



CMS-HIG-18-012

Search for new neutral Higgs bosons through the $H \rightarrow ZA \rightarrow \ell^+ \ell^- b \bar{b}$ process in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

This paper reports on a search for an extended scalar sector of the standard model, where a new CP-even (odd) boson decays to a Z boson and a lighter CP-odd (even) boson, and the latter further decays to a b quark pair. The Z boson is reconstructed via its decays to electron or muon pairs. The analysed data were recorded in proton-proton collisions at a center-of-mass energy $\sqrt{s} = 13$ TeV, collected by the CMS experiment at the LHC during 2016, corresponding to an integrated luminosity of 35.9 fb^{-1} . Data and predictions from the standard model are in agreement within the uncertainties. Upper limits at 95% confidence level are set on the production cross section times branching fraction, with masses of the new bosons up to 1000 GeV. The results are interpreted in the context of the two-Higgs-doublet model.

Submitted to the Journal of High Energy Physics

1 Introduction

The CMS and ATLAS experimental programmes are focusing efforts on the measurement of the properties of the Higgs boson discovered in 2012 [1–3], which has a mass of about 125 GeV [4–6]. All measurements to date are consistent with the expectations for a standard model (SM) Higgs boson within the experimental uncertainties.

Additional Higgs bosons are predicted in several extensions of the SM. Examples of these extensions are the two-Higgs-doublet model (2HDM) [7], whose phenomenology is based on the presence of an additional scalar Higgs doublet, and the minimal supersymmetric extension of the SM (MSSM) [8], which is a particular realisation of the 2HDM. The two Higgs doublets entail the presence of five physical states: two neutral and CP-even bosons (h and H); a neutral and CP-odd boson (A); and two charged scalar bosons (H^\pm). Under particular theoretical assumptions, the model is often described by the following parameters: the mass of the CP-even boson H, m_H ; the mass of the pseudoscalar A, m_A ; the ratio of the vacuum expectation values of the two doublets, $\tan \beta$; the mixing angle α between the two CP-even bosons; and the soft-breaking term m_{12}^2 .

Different couplings of the two doublets to right-handed quarks and charged leptons are predicted in various formulations of the 2HDM: in the Type-I formulation, all fermions couple to only one Higgs doublet; in the Type-II formulation, the up-type quarks couple to a different doublet than the down-type quarks and leptons; in the “lepton-specific” formulation, the quarks couple to one of the Higgs doublets and the leptons couple to the other; and in the “flipped” formulation, the up-type quarks and leptons couple to one of the Higgs doublets, while the down-type quarks couple to the other.

Different models and assumptions also alter the mass hierarchies, as shown in Fig. 1. There, and in the rest of the paper, h is identified with the observed Higgs boson. Two scenarios are possible. In the conventional scenario, the pseudoscalar is degenerate in mass with the charged scalars and is heavier than the scalar H, thus allowing for the $A \rightarrow ZH$ process. While in the twisted [9] scenario, the scalar H is degenerate in mass with the charged scalars and is heavier than the pseudoscalar, thus allowing for the $H \rightarrow ZA$ process. Moreover, in the parameter space region where $\cos(\beta - \alpha)$ approaches 0, the CP-even h has properties indistinguishable from a SM Higgs boson with the same mass. In this region, known as the alignment limit, the branching fraction of the heavy scalar H to a Z boson and a lighter pseudoscalar A is the largest. The branching fractions for several decay channels of the H and A bosons for $m_H = 300$ GeV and $m_A = 200$ GeV are shown in Fig. 2 as a function of $\cos(\beta - \alpha)$ (left) and $\tan \beta$ (right).

This paper reports on a search for a new CP-even (odd) neutral Higgs boson decaying into Z and a lighter CP-odd (even) neutral Higgs boson, where the Z decays into an opposite-sign electron or muon pair, and the light Higgs boson into a b quark pair. The analysis is performed under the assumption of the twisted mass hierarchy scenario, and subsequently extended to the conventional scenario by interchanging the masses of the two bosons. The search is based on LHC proton-proton (pp) collision data at a center-of-mass energy $\sqrt{s} = 13$ TeV collected by the CMS experiment during 2016, corresponding to an integrated luminosity of 35.9 fb^{-1} . The analysis exploits the invariant mass distributions of the $\ell\ell b\bar{b}$, with ℓ electron or muon, and $b\bar{b}$ systems to search for a resonant-like excess of events compatible with the H and A masses.

Searches for $H \rightarrow ZA$ production in the same final state have been performed at 13 TeV [10] by the ATLAS Collaboration and at 8 TeV [11] by the CMS Collaboration. The search for $A \rightarrow Zh$, where h is the observed CP-even boson with mass of about 125 GeV, has been also performed by the ATLAS Collaboration at 8 TeV [12] and by the CMS Collaboration at 8 TeV [13] and

13 TeV [14].

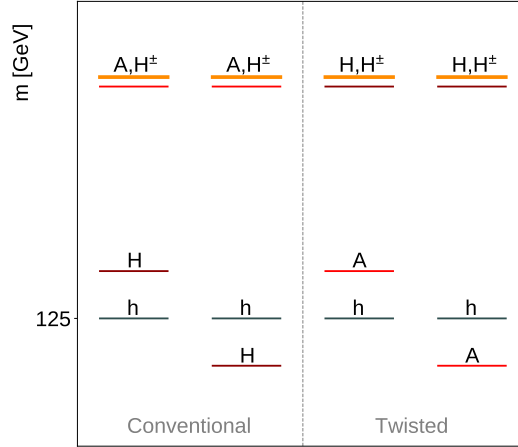


Figure 1: Possible 2HDM mass hierarchies: conventional, where A is degenerate in mass with the charged scalars; and twisted [9], where H is degenerate in mass with the charged scalars. In both scenarios, the lighter boson between A and H can be either heavier or lighter than the observed Higgs boson $h(125)$.

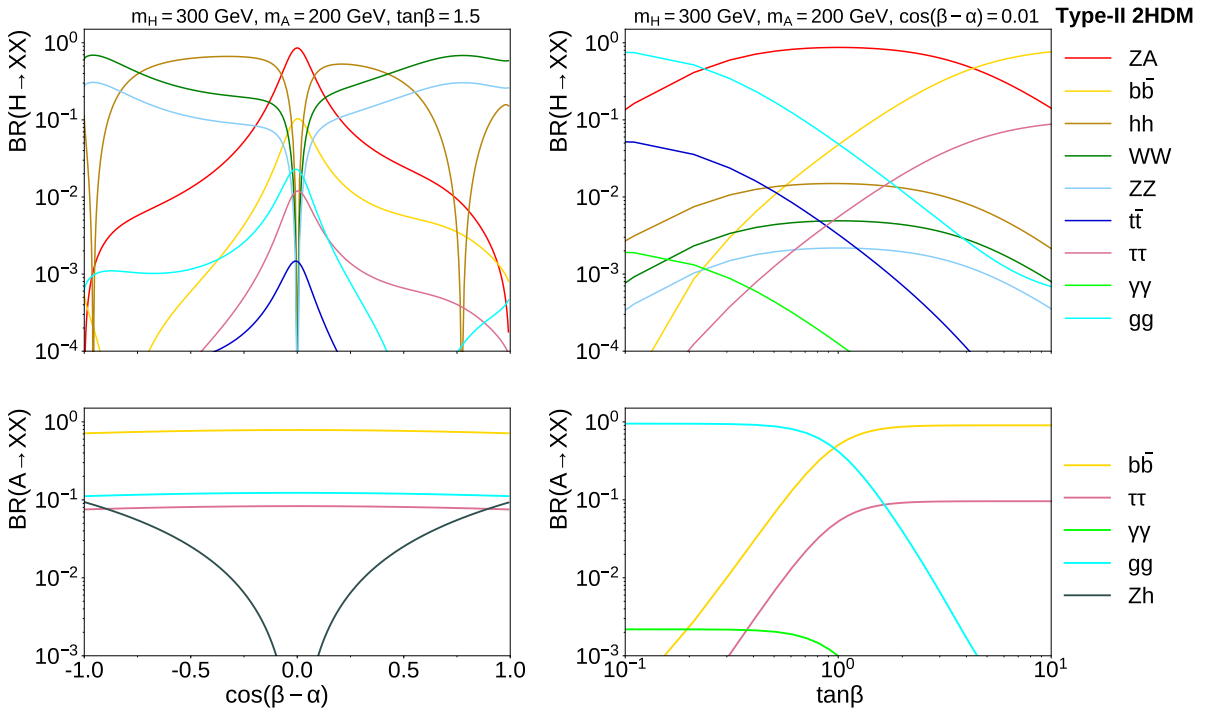


Figure 2: The H and A branching fractions as a function of $\cos(\beta - \alpha)$ in Type-II 2HDM for the following set of parameters: $\tan \beta = 1.5$, $m_H = 300$ GeV, $m_A = 200$ GeV (left). The H and A branching fractions as a function of $\tan \beta$ in Type-II 2HDM for the following set of parameters: $\cos(\beta - \alpha) = 0.01$, $m_H = 300$ GeV and $m_A = 200$ GeV (right).

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 pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionisation chambers embedded in the steel flux-return yoke outside the solenoid. A two-level trigger system [15] is used to reduce the rate of recorded events to a level suitable for data acquisition and storage. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [16].

3 Event simulation and background predictions

Background samples for this search are produced for Z boson production through the Drell-Yan (DY) process, top quark pair production ($t\bar{t}$), single top quark, diboson, triboson, $t\bar{t}V$ ($V = W, Z$), W +jets, and SM Higgs boson production. They are generated at next-to-leading order (NLO) precision in perturbative quantum chromodynamics (QCD). In particular, the DY, $t\bar{t}V$, W +jets, triboson, and part of the diboson background samples are produced with MADGRAPH5_aMC@NLO versions 2.2.2 [17] with the FxFx [18] procedure for NLO jet merging and MADSPIN [19] to properly propagate spin information in the matrix element of the process. The $t\bar{t}$, single top quark, SM Higgs boson production, and the remaining diboson background samples are produced with POWHEG version 2 [20–24].

Signal samples of 207 different mass hypotheses are produced for the process $H \rightarrow ZA \rightarrow \ell\ell b\bar{b}$, with m_H and m_A ranging from 120 to 1000 GeV and from 30 to 1000 GeV, respectively. The choice of the mass hypotheses is strongly motivated by the need of achieving a complete coverage of the parameter space. The spacing between two adjacent mass hypotheses is chosen so as to take into account the worsening of the signal resolution as the mass increases, such that the signal shape can be interpolated with good accuracy over the whole search region. These samples are produced using MADGRAPH5_aMC@NLO version 2.3.2 [17] interfaced with PYTHIA 8.212 [25] for parton shower and hadronisation. The parton distribution function (PDF) set used is NNPDF 3.0 [26] at leading order (LO) in the four-flavour scheme, and the factorisation and renormalisation scales are estimated dynamically. The underlying event tune is CUEPT8M1 [27], derived from the MONASH tune [28].

For all processes, the detector response is simulated using a detailed description of the CMS apparatus, based on the GEANT4 package [29]. Additional pp interactions in the same and/or neighbouring bunch crossings (pileup) are generated with PYTHIA 8.212 [25], and overlapped with the simulated events of interest in order to reproduce the pileup measured in data.

All background processes are normalised to their most accurate theoretical cross sections. The $t\bar{t}$, DY, single top quark, W^+W^- , and W +jets samples are normalised to next-to-next-to-leading order (NNLO) precision in QCD [30–33], while the remaining diboson, triboson and $t\bar{t}V$ processes are normalised to NLO precision in QCD [17, 34]. The SM Higgs boson production cross section is computed at NNLO QCD precision and NLO electroweak precision [35]. We indicate the SM Higgs boson, the $t\bar{t}V$, and the W +jets backgrounds with *Other* in the figures.

4 Event reconstruction and selection

Events considered for this search are selected by a trigger based on the dilepton signature. The leading and subleading transverse momentum (p_T) thresholds applied by the triggers are channel dependent, and vary from 17 to 23 GeV (8 to 12 GeV) for the leading (subleading) lepton.

Trigger efficiencies are measured with a “tag-and-probe” method [36] as a function of lepton p_T and η in a data control region consisting of $Z \rightarrow \ell\ell$ events. Events with two oppositely charged leptons ($e^\pm e^\mp$, $\mu^\pm \mu^\mp$) are selected using asymmetric p_T requirements, chosen to be above the corresponding trigger thresholds, for the leading and subleading leptons. These requirements are 25 and 15 GeV, respectively, for $e^\pm e^\mp$ events; and 20 and 10 GeV, respectively, for $\mu^\pm \mu^\mp$ events. Electrons in the range $|\eta| < 2.5$ and muons in the range $|\eta| < 2.4$ are considered. Events with different-flavour leptons ($e^\pm \mu^\mp$) are also selected. The p_T requirement for the leading lepton is 25 and 15 (10) GeV for the subleading electron (muon). These events mostly arise from $t\bar{t}$ production, and this region is used in the final template fit described in Section 7 to obtain an estimate of the normalisation of the non-resonant background processes ($t\bar{t}$, single top quark, diboson, and triboson) and of the shape of the $t\bar{t}$ process only. For simplicity, we will refer to events with two electrons, muons, and mixed-flavour leptons as ee , $\mu\mu$, and $e\mu$, respectively, throughout this paper.

A particle-flow (PF) algorithm [37] aims at reconstructing all particles (PF candidates) in an event by combining information from all subdetectors. The PF candidates include photons, electrons, muons, neutral hadrons, and charged hadrons. The candidate vertex with the largest value of summed physics-object p_T^2 is taken to be the primary pp interaction vertex. The physics objects are the jets, clustered using the jet finding algorithm [38, 39] 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. Electrons, reconstructed by associating tracks with ECAL clusters, are identified by a sequential selection using information on the cluster shape in the ECAL, track quality, and the matching between the track and the ECAL cluster. Additionally, electrons from photon conversions are rejected [40]. Muons are reconstructed from tracks found in the muon system, associated with tracks in the silicon tracking detectors. They are identified based on the quality of the track fit and the number of associated hits in the various tracking detectors [41]. The lepton isolation, defined as the scalar p_T sum of all PF candidates in a cone of radius $\Delta R = 0.4$ around the lepton, excluding the lepton itself and corrected for contributions from particles not coming from the primary vertex, divided by the lepton p_T , is required to be < 0.06 for electrons and < 0.15 for muons. Here, ΔR is defined in terms of the track separation in η and azimuthal angle (ϕ , in radians) as $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$. Moreover, the lepton tracks are required to be connected to the primary vertex. Lepton identification and isolation efficiencies in the simulation are corrected for residual differences with respect to data. These corrections are measured in a data sample enriched in $Z \rightarrow \ell\ell$ events, using the “tag-and-probe” method, and are parameterised as a function of lepton p_T and η .

Jet reconstruction is performed by clustering the PF candidates to form jets using the anti- k_T clustering algorithm [38] with a distance parameter of 0.4, implemented in the FASTJET package [39]. Jet energies are corrected for residual nonuniformity and nonlinearity of the detector response [42]. Jets are required to have $p_T > 20$ GeV, $|\eta| < 2.4$, and be separated from identified leptons by a distance $\Delta R > 0.3$. The missing transverse momentum vector, defined as the projection onto the transverse plane relative to the beam axis, of the negative vector sum of the momenta of all PF candidates, is referred to as \vec{p}_T^{miss} [43, 44]. Its magnitude is denoted by p_T^{miss} . Corrections to the jet energies are propagated to \vec{p}_T^{miss} .

The DeepCSV algorithm [45] is used to identify jets originating from b quarks. Jets are considered as b tagged if they have $p_T > 20$ GeV and they pass the medium working point of the algorithm, which provides around 70% efficiency with a mistag rate of less than 1%, while the mistag rate for c jets is around 10%. Correction factors are applied in the simulation to the selected jets to account for the different response of the DeepCSV algorithm between data and simulation [45]. Among all possible dijet combinations fulfilling the previous criteria, we select

the two jets with the highest DeepCSV algorithm outputs.

The final object selection consists of two opposite-sign leptons and two b-tagged jets, after which a requirement of $70 < m_{\ell\ell} < 110$ GeV is applied to enhance the presence of $Z \rightarrow \ell\ell$ events. In addition, the events are required to have a $p_T^{\text{miss}} < 80$ GeV in order to reduce the background contributions from processes with large p_T^{miss} , such as $t\bar{t}$ production. Both requirements have negligible impacts on the signal efficiency.

The main background processes, in decreasing order of importance, are DY in association with b quarks and $t\bar{t}$ production where both top quarks decay leptonically (fully leptonic $t\bar{t}$). The contribution from QCD multijet events with jets misidentified as leptons constitutes a negligible background after requiring a pair of well-identified leptons, as described in Section 4.

5 Signal extraction

We search for the process $H \rightarrow ZA \rightarrow \ell\ell b\bar{b}$ by fully reconstructing its final-state objects and applying selection requirements in order to remove as many background events as possible, as explained in Section 4. From the reconstructed objects, we search for resonances in the invariant masses. Specifically, the invariant mass of the A can be reconstructed from the b jet pair; and that of the H from the b jet pair and the lepton pair. Two categories are defined based on the lepton flavours considered: ee and $\mu\mu$. The Z mass, reconstructed from two opposite-sign leptons, is used in the selection criteria described in Section 4 since it is common to all signals studied in this paper. The masses of the other two particles, H and A, vary according to the signal scenarios considered. Therefore, a simple and effective model independent approach to isolate the signal is to search for an excess of events in the reconstructed m_{jj} and $m_{\ell\ell jj}$ distributions centered around the H and A candidate mass for each signal hypothesis. These distributions for $\mu\mu + ee$ events are shown in Fig. 3, where the background shapes and normalisations are obtained from simulation.

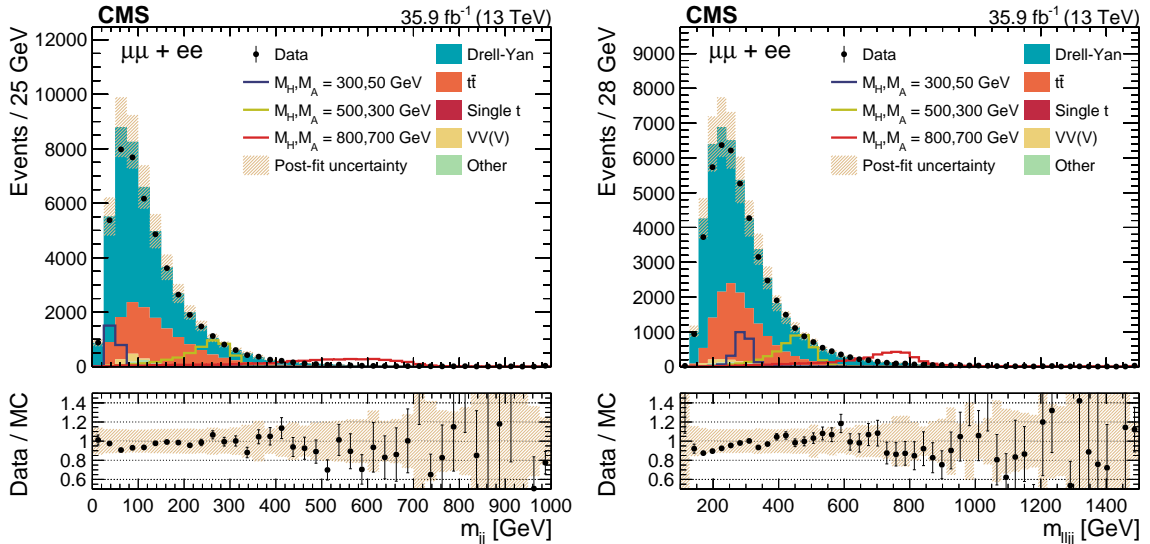


Figure 3: The m_{jj} (left) and $m_{\ell\ell jj}$ (right) distributions in data and background events after requiring all the analysis selections, for $\mu\mu + ee$ events. The background shapes and normalisations are obtained from simulation. The various signal hypotheses displayed have been scaled to a cross section of 1 pb for illustrative purposes. Error bars indicate statistical uncertainties, while shaded bands show systematic uncertainties prior to the fit (introduced in Section 6).

Since the m_{jj} and $m_{\ell\ell jj}$ distributions are inherently positively correlated under a particular signal hypothesis, an elliptical signal region is chosen in order to optimize the sensitivity of the search. Figure 4 (left) shows the reconstructed mass distributions for three different signals in the $m_{\ell\ell jj}$ vs. m_{jj} plane along with their defined elliptical signal regions. Because the shape of the signal is driven by the energy resolution of the final-state objects, ellipses take different sizes and tilt angles, depending on the masses being considered. A parametrisation is therefore performed in order to guarantee a good description of the signal shape for each signal hypothesis. For each ellipse, it provides the center, the major and minor semi-axes, and the tilt angle. Since each ellipse must be well-centered around the maximum of the two-dimensional (2D) mass distribution, the reconstructed center is extracted from a one-dimensional Gaussian fit in both m_{jj} and $m_{\ell\ell jj}$. The diagonalisation of the covariance matrix of the 2D distribution provides the axes of the ellipse and its tilt angle.

Since the shape of the signal is not exactly Gaussian, concentric elliptically shaped regions are defined in the parameter space using a parameter called ρ . Specifically, an ellipse with $\rho = i$ contains roughly i standard deviation of the signal events. Selected events in the $m_{\ell\ell jj}$ vs. m_{jj} plane are classified in six regions around the center of the ellipse defined for each signal point. The regions are built in ρ steps of 0.5, from 0 to 3, as illustrated in Fig. 4 (right), and lead to a template containing six bins used to perform the statistical analysis. By construction, the bulk of the signal is located at small values of ρ . The yield in data and the expected yields in simulation are reported in Table 1 for each elliptical bin under the mass hypothesis $m_H = 500$ GeV and $m_A = 200$ GeV. The ee and $\mu\mu$ categories are summed.

Table 1: Expected and observed event yields prior to the fit in the signal region with $m_H = 500$ GeV and $m_A = 200$ GeV for each elliptical bin. The signal is normalised to its theoretical cross section for the Type-II 2HDM benchmark $\tan\beta = 1.5$ and $\cos(\beta - \alpha) = 0.01$. The ee and $\mu\mu$ categories are summed.

Process	Yield					
	$0 \leq \rho < 0.5$	$0.5 \leq \rho < 1$	$1 \leq \rho < 1.5$	$1.5 \leq \rho < 2$	$2 \leq \rho < 2.5$	$2.5 \leq \rho < 3$
DY	181 ± 14	438 ± 22	607 ± 27	987 ± 34	1440 ± 42	2273 ± 53
$t\bar{t}$	166 ± 2	420 ± 4	603 ± 5	826 ± 5	1165 ± 6	1597 ± 8
Single top quark	2.2 ± 0.5	6.2 ± 0.8	9 ± 1	17 ± 1	25.5 ± 1.7	38 ± 2
VV(V)	0.6 ± 0.1	1.9 ± 0.2	2.5 ± 0.2	3.9 ± 0.5	5.2 ± 0.4	9.1 ± 0.4
Other	0.9 ± 0.2	3.7 ± 0.3	5.1 ± 0.3	8.4 ± 0.4	11.7 ± 0.5	18.1 ± 0.6
Total bkg.	351 ± 14	870 ± 22	1227 ± 27	1842 ± 34	2647 ± 42	3935 ± 54
Data	365	854	1231	1834	2608	3906
Signal	71.5 ± 1.3	122.7 ± 1.7	86.1 ± 1.4	48 ± 1	26.6 ± 0.8	17.5 ± 0.6

6 Systematic uncertainties

We consider different sources of systematic uncertainties that may affect the statistical interpretation of the results, through their modification of both the normalisation and the shape of the distributions for the signal and background processes.

Theoretical uncertainties in the cross sections of the background processes estimated using simulation are considered as systematic uncertainties in the yield predictions. The uncertainty in the total integrated luminosity is determined to be 2.5% [46].

The signal region contains events that have at least two b-tagged jets. One can build a control region by requiring events to pass the selection, as described in Section 4, but with no b tag requirement for the jets. In that region, a discrepancy between data and simulation of up to 10% is observed in the shape of the mass distributions, which hints for a mismodeling of the

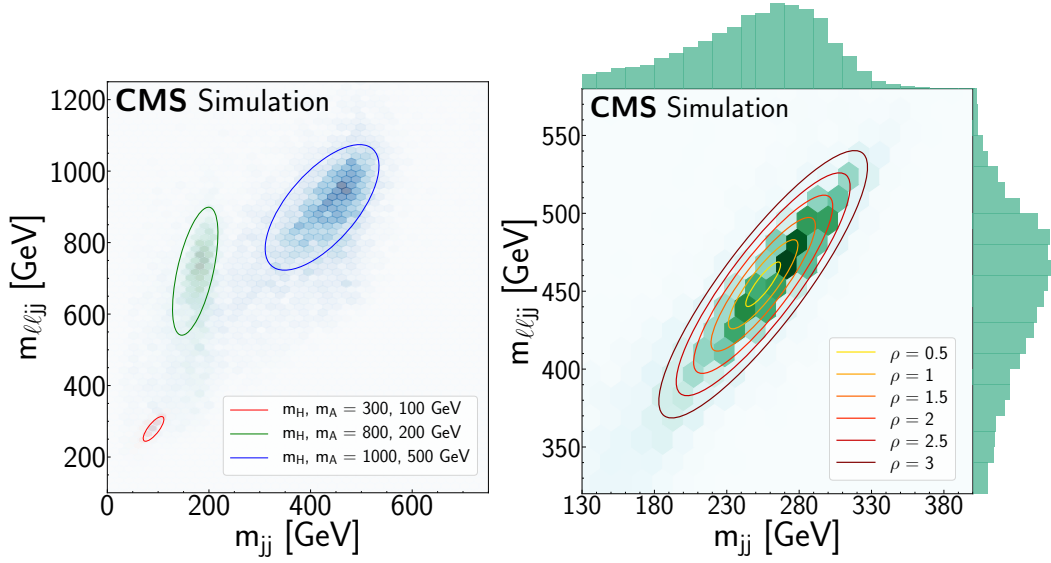


Figure 4: The $m_{\ell\ell jj}$ vs. m_{jj} plane for signal samples under three different mass hypotheses, on which the parametrised ellipses are shown (left). A signal hypothesis with $m_H = 500$ GeV and $m_A = 300$ GeV is shown in the $m_{\ell\ell jj}$ vs. m_{jj} plane (right). The different ellipses show the variation of the ρ parameter in steps of 0.5, from 0 to 3. The intensity of the color in each hexagonal bin is proportional to the number of events in it.

DY + heavy-flavour jets background in some specific regions of the reconstructed mass plane. To account for this mismodeling, the observed data-MC discrepancy is fitted with a polynomial function, which is used to reweight each DY + heavy-flavour jets simulated event in the signal region, and a shape uncertainty equal to 100% of the correction is applied. In order to avoid assigning only one shape uncertainty to regions characterised by very different values of the above-mentioned correction, this uncertainty is considered independently in 42 regions of approximately $150 \times 150 \text{ GeV}^2$ in the $m_{\ell\ell jj}$ vs. m_{jj} plane. This procedure ensures enough degrees of freedom in the maximum likelihood fit (used to extract the best fit signal cross section, as explained in Section 7) to properly account for the mismodeling of the DY + heavy-flavour jets background shape.

The following sources of systematic uncertainties that affect the normalisation and shape of the templates used in the statistical evaluation are considered:

- *Trigger efficiency, lepton identification and isolation:* uncertainties in the measurement of trigger efficiencies, as well as electron and muon isolation and identification efficiencies, are considered. These are evaluated as a function of lepton p_T and η , and their effect on the analysis is estimated by varying the corrections to the efficiencies by ± 1 standard deviation.
- *Jet energy scale and resolution:* uncertainties in the jet energy scale are of the order of a few percent and are estimated as a function of jet p_T and η [42]. A difference in the jet energy resolution of about 10% between data and simulation is accounted for by worsening the jet energy resolution in simulation by η -dependent factors. The uncertainty due to these corrections is estimated by a variation of the factors applied by ± 1 standard deviation. Variations of jet energies are propagated to \vec{p}_T^{miss} .
- *b tagging:* b tagging efficiency and light-flavour mistag rate corrections and associated uncertainties are determined as a function of the jet p_T [45]. Their effect on the analysis is estimated by varying these corrections by ± 1 standard deviation.

- *Pileup*: the measured total inelastic cross section is varied by $\pm 4.6\%$ [47] to produce different expected pileup distributions.
- *Renormalisation and factorisation scale uncertainty*: this uncertainty is estimated by varying the renormalisation (μ_R) and the factorisation (μ_F) scales used during the generation of the simulated samples independently by factors of 0.5, 1, or 2. Cases where the two scales are at opposite extremes, are not considered. An envelope is built from the 6 possible combinations by keeping maximum and minimum variations for each bin of the distributions, and is used as an estimate of the scale uncertainties for all the background and signal samples.
- *PDF uncertainty*: the magnitudes of the uncertainties related to the PDFs and the variation of the strong coupling constant for each simulated background and signal process are obtained using variations of the NNPDF 3.0 set [26], following the PDF4LHC prescriptions [32].
- *Drell–Yan additional uncertainty*: additional shape uncertainties are applied to DY events to correct for mismodeling of this background as explained above. Their values range up to 10%, depending on the region of the reconstructed mass plane.
- *Simulated sample size*: the finite nature of simulated samples is considered as an additional source of systematic uncertainty. For each bin of the distributions, one additional uncertainty is added, where only the considered bin is altered by ± 1 standard deviation, keeping the others at their nominal value.

The variations that these uncertainties induce on the total event yields in the analysis selection are summarised in Table 2 for a specific signal hypothesis, where the ee and $\mu\mu$ categories are combined together, yielding, for some uncertainties, a range of variations.

7 Results

A binned maximum likelihood fit is performed in order to extract best fit signal cross sections. The fit is performed using the six binned templates mentioned above in the ee and $\mu\mu$ channels. An additional six-bin template is included in the fit containing the $e\mu$ selection to further constrain the $t\bar{t}$ process, which is the major background component in this region, together with the minor non-resonant background processes. The systematic uncertainties are introduced as nuisance parameters in the fit. For each systematic uncertainty affecting the shape (normalisation) of the templates, a nuisance parameter is constrained with a Gaussian (log-normal) prior.

The best fit values for all the nuisance parameters, as well as the corresponding uncertainties, are extracted by performing a binned maximum likelihood fit to the data. Only nuisance parameters affecting the backgrounds are considered.

Figure 5 shows final distributions of events after a background-only fit in bins of ρ under two different mass hypotheses for the $\mu\mu + ee$ and $e\mu$ categories with all the nuisance parameters set to their best fit values. The corresponding signals are also displayed and normalised to 1 pb for illustrative purposes.

No significant deviations from the SM expectations are observed. The highest asymptotic local significance observed corresponds to 3.9 standard deviations for the signal hypothesis with $m_H = 627 \text{ GeV}$ and $m_A = 162 \text{ GeV}$, which globally becomes 1.3 standard deviations once accounting for the look elsewhere effect [48], evaluated with the method described in [49]. The local p-value in the $m_{\ell\ell jj}$ vs. m_{jj} plane is displayed in Fig. 6.

Table 2: Summary of the systematic uncertainties prior to the fit and the variation, in percentages, that they induce on the total event yields for the dominant background and signal processes, under a particular signal hypothesis with $m_H = 379$ GeV and $m_A = 172$ GeV.

Source	Background yield variation	Signal yield variation
Electron identification and isolation	2.7%	2.6%
Integrated luminosity	2.5%	2.5%
Jet energy scale	2.1–2.4%	0.1–0.3%
b tagging (heavy-flavour jets)	2.3%	2.0%
PDFs	1.0%	0.5%
Pileup	0.3–0.9%	0.7–1.3%
b tagging (light-flavour jets)	0.7–0.8%	<0.1%
Muon identification and isolation	0.5%	0.4%
Trigger efficiency	0.1–0.3%	0.1–0.3%
Jet energy resolution	0.2%	0.2%
Affecting only $t\bar{t}$ (31.8% of the total bkg.)		
μ_R and μ_F scales	12.2–12.3%	
$t\bar{t}$ cross section	5.3%	
Affecting only Drell–Yan (64.5% of the total bkg.)		
μ_R and μ_F scales	9.6%	
Drell–Yan cross section	4.9%	
Drell–Yan additional uncertainty	2.1–2.2%	
Simulated sample size	0.5–1.3%	
Affecting only VV (1.1% of the total bkg.)		
μ_R and μ_F scales	4.3–4.8%	
Affecting only signal		
μ_R and μ_F scales		1.8%

Figure 7 shows model independent upper limits at 95% confidence level (CL), $\sigma_{95\%}$, on the product of the production cross section and branching fraction ($\sigma\mathcal{B}$) for $H(A) \rightarrow ZA(H) \rightarrow \ell\ell b\bar{b}$, evaluated using the CL_s criterion [50, 51] in the asymptotic approximation [52] as a function of the H and A and mass hypotheses. Model dependent exclusion regions at 95% CL in the m_H vs. m_A plane can be obtained by comparing $\sigma_{95\%}$ to the theoretical cross section predicted by a particular model. Figure 8 shows the expected and observed 95% CL exclusion regions for the Type-II 2HDM benchmark scenario $\tan\beta = 1.5$ and $\cos(\beta - \alpha) = 0.01$, while Fig. 9 shows the 95% CL exclusion region in the $\tan\beta$ vs. $\cos(\beta - \alpha)$ plane for $m_H = 379$ GeV and $m_A = 172$ GeV.

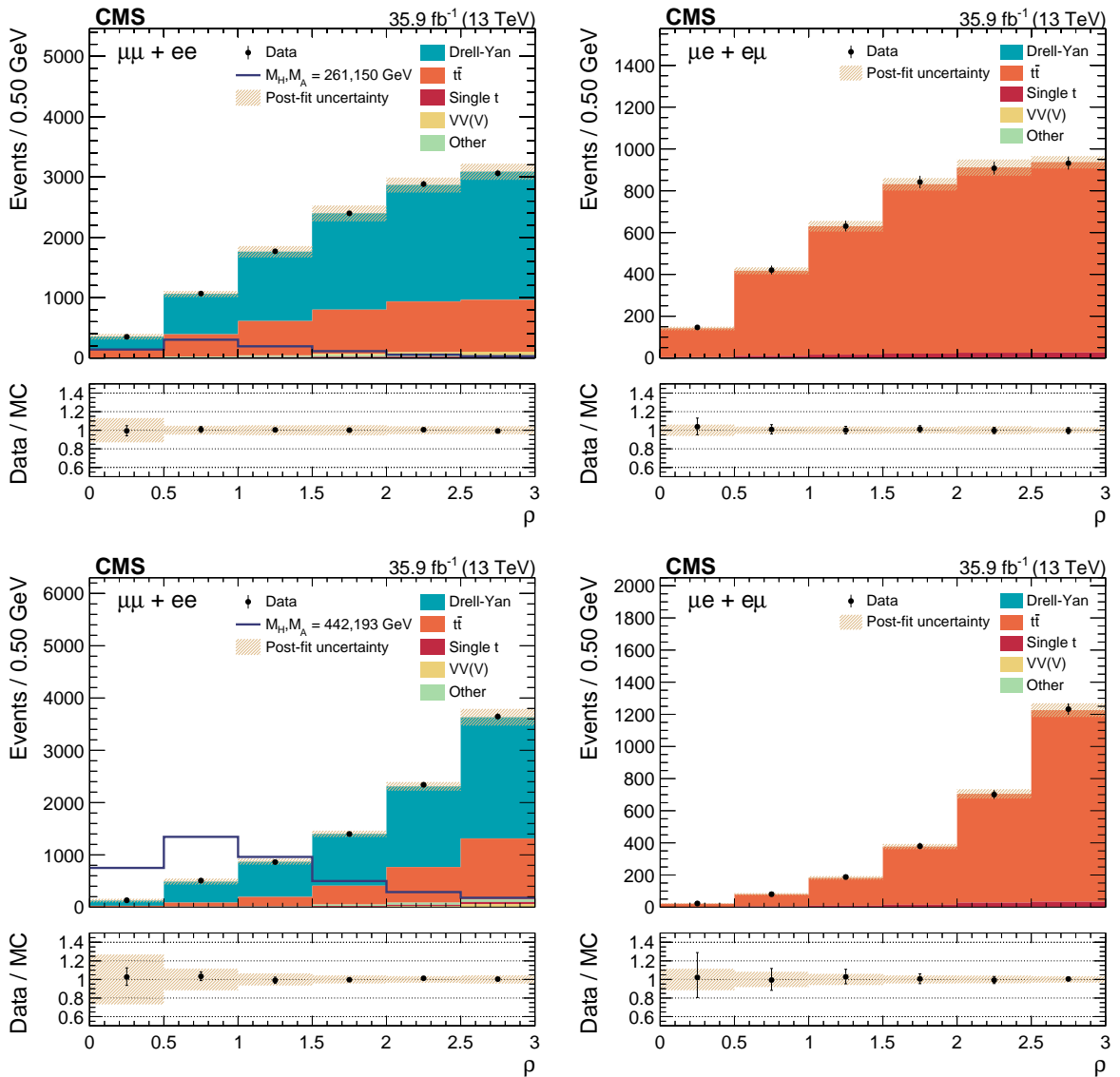


Figure 5: Post-fit ρ distributions from a background-only fit for the same-flavour lepton (left) and mixed-flavour lepton (right) events corresponding to a signal hypothesis with $m_H = 261$ GeV and $m_A = 150$ GeV (upper) and $m_H = 442$ GeV and $m_A = 193$ GeV (lower). The signal is normalised to 1 pb. Error bars indicate statistical uncertainties, while shaded bands show systematic uncertainties after the fit.

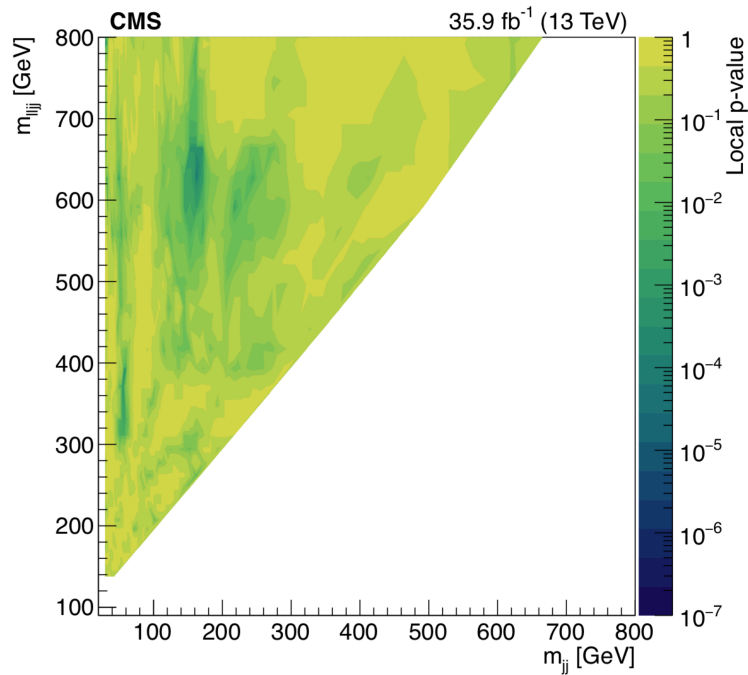


Figure 6: Distribution of the local p-value in the $m_{\ell\ell jj}$ vs. m_{jj} plane.

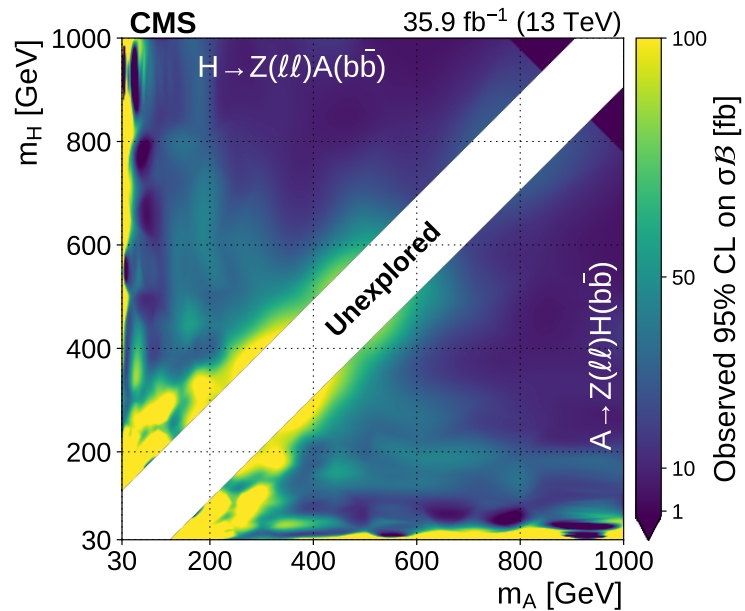


Figure 7: Observed 95% CL upper limits on the product of the production cross section and branching fraction $\sigma\mathcal{B}$ for $H(A) \rightarrow ZA(H) \rightarrow \ell\ell b\bar{b}$ as a function of m_A and m_H . The limits are computed using the asymptotic CL_s method, combining the ee and $\mu\mu$ channels.

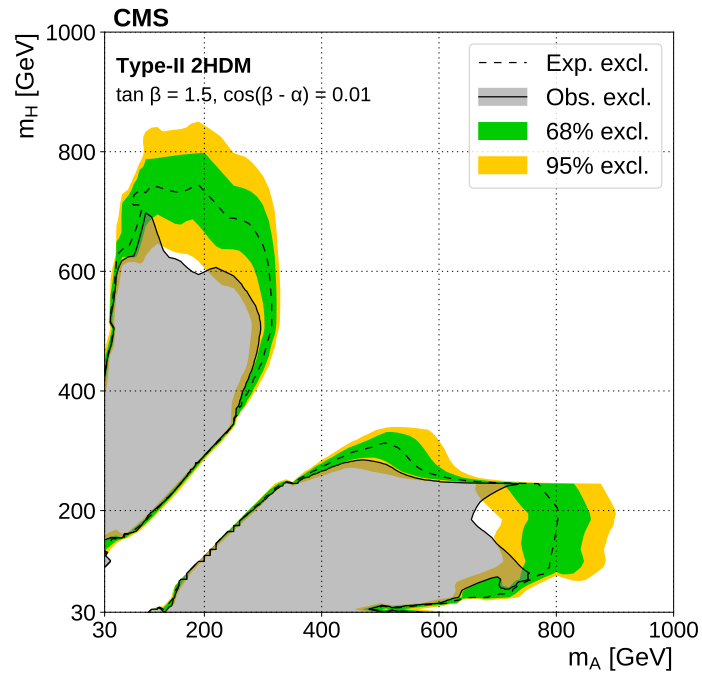


Figure 8: Expected and observed 95% CL exclusion contours for the Type-II 2HDM benchmark $\tan \beta = 1.5$ and $\cos(\beta - \alpha) = 0.01$ as a function of m_A and m_H . The inner (green) band and the outer (yellow) band indicate the regions containing 68 and 95%, respectively, of the distribution of the exclusion contours expected under the background-only hypothesis. The limits are computed using the asymptotic CL_s method, combining the ee and $\mu\mu$ channels.

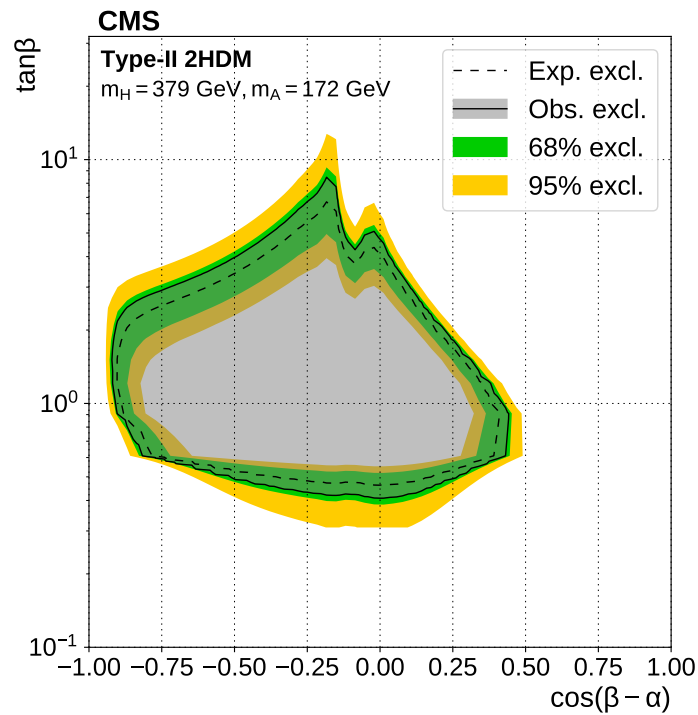


Figure 9: Expected and observed 95% CL exclusion contours for $m_H = 379 \text{ GeV}$ and $m_A = 172 \text{ GeV}$ as a function of $\tan\beta$ and $\cos(\beta - \alpha)$. The inner (green) band and the outer (yellow) band indicate the regions containing 68 and 95%, respectively, of the distribution of the exclusion contours expected under the background-only hypothesis. The limits are computed using the asymptotic CL_s method, combining the ee and $\mu\mu$ channels.

8 Summary

This paper reports on a search for a new CP-even (odd) neutral Higgs boson, decaying into a Z boson and a lighter CP-odd (even) neutral Higgs boson, where the Z decays into an electron or muon pair, and the light Higgs boson into a b quark pair. The search is based on LHC proton-proton collision data at a center-of-mass energy $\sqrt{s} = 13$ TeV collected by the CMS experiment during 2016, corresponding to an integrated luminosity of 35.9 fb^{-1} . We consider decays such as $H \rightarrow ZA \rightarrow \ell\ell b\bar{b}$, where H and A are the additional CP-even and -odd Higgs bosons above-mentioned, respectively, in the context of the two-Higgs-doublet model (2HDM). They are searched for in the mass range from 120 to 1000 GeV for H and 30 to 1000 GeV for A. The search is subsequently extended to the $A \rightarrow ZH \rightarrow \ell\ell b\bar{b}$ process via interchanging the two mass parameters.

No significant deviations from the standard model expectations are observed. Model independent upper limits on the product of cross section and branching fraction are set. Limits are also set on the parameters of the 2HDM, assuming the Type-II formulation. Under the specific benchmark scenario corresponding to $\tan\beta = 1.5$ and $\cos(\beta - \alpha) = 0.01$, regions with m_H in the range 150–700 GeV and m_A in the range 30–295 GeV with $m_H > m_A$, or alternatively for m_H in the range 30–280 GeV and m_A in the range 150–700 GeV with $m_H < m_A$ are excluded at 95% confidence level. Results are also interpreted in the scenario where $m_H = 379$ GeV and $m_A = 172$ GeV. In this context, the region with $\cos(\beta - \alpha)$ in the range -0.9 – 0.3 and $\tan\beta$ in the range 0.5 – 7.0 is excluded at 95% confidence level. With respect to previous searches, a larger region of the Type-II 2HDM parameter space is excluded.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NKFI (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie programme and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 752730, and 765710 (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la

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

5: Also at UFMS, Nova Andradina, Brazil

6: Also at Universidade Federal de Pelotas, Pelotas, Brazil

7: Also at Université Libre de Bruxelles, Bruxelles, Belgium

8: Also at University of Chinese Academy of Sciences, Beijing, China

9: Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC

'Kurchatov Institute', Moscow, Russia

10: Also at Joint Institute for Nuclear Research, Dubna, Russia

11: Also at Cairo University, Cairo, Egypt

12: Now at British University in Egypt, Cairo, Egypt

13: Also at Purdue University, West Lafayette, USA

14: Also at Université de Haute Alsace, Mulhouse, France

15: Also at Erzincan Binali Yildirim University, Erzincan, Turkey

16: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

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

18: Also at University of Hamburg, Hamburg, Germany

19: Also at Brandenburg University of Technology, Cottbus, Germany

20: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary, Debrecen, Hungary

21: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary

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

23: Also at IIT Bhubaneswar, Bhubaneswar, India, Bhubaneswar, India

24: Also at Institute of Physics, Bhubaneswar, India

25: Also at Shoolini University, Solan, India

26: Also at University of Visva-Bharati, Santiniketan, India

27: Also at Isfahan University of Technology, Isfahan, Iran

28: Now at INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy

29: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy

30: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy

31: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy

32: Also at Riga Technical University, Riga, Latvia, Riga, Latvia

33: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia

34: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico

35: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland

36: Also at Institute for Nuclear Research, Moscow, Russia

37: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia

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

39: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia

40: Also at University of Florida, Gainesville, USA

41: Also at Imperial College, London, United Kingdom

42: Also at P.N. Lebedev Physical Institute, Moscow, Russia

43: Also at California Institute of Technology, Pasadena, USA

44: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia

45: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia

46: Also at Università degli Studi di Siena, Siena, Italy

47: Also at INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy, Pavia, Italy

48: Also at National and Kapodistrian University of Athens, Athens, Greece

49: Also at Universität Zürich, Zurich, Switzerland

50: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria, Vienna, Austria

51: Also at Burdur Mehmet Akif Ersoy University, BURDUR, Turkey

52: Also at Adiyaman University, Adiyaman, Turkey

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- 53: Also at Şırnak University, Sırnak, Turkey
54: Also at Beykent University, Istanbul, Turkey, Istanbul, Turkey
55: Also at Istanbul Aydın University, Istanbul, Turkey
56: Also at Mersin University, Mersin, Turkey
57: Also at Piri Reis University, Istanbul, Turkey
58: Also at Gaziosmanpasa University, Tokat, Turkey
59: Also at Ozyegin University, Istanbul, Turkey
60: Also at Izmir Institute of Technology, Izmir, Turkey
61: Also at Marmara University, Istanbul, Turkey
62: Also at Kafkas University, Kars, Turkey
63: Also at Istanbul Bilgi University, Istanbul, Turkey
64: Also at Hacettepe University, Ankara, Turkey
65: Also at Vrije Universiteit Brussel, Brussel, Belgium
66: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
67: Also at IPPP Durham University, Durham, United Kingdom
68: Also at Monash University, Faculty of Science, Clayton, Australia
69: Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA
70: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
71: Also at Vilnius University, Vilnius, Lithuania
72: Also at Bingol University, Bingol, Turkey
73: Also at Georgian Technical University, Tbilisi, Georgia
74: Also at Sinop University, Sinop, Turkey
75: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
76: Also at Texas A&M University at Qatar, Doha, Qatar
77: Also at Kyungpook National University, Daegu, Korea, Daegu, Korea
78: Also at University of Hyderabad, Hyderabad, India