

K. Androsov⁶², M. Backhaus, P. Berger, A. Calandri, N. Chernyavskaya, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, F. Eble, F. Glessgen, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lusterhmann, A.-M. Lyon, R.A. Manzoni, C. Martin Perez, M.T. Meinhard, F. Micheli, F. Nessi-Tedaldi, J. Niedziela, F. Pauss, V. Perovic, G. Perrin, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, V. Stampf, J. Steggemann⁶², R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland

C. Amsler⁶⁴, P. Bäertschi, C. Botta, D. Brzhechko, M.F. Canelli, K. Cormier, A. De Wit, R. Del Burgo, J.K. Heikkilä, M. Huwiler, A. Jofrehei, B. Kilminster, S. Leontsinis, A. Macchiolo, P. Meiring, V.M. Mikuni, U. Molinatti, I. Neutelings, A. Reimers, P. Robmann, S. Sanchez Cruz, K. Schweiger, Y. Takahashi

National Central University, Chung-Li, Taiwan

C. Adloff⁶⁵, C.M. Kuo, W. Lin, A. Roy, T. Sarkar³⁶, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

L. Ceard, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, H.y. Wu, E. Yazgan, P.r. Yu

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand

B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas

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

F. Boran, S. Damarseckin⁶⁶, Z.S. Demiroglu, F. Dolek, I. Dumanoglu⁶⁷, E. Eskut, Y. Guler, E. Gurpinar Guler⁶⁸, I. Hos⁶⁹, C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir⁷⁰, A. Polatoz, A.E. Simsek, B. Tali⁷¹, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

B. Isildak⁷², G. Karapinar⁷³, K. Ocalan⁷⁴, M. Yalvac⁷⁵

Bogazici University, Istanbul, Turkey

B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya⁷⁶, O. Kaya⁷⁷, Ö. Özçelik, S. Tekten⁷⁸, E.A. Yetkin⁷⁹

Istanbul Technical University, Istanbul, Turkey

A. Cakir, K. Cankocak⁶⁷, Y. Komurcu, S. Sen⁸⁰

Istanbul University, Istanbul, Turkey

S. Cerci⁷¹, B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci⁷¹

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

B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

L. Levchuk

University of Bristol, Bristol, United Kingdom

D. Anthony, E. Bhal, S. Bologna, J.J. Brooke, A. Bundock, E. Clement, D. Cussans, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou⁸¹, R. White

Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell, A. Belyaev⁸², C. Brew, R.M. Brown, D.J.A. Cockerill, K.V. Ellis, K. Harder,

S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom

R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, O. Buchmuller, V. Cepaitis, G.S. Chahal⁸³, D. Colling, P. Dauncey, G. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, D.G. Monk, J. Nash⁸⁴, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, A. Tapper, K. Uchida, T. Virdee¹⁹, M. Vojinovic, N. Wardle, S.N. Webb, D. Winterbottom, A.G. Zecchinelli

Brunel University, Uxbridge, United Kingdom

K. Coldham, J.E. Cole, A. Khan, P. Kyberd, I.D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, USA

S. Abdullin, A. Brinkerhoff, B. Caraway, J. Dittmann, K. Hatakeyama, A.R. Kanuganti, B. McMaster, N. Pastika, S. Sawant, C. Sutantawibul, J. Wilson

Catholic University of America, Washington, DC, USA

R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

The University of Alabama, Tuscaloosa, USA

A. Buccilli, S.I. Cooper, D. Di Croce, S.V. Gleyzer, C. Henderson, C.U. Perez, P. Rumerio⁸⁵, C. West

Boston University, Boston, USA

A. Akpınar, A. Albert, D. Arcaro, C. Cosby, Z. Demiragli, E. Fontanesi, D. Gastler, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, S. Yuan, D. Zou

Brown University, Providence, USA

G. Benelli, B. Burkley, X. Coubez²⁰, D. Cutts, M. Hadley, U. Heintz, J.M. Hogan⁸⁶, G. Landsberg, K.T. Lau, M. Lukasik, J. Luo, M. Narain, S. Sagir⁸⁷, E. Usai, W.Y. Wong, X. Yan, D. Yu, W. Zhang

University of California, Davis, Davis, USA

J. Bonilla, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, P.T. Cox, R. Erbacher, G. Haza, F. Jensen, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, B. Regnery, D. Taylor, Y. Yao, F. Zhang

University of California, Los Angeles, USA

M. Bachtis, R. Cousins, A. Datta, D. Hamilton, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, N. Mccoll, W.A. Nash, S. Regnard, D. Saltzberg, B. Stone, V. Valuev

University of California, Riverside, Riverside, USA

K. Burt, Y. Chen, R. Clare, J.W. Gary, M. Gordon, G. Hanson, G. Karapostoli, O.R. Long, N. Manganello, M. Olmedo Negrete, W. Si, S. Wimpenny, Y. Zhang

University of California, San Diego, La Jolla, USA

J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, N. Deelen, D. Diaz, J. Duarte, R. Gerosa, L. Giannini, D. Gilbert, J. Guiang, R. Kansal, V. Krutelyov, R. Lee, J. Letts, M. Masciovecchio, S. May, M. Pieri, B.V. Sathia Narayanan, V. Sharma, M. Tadel, A. Vartak, F. Würthwein, Y. Xiang, A. Yagil

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

N. Amin, C. Campagnari, M. Citron, A. Dorsett, V. Dutta, J. Incandela, M. Kilpatrick, J. Kim, B. Marsh, H. Mei, M. Oshiro, M. Quinnan, J. Richman, U. Sarica, D. Stuart, S. Wang

California Institute of Technology, Pasadena, USA

A. Bornheim, O. Cerri, I. Dutta, J.M. Lawhorn, N. Lu, J. Mao, H.B. Newman, J. Ngadiuba, T.Q. Nguyen, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, Z. Zhang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA

J. Alison, S. An, M.B. Andrews, P. Bryant, T. Ferguson, A. Harilal, C. Liu, T. Mudholkar, M. Paulini, A. Sanchez

University of Colorado Boulder, Boulder, USA

J.P. Cumalat, W.T. Ford, A. Hassani, E. MacDonald, R. Patel, A. Perloff, C. Savard, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, USA

J. Alexander, S. Bright-thonney, Y. Cheng, D.J. Cranshaw, S. Hogan, J. Monroy, J.R. Patterson, D. Quach, J. Reichert, M. Reid, A. Ryd, W. Sun, J. Thom, P. Wittich, R. Zou

Fermi National Accelerator Laboratory, Batavia, USA

M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, 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, M. Cremonesi, K.F. Di Petrillo, V.D. Elvira, Y. Feng, J. Freeman, Z. Gecse, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, R. Heller, T.C. Herwig, J. Hirschauer, 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, V. O'Dell, V. Papadimitriou, K. Pedro, C. Pena⁵⁶, O. Prokofyev, F. Ravera, A. Reinsvold Hall, L. Ristori, B. Schneider, E. Sexton-Kennedy, N. Smith, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, H.A. Weber

University of Florida, Gainesville, USA

D. Acosta, P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, F. Errico, R.D. Field, D. Guerrero, B.M. Joshi, M. Kim, E. Koenig, J. Konigsberg, A. Korytov, K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, A. Muthirakalayil Madhu, N. Rawal, D. Rosenzweig, S. Rosenzweig, K. Shi, J. Sturdy, J. Wang, E. Yigitbasi, X. Zuo

Florida State University, Tallahassee, USA

T. Adams, A. Askew, R. Habibullah, V. Hagopian, K.F. Johnson, R. Khurana, T. Kolberg, G. Martinez, H. Prosper, C. Schiber, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, USA

M.M. Baarmand, S. Butalla, T. Elkafrawy⁸⁸, M. Hohlmann, R. Kumar Verma, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

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

M.R. Adams, H. Becerril Gonzalez, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, A.H. Merrit, C. Mills, G. Oh, T. Roy, S. Rudrabhatla, M.B. Tonjes, N. Varelas, J. Viinikainen, X. Wang, Z. Wu, Z. Ye

The University of Iowa, Iowa City, USA

M. Alhusseini, K. Dilsiz⁸⁹, R.P. Gandrajula, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili⁹⁰, J. Nachtman, H. Ogul⁹¹, Y. Onel, A. Penzo, C. Snyder, E. Tiras⁹²

Johns Hopkins University, Baltimore, USA

O. Amram, B. Blumenfeld, L. Corcodilos, J. Davis, M. Eminizer, A.V. Gritsan, S. Kyriacou, P. Maksimovic, J. Roskes, M. Swartz, T.Á. Vámi

The University of Kansas, Lawrence, USA

A. Abreu, J. Anguiano, C. Baldenegro Barrera, P. Baringer, A. Bean, A. Bylinkin, Z. Flowers, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, M. Lazarovits, C. Lindsey, J. Marquez, N. Minafra, M. Murray, M. Nickel, C. Rogan, C. Royon, R. Salvatico, S. Sanders, E. Schmitz, C. Smith, J.D. Tapia Takaki, Q. Wang, Z. Warner, J. Williams, G. Wilson

Kansas State University, Manhattan, USA

S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, T. Mitchell, A. Modak, K. Nam

Lawrence Livermore National Laboratory, Livermore, USA

F. Rebassoo, D. Wright

University of Maryland, College Park, USA

E. Adams, A. Baden, O. Baron, A. Belloni, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, A.C. Mignerey, S. Nabili, M. Seidel, A. Skuja, L. Wang, K. Wong

Massachusetts Institute of Technology, Cambridge, USA

D. Abercrombie, G. Andreassi, R. Bi, S. Brandt, W. Busza, I.A. Cali, Y. Chen, M. D'Alfonso, J. Eysermans, G. Gomez Ceballos, M. Goncharov, P. Harris, M. Hu, M. Klute, D. Kovalskyi, J. Krupa, Y.-J. Lee, B. Maier, C. Mironov, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, K. Tatar, J. Wang, Z. Wang, B. Wyslouch

University of Minnesota, Minneapolis, USA

R.M. Chatterjee, A. Evans, P. Hansen, J. Hiltbrand, Sh. Jain, M. Krohn, Y. Kubota, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

University of Nebraska-Lincoln, Lincoln, USA

K. Bloom, M. Bryson, S. Chauhan, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, J.R. González Fernández, C. Joo, I. Kravchenko, M. Musich, I. Reed, J.E. Siado, G.R. Snow[†], W. Tabb, F. Yan

State University of New York at Buffalo, Buffalo, USA

G. Agarwal, H. Bandyopadhyay, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, J. Pekkanen, S. Rappoccio, A. Williams

Northeastern University, Boston, USA

G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, J. Li, G. Madigan, B. Marzocchi, D.M. Morse, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, USA

S. Bhattacharya, J. Bueghly, Z. Chen, A. Gilbert, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, M. Velasco

University of Notre Dame, Notre Dame, USA

R. Band, R. Bucci, A. Das, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, K. Lannon, J. Lawrence, N. Loukas, N. Marinelli, I. Mcalister, T. McCauley, F. Meng, K. Mohrman, Y. Musienko⁴⁸, R. Ruchti, P. Siddireddy, M. Wayne, A. Wightman, M. Wolf, M. Zarucki, L. Zygala

The Ohio State University, Columbus, USA

B. Bylsma, B. Cardwell, L.S. Durkin, B. Francis, C. Hill, M. Nunez Ornelas, K. Wei, B.L. Winer, B.R. Yates

Princeton University, Princeton, USA

F.M. Addesa, B. Bonham, P. Das, G. Dezoort, P. Elmer, A. Frankenthal, B. Greenberg, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, G. Kopp, S. Kwan, D. Lange, M.T. Lucchini, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, USA

S. Malik, S. Norberg

Purdue University, West Lafayette, USA

A.S. Bakshi, V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, S. Karmarkar, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, C.C. Peng, S. Piperov, A. Purohit, J.F. Schulte, M. Stojanovic¹⁶, J. Thieman, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, USA

J. Dolen, N. Parashar

Rice University, Houston, USA

A. Baty, M. Decaro, S. Dildick, K.M. Ecklund, S. Freed, P. Gardner, F.J.M. Geurts, A. Kumar, W. Li, B.P. Padley, R. Redjimi, W. Shi, A.G. Stahl Leitton, S. Yang, L. Zhang, Y. Zhang

University of Rochester, Rochester, USA

A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, E. Ranken, R. Taus

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

B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, O. Karacheban²³, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, H. Wang

University of Tennessee, Knoxville, USA

H. Acharya, A.G. Delannoy, S. Spanier

Texas A&M University, College Station, USA

O. Bouhali⁹³, M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁹⁴, H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, USA

N. Akchurin, J. Damgov, V. Hegde, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, I. Volobouev, Z. Wang, A. Whitbeck

Vanderbilt University, Nashville, USA

E. Appelt, S. Greene, A. Gurrola, W. Johns, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska

University of Virginia, Charlottesville, USA

M.W. Arenton, B. Cox, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, A. Li, C. Neu, B. Tannenwald, S. White, E. Wolfe

Wayne State University, Detroit, USA

N. Poudyal

University of Wisconsin - Madison, Madison, WI, USA

K. Black, T. Bose, J. Buchanan, C. Caillol, S. Dasu, I. De Bruyn, P. Everaerts, F. Fienga, C. Galloni, H. He, M. Herndon, A. Hervé, U. Hussain, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, A. Mohammadi, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, S. Trembath-reichert, W. Vetens

†: Deceased

- 1: Also at Vienna University of Technology, Vienna, Austria
- 2: Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt, Alexandria, Egypt
- 3: Also at Université Libre de Bruxelles, Bruxelles, Belgium
- 4: Also at Universidade Estadual de Campinas, Campinas, Brazil
- 5: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
- 6: Also at University of Chinese Academy of Sciences, Beijing, China
- 7: Also at Department of Physics, Tsinghua University, Beijing, China, Beijing, China
- 8: Also at UFMS, Nova Andradina, Brazil
- 9: Also at Nanjing Normal University Department of Physics, Nanjing, China
- 10: Now at The University of Iowa, Iowa City, USA
- 11: Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia
- 12: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 13: Also at Cairo University, Cairo, Egypt
- 14: Also at Helwan University, Cairo, Egypt
- 15: Now at Zewail City of Science and Technology, Zewail, Egypt
- 16: Also at Purdue University, West Lafayette, USA
- 17: Also at Université de Haute Alsace, Mulhouse, France
- 18: Also at Erzincan Binali Yildirim University, Erzincan, Turkey
- 19: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 20: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- 21: Also at University of Hamburg, Hamburg, Germany
- 22: Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran, Isfahan, Iran
- 23: Also at Brandenburg University of Technology, Cottbus, Germany
- 24: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- 25: Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- 26: Also at Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary
- 27: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary, Debrecen, Hungary
- 28: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 29: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary, Budapest, Hungary
- 30: Also at Wigner Research Centre for Physics, Budapest, Hungary
- 31: Also at IIT Bhubaneswar, Bhubaneswar, India, Bhubaneswar, India
- 32: Also at Institute of Physics, Bhubaneswar, India
- 33: Also at G.H.G. Khalsa College, Punjab, India
- 34: Also at Shoolini University, Solan, India
- 35: Also at University of Hyderabad, Hyderabad, India
- 36: Also at University of Visva-Bharati, Santiniketan, India
- 37: Also at Indian Institute of Technology (IIT), Mumbai, India
- 38: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- 39: Also at Sharif University of Technology, Tehran, Iran
- 40: Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- 41: Now at INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy

-
- 42: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- 43: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- 44: Also at Università di Napoli 'Federico II', NAPOLI, Italy
- 45: Also at Riga Technical University, Riga, Latvia, Riga, Latvia
- 46: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- 47: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- 48: Also at Institute for Nuclear Research, Moscow, Russia
- 49: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- 50: Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
- 51: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 52: Also at University of Florida, Gainesville, USA
- 53: Also at Imperial College, London, United Kingdom
- 54: Also at Moscow Institute of Physics and Technology, Moscow, Russia, Moscow, Russia
- 55: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 56: Also at California Institute of Technology, Pasadena, USA
- 57: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- 58: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 59: Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- 60: Also at INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy, Pavia, Italy
- 61: Also at National and Kapodistrian University of Athens, Athens, Greece
- 62: Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- 63: Also at Universität Zürich, Zurich, Switzerland
- 64: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria, Vienna, Austria
- 65: Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- 66: Also at Şırnak University, Sirnak, Turkey
- 67: Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey
- 68: Also at Konya Technical University, Konya, Turkey
- 69: Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
- 70: Also at Piri Reis University, Istanbul, Turkey
- 71: Also at Adiyaman University, Adiyaman, Turkey
- 72: Also at Ozyegin University, Istanbul, Turkey
- 73: Also at Izmir Institute of Technology, Izmir, Turkey
- 74: Also at Necmettin Erbakan University, Konya, Turkey
- 75: Also at Bozok Universititesi Rektörlüğü, Yozgat, Turkey, Yozgat, Turkey
- 76: Also at Marmara University, Istanbul, Turkey
- 77: Also at Milli Savunma University, Istanbul, Turkey
- 78: Also at Kafkas University, Kars, Turkey
- 79: Also at Istanbul Bilgi University, Istanbul, Turkey
- 80: Also at Hacettepe University, Ankara, Turkey
- 81: Also at Vrije Universiteit Brussel, Brussel, Belgium
- 82: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 83: Also at IPPP Durham University, Durham, United Kingdom
- 84: Also at Monash University, Faculty of Science, Clayton, Australia

- 85: Also at Università di Torino, TORINO, Italy
- 86: Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA
- 87: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- 88: Also at Ain Shams University, Cairo, Egypt
- 89: Also at Bingol University, Bingol, Turkey
- 90: Also at Georgian Technical University, Tbilisi, Georgia
- 91: Also at Sinop University, Sinop, Turkey
- 92: Also at Erciyes University, KAYSERI, Turkey
- 93: Also at Texas A&M University at Qatar, Doha, Qatar
- 94: Also at Kyungpook National University, Daegu, Korea, Daegu, Korea