CERN-PH-EP/2015-284
2021/11/20

CMS-HIG-14-033

Search for a low-mass pseudoscalar Higgs boson produced in association with a $b\bar{b}$ pair in pp collisions at $\sqrt{s} = 8$ TeV

The CMS Collaboration*

Abstract

A search is reported for a light pseudoscalar Higgs boson decaying to a pair of τ leptons, produced in association with a $b\bar{b}$ pair, in the context of two-Higgs-doublet models. The results are based on pp collision data at a centre-of-mass energy of 8 TeV collected by the CMS experiment at the LHC and corresponding to an integrated luminosity of 19.7 fb^{-1} . Pseudoscalar boson masses between 25 and 80 GeV are probed. No evidence for a pseudoscalar boson is found and upper limits are set on the product of cross section and branching fraction to τ pairs between 7 and 39 pb at the 95% confidence level. This excludes pseudoscalar A bosons with masses between 25 and 80 GeV, with SM-like Higgs boson negative couplings to down-type fermions, produced in association with $b\bar{b}$ pairs, in Type II, two-Higgs-doublet models.

Published in Physics Letters B as doi:10.1016/j.physletb.2016.05.003.

1 Introduction

The discovery of a new boson with a mass close to 125 GeV [1–3], consistent with the standard model (SM) Higgs boson, has shed light on one of the most important questions of physics: the origin of the mass of elementary particles. Although all the measurements made up to now are in impressive agreement with the predictions of the SM [4, 5], the SM cannot address several crucial issues such as the hierarchy problem, the origin of the matter-antimatter asymmetry and the nature of dark matter [6–9]. Theories predicting new physics beyond the standard model have been proposed to address these open questions. Many of them predict the existence of more than one Higgs boson.

Two-Higgs-doublet models (2HDM) [10–14] are a particularly simple extension of the SM. Starting with the two doublet fields Φ_1 and Φ_2 and assuming an absence of CP violation in the Higgs sector, after $SU(2)_L$ symmetry breaking five physical states are left: two CP-even (h and H), one CP-odd (A), and two charged (H^\pm) bosons. To avoid tree-level flavour changing neutral currents, one imposes a Z_2 symmetry according to which the Lagrangian is required to be invariant under $\Phi_1 \rightarrow \Phi_1$, $\Phi_2 \rightarrow -\Phi_2$. The result is four distinct classes of models, corresponding to different patterns of quark and lepton couplings. The most commonly considered are Type I and Type II. In Type I, all quarks and leptons obtain masses from $\langle \Phi_1 \rangle$. In Type II, up-type quarks masses are derived from $\langle \Phi_1 \rangle \equiv v_1$ and down-type quarks and charged leptons masses are derived from $\langle \Phi_2 \rangle \equiv v_2$. In the limit of an exact Z_2 symmetry [15], the Higgs sector of a 2HDM can be described by six parameters: four Higgs boson masses (m_h , m_H , m_A , and m_{H^\pm}), the ratio of the vacuum expectation values of the two doublets ($\tan \beta \equiv v_2/v_1$) and the mixing angle α of the two neutral CP-even Higgs states. Allowing a soft breaking of the Z_2 symmetry introduces a new Higgs mixing parameter m_{12}^2 [11]. In the “decoupling limit” of 2HDMs [16, 17], the masses m_H , m_A , and m_{H^\pm} are all large, $\cos(\beta - \alpha) \ll 1$, and h is the observed boson at 125 GeV and is SM-like. An SM-like h or H at 125 GeV can also be obtained in the “alignment limit” [16, 17] without the other bosons being heavy. This is an interesting case and can be compatible with the SM-like Higgs boson total width measurements and branching fractions even if one or more of the light Higgs bosons have a mass below half of 125 GeV provided one adjusts the model parameters so that the branching fraction of the SM Higgs boson to pairs of light Higgs bosons is very small. This scenario can be tested at the CERN LHC by searching for singly produced light bosons decaying to a pair of τ leptons with large cross sections. In Type II 2HDMs, if the Higgs coupling to the third generation of quarks is enhanced, as happens at large $\tan \beta$, a large production cross section is expected for the production of the low-mass A boson in association with $b\bar{b}$. The cross section is of the order of 1 pb for regions of the 2HDM parameter space with $\sin(\beta - \alpha) \approx 1$, $\cos(\beta - \alpha) > 0$ and small m_{12}^2 . The cross section can be much larger, between 10 and 100 pb, for some other regions of the parameter space, i.e. $\sin(\beta \pm \alpha) \approx 1$, $\cos(\beta - \alpha) < 0$ and $\tan \beta > 5$ [18, 19], where the coupling of the SM-like h boson to down-type fermions is negative (“wrong sign” Yukawa coupling). Consequently, given the large production cross section of the A boson in such scenarios, the LHC data are sensitive to its presence for some combinations of model parameters.

Previous searches for di- τ resonances [20, 21] have mainly focused on masses greater than the mass of the Z boson, for example in the context of the minimal supersymmetric standard model (MSSM) [22–24], which is a highly constrained 2HDM of Type II. In fact, a light pseudoscalar Higgs boson is excluded in the MSSM, but an A boson can still have quite a low mass in general 2HDMs, even given all the constraints from LEP, Tevatron and LHC data [18, 19].

This letter presents a search for a low-mass pseudoscalar Higgs boson produced in association with a $b\bar{b}$ pair and decaying to a pair of τ leptons. Associated production of the A boson with a

$b\bar{b}$ pair has the advantage that there is a higher signal over background ratio relative to gluon-gluon fusion production. Such a signature is also relevant in the context of light pseudoscalar mediators and coy dark sectors [25]. The analysis is based on pp collision data at a centre-of-mass energy of 8 TeV recorded by the CMS experiment at the LHC in 2012. The integrated luminosity amounts to 19.7 fb^{-1} . The τ leptons are reconstructed via their muon, electron and hadronic decays. In the following, the terms leptons refer to electrons and muons, whereas τ s that decay into hadrons+ ν_τ are denoted by τ_h . The invariant mass distributions of the τ pairs in all three channels are used to search for pseudoscalar bosons with masses between 25 and 80 GeV.

2 The CMS detector and event samples

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Muons are detected in gas-ionisation detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. A 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. [26].

The first level of the CMS triggering system (Level-1), composed of custom hardware processors, uses information from the calorimeters and the muons detectors to select the most interesting events in a fixed time interval of less than $4 \mu\text{s}$. The high-level trigger (HLT) processor farm further decreases the event rate from around 100 kHz to less than 1 kHz, before data storage.

A set of Monte Carlo (MC) simulated events is used to model the signal and backgrounds. Drell-Yan, W boson production associated to additional jets, production of top quark pairs ($t\bar{t}$), and diboson (WW, WZ and ZZ) backgrounds are generated using the leading order (LO) MADGRAPH 5.1 package [27]. Single top quark samples are produced using the next-to-leading-order (NLO) generator POWHEG (v1.0) [28]. Simulated samples of gluon-gluon fusion to $b\bar{b}A$ signal events are generated with PYTHIA 6.426 [29] for masses between 25 and 80 GeV in 5 GeV steps. As no loop is involved at leading order in the $b\bar{b}A$ production process, the product of acceptance and efficiency for signal only depends on the A boson mass, with no dependence on other model parameters. The simulated samples are produced using the CTEQ6L1 parton distribution function (PDF) set [30]. All the generated signal and background samples are processed with the simulation of the CMS detector based on GEANT 4 [31].

Additional events are added to the MC-simulated events, with weights corresponding to the luminosity profile in data, to simulate LHC conditions and the presence of other soft pp interactions (pileup) in the same or neighbouring bunch crossings of the main interaction. Finally, identical algorithms and procedures are used to reconstruct both simulated events and the collected data.

3 Event reconstruction

Event reconstruction is based on the particle-flow (PF) algorithm [32, 33], which aims to exploit the information from all subdetectors to identify individual particles (PF candidates): charged and neutral hadrons, muons, electrons, and photons. Complex objects, such as τ leptons that

decay into hadrons and a neutrino, jets, and the imbalance in the transverse momentum in the event are reconstructed from PF candidates.

The deterministic annealing algorithm [34, 35] is used to reconstruct the collision vertices. The vertex with the maximum sum of squared transverse momenta (p_T^2) of all associated tracks is considered as the primary vertex. Muons, electrons, and τ_h s are required to originate from the primary collision vertex.

Muon reconstruction starts by matching tracks in the silicon tracker with tracks in the outer muon spectrometer [36]. A global muon track is fitted to the hits from both tracks. A preselection is applied to these muon tracks that includes requirements on their impact parameters, to distinguish genuine prompt muons from spurious muons or muons from cosmic rays. In addition, muons are required to pass isolation criteria to separate prompt muons from those associated with a jet, usually from the semi-leptonic decays of heavy quarks. The muon relative isolation is defined as the following [26]:

$$I_{\text{rel}} = \left[\sum_{\text{charged}} p_T + \max \left(0, \sum_{\text{neutral}} p_T + \sum_{\gamma} p_T - \frac{1}{2} \sum_{\text{charged,PU}} p_T \right) \right] / p_T^{\mu}, \quad (1)$$

where all sums are over the scalar p_T of particles inside a cone with size of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ relative to the muon direction, where η is the pseudorapidity and ϕ is the azimuthal angle (in radians) in the plane transverse to the beam axis, and “charged” corresponds to charged hadrons, muons, and electrons originating from the primary vertex, “neutral” refers to neutral hadrons and “charged,PU” refers to charged hadrons, muons, and electrons originating from other reconstructed vertices. The last of these sums is used to subtract the neutral pileup component in the computation, and the factor of 1/2 reflects the approximate ratio of neutral to charged particles in jets [37].

Electron reconstruction starts from ECAL superclusters, which are groups of one or more associated clusters of energy deposited in the ECAL. Superclusters are matched to track seeds in the inner tracker (the closest layers of the tracker to the interaction point) and electron tracks are formed from those. Trajectories are reconstructed based on the modelling of electron energy loss due to bremsstrahlung, and are fitted using the Gaussian sum filter algorithm [38]. Electron identification is based on a multivariate (MVA) boosted decision tree technique [39] to discriminate genuine electrons from jets misidentified as electrons [40]. The most powerful variables for the discrimination of τ_h candidates are the ratio of energy depositions in the ECAL and HCAL, the angular difference between the track and supercluster, and the distribution of energy depositions in the electron shower. Relative isolation is defined in an analogous way to that of Eq. (1) and is used to distinguish prompt electrons from electrons within a jet.

Jets are reconstructed from PF candidates using the anti- k_T [41] algorithm with a distance parameter of 0.5, in the FASTJET package [42]. Several corrections are applied to the jet energies to reduce the effect of pileup and correct for the nonlinear response of the calorimeters [37]. To identify and reject jets from pileup, an MVA discriminator is defined based on information from the vertex and the jet distribution [43]. Jets identified as originating from a b quark, called b-tagged jets, are identified using the combined secondary vertex (CSV) algorithm [44], which is based on a likelihood technique, and exploits information such as the impact parameters of charged-particle tracks and the properties of reconstructed decay vertices.

The hadron-plus-strips (HPS) algorithm [45, 46] is used to reconstruct the τ_h candidates. It starts from a jet, and searches for candidates produced by the main hadronic decay modes of

the τ lepton: either directly to one charged hadron, or via intermediate ρ and $a_1(1280)$ mesons to one charged hadron plus one or two neutral pions, or three charged hadrons with up to one neutral pion. The charged hadrons are usually long-lived pions, while the neutral pions decay rapidly into two photons. The HPS algorithm takes into account the possible conversion of photons into e^+e^- pairs in material in front of the ECAL, and their corresponding bremsstrahlung in the magnetic field with consequent broadening of the distribution of the shower. Strips are formed from energy depositions in the ECAL arising from electrons and photons. The strip sizes in ECAL are 0.05×0.20 in $\eta \times \phi$. The τ_h decay modes are reconstructed by combining the charged hadrons with ECAL strips. Neutrinos produced in τ_h decays are not reconstructed but contribute to E_T^{miss} . Isolation requirements based on an MVA technique take into account the p_T of PF candidates around the τ lepton direction and information related to its lifetime, such as the transverse impact parameter of the leading track of the τ_h candidate and its significance for decays to one charged hadron or the distance between the τ_h production and decay vertices and its significance for decays to three charged hadrons. Electrons can be misidentified as τ_h candidates with one track and ECAL strip. An MVA discriminator based on properties of the reconstructed electron, such as the distribution of the shower and the ratio of the ECAL and HCAL deposited energies, is used to improve pion/electron separation. Finally, another MVA discriminator is used to suppress muons reconstructed as τ_h candidates with one track. It exploits information about the energy deposited in the calorimeters with τ_h candidates, as well as hits and segments reconstructed in the muon spectrometers that can be matched to the components of the τ_h .

The missing transverse momentum vector \vec{p}_T^{miss} is defined as the projection on the plane perpendicular to the beams of the negative vector sum of the momenta of all reconstructed particles in an event. Its magnitude is referred to as E_T^{miss} . To improve the resolution, and reduce the effect of pileup, a \vec{p}_T^{miss} based on an MVA regression technique [47] is used, which takes into account several collections of particles from different vertices.

The invariant mass of the τ pair ($m_{\tau\tau}$) is used as the observable for the statistical interpretation of results in all channels and is reconstructed using the SVFIT algorithm [48]. The SVFIT algorithm uses a maximum likelihood technique where the likelihood takes as input the four-momenta of the visible decay products of the τ , the projection of \vec{p}_T^{miss} along the x - and y -axes, as well as the covariance matrix of the components of \vec{p}_T^{miss} .

The relative $m_{\tau\tau}$ resolution obtained through the SVFIT algorithm is about 15% over the whole mass range. It is slightly higher for the $e\mu$ channel because of the presence of one additional neutrino.

4 Event selection

Three di- τ final states are considered: $\mu\tau_h$, $e\tau_h$, and $e\mu$. The $\mu\mu$ and ee final states are discarded because of their small branching fractions and large backgrounds, while $\tau_h\tau_h$ is not considered because of inefficiencies due to the trigger threshold.

The selection of events in the $\mu\tau_h$ or $e\tau_h$ final state starts from a trigger that requires a combination of a muon or electron with $p_T > 17$ or 22 GeV, respectively, and an isolated τ_h with $p_T > 20$ GeV. This combined trigger is seeded by a single muon or electron, with $p_T > 16$ or 20 GeV at Level-1. The offline selection requires a muon or electron with $p_T > 18$ or 24 GeV, respectively, and $|\eta| < 2.1$, and an oppositely charged τ_h candidate with $p_T > 22$ GeV and $|\eta| < 2.3$. Leptons are required to pass a tight identification [36, 40] and have a relative isolation, $I_{\text{rel}}, < 0.1$. The τ_h candidates have to pass a tight working point of the MVA discriminant

that combines isolation and lifetime information (resulting in a τ_h reconstruction and isolation efficiency of about 30% and a jet to τ_h misidentification rate between 0.5 and 1.0 per mille), as well as the requirements to suppress electron and muon candidates misidentified as τ_h , described in Section 3. Leptons and τ_h candidates are required to be separated by $\Delta R > 0.5$. Events with additional identified and isolated electrons or muons are discarded. To suppress W +jets and $t\bar{t}$ backgrounds, the transverse mass between the lepton transverse momentum \vec{p}_T^ℓ and \vec{p}_T^{miss} , defined in Eq. 2, is required to be smaller than 30 GeV,

$$M_T(\ell, \vec{p}_T^{\text{miss}}) = \sqrt{2p_T^\ell E_T^{\text{miss}}(1 - \cos \Delta\phi)}, \quad (2)$$

where $\Delta\phi$ is the azimuthal angle between the lepton transverse momentum and the \vec{p}_T^{miss} vectors.

Events selected in the $e\mu$ channel must pass a trigger that requires a combination of an electron and a muon, with $p_T > 17(8)$ GeV for the leading (subleading) lepton. Depending on the flavour of the leading lepton that passes the trigger selection, events are required to have either a muon with $p_T > 18$ GeV and an electron with $p_T > 10$ GeV, or a muon with $p_T > 10$ GeV and an electron with $p_T > 20$ GeV. The fiducial regions for muons (electrons) are defined by $|\eta| < 2.1(2.3)$. Additionally, leptons with opposite charge are selected and required to be spatially separated by $\Delta R > 0.5$.

The muons and electrons are required to be isolated, with relative isolation less than 0.15 in the barrel ($|\eta| < 1.479$) and less than 0.1 in the endcaps ($|\eta| > 1.479$). In addition, both muons and electrons are required to pass the tight identification criteria as described in Section 3. Events having additional identified and isolated leptons are vetoed, similarly to the $\mu\tau_h$ and $e\tau_h$ channels. To reduce the large $t\bar{t}$ background in the $e\mu$ final state, a linear combination of the P_ζ and P_ζ^{vis} variables [49] is used. P_ζ and P_ζ^{vis} are defined as follows:

$$P_\zeta = (\vec{p}_T^\mu + \vec{p}_T^e + \vec{p}_T^{\text{miss}}) \cdot \hat{\zeta} \quad \text{and} \quad P_\zeta^{\text{vis}} = (\vec{p}_T^\mu + \vec{p}_T^e) \cdot \hat{\zeta}, \quad (3)$$

where $\hat{\zeta}$ is the unit vector of the axis bisecting the angle between \vec{p}_T^μ and \vec{p}_T^e of the muon and electron candidates, respectively. These variables take into account the fact that the neutrinos produced in τ decays are mostly collinear with the visible τ decay products, but this is not true for neutrinos from the other sources, nor for misidentified τ_h candidates from background. The linear combination $P_\zeta - \alpha P_\zeta^{\text{vis}}$ is required to be greater than -40 GeV, with an optimal value of α of 1.85, determined in the CMS search for a MSSM Higgs boson in the $\tau\tau$ final state [21]. To further reduce $t\bar{t}$ and electroweak backgrounds in the $e\mu$ final state, the M_T between the dilepton transverse momentum and \vec{p}_T^{miss} , defined as in Eq. 2, is required to be less than 25 GeV.

In addition to the above selections, events in all channels are also required to have at least one b-tagged jet with $p_T > 20$ GeV and $|\eta| < 2.4$, which passes the working point of the CSV b-tagging discriminant (corresponding to b-tagging efficiency of about 65% and light-jet misidentification rate of about 1%) and the pileup MVA discriminant for jets, and is separated by at least $\Delta R = 0.5$ from the signal leptons.

5 Background estimation

One of the main backgrounds in all three channels is $Z/\gamma^* \rightarrow \tau\tau$. Drell-Yan events with invariant mass larger than 50 GeV are modelled using “embedded” event samples, as follows: $Z \rightarrow \mu\mu$ events are selected in data with an invariant mass larger than 50 GeV to remove

the mass range biased by a trigger requirement. The reconstructed muons are replaced by simulated τ leptons that are subsequently decayed via TAUOLA [50]. To model the detector response to the τ decay products the GEANT based detector simulation is used. Jets, \vec{p}_T^{miss} , and τ_h are then reconstructed, while lepton isolations are recomputed [51]. This substantially reduces the uncertainties related to the modelling of the E_T^{miss} , the jet energy scale, and the b jet efficiency. Low-mass $Z/\gamma^* \rightarrow \tau\tau$ events, which cannot be covered by the embedded samples, are taken directly from a simulated sample.

Multijet events originated by QCD processes comprise another major background, especially at low di- τ mass. The contribution of the QCD multijet background arises from jet $\rightarrow \tau_h$ misidentification and to a lesser extent from jet $\rightarrow \mu$ and jet $\rightarrow e$ misidentification, depending on the final state. Other contributions are due to the presence of muons or electrons from the semi-leptonic decays of heavy flavour quarks. This background is estimated from data.

Multijet background normalisation in the $\mu\tau_h$ and $e\tau_h$ final states is determined from a sample defined in the same way as the signal selection described in Section 4, except that the lepton and the τ_h candidate are required to have electric charge of same sign (SS). The events with the SS selection are dominated by multijets, and the limited contribution from the other processes is subtracted using predictions from simulated events. To take into account the difference in the multijet normalisation between the SS and opposite-sign (OS) regions, an OS/SS extrapolation factor is used to multiply the multijet yield in the SS region. This factor is measured in signal-free events selected with inverted lepton isolations ($0.2 < I_{\text{rel}} < 0.5$) and a relaxed τ_h isolation. The OS/SS extrapolation factor is parameterised as a function of $m_{\tau\tau}$, and fitted with an exponentially decreasing function. This ratio is approximately equal to 1.2 for di- τ masses of 20 GeV, and decreases to about 1.1 for masses above 50 GeV.

The $m_{\tau\tau}$ distribution for the QCD multijet background is obtained from a control region in data by inverting the lepton isolation and relaxing the τ_h isolation. These two selections are required to attain a control region populated with QCD multijet events and obtain a sufficiently smooth $m_{\tau\tau}$ distribution. A correction has been applied to account for the differences between the nominal selection and the selection used to estimate the QCD multijet $m_{\tau\tau}$ distribution. The correction depends on the τ_h misidentification rate (the probability for a τ_h , that passes a looser isolation requirement, to pass the tight isolation selection). This rate is parameterised as a function of the p_T of the τ_h in three bins of pseudorapidity. It was checked that the $m_{\tau\tau}$ distributions obtained when the lepton isolation is inverted and the τ_h isolation is relaxed, are consistent within statistical uncertainties with the normal search procedure.

In the $e\mu$ final state, the QCD multijet background is measured simultaneously with other backgrounds using misidentified leptons in data, through a “misidentified-lepton” method [51], and requiring at least one jet misidentified as a lepton. The probability for loosely preselected leptons, mainly dominated by leptons within jets, to be identified as good leptons is measured in samples depleted of isolated leptons as a function of the p_T and η . Weights obtained from this measurement are applied to events in data with electrons and muons passing the loose preselection but not the nominal selection criteria, to extract the QCD multijet background contribution.

In the $\mu\tau_h$ and $e\tau_h$ final states, the W+jets background arises from events with a genuine isolated and identified lepton from the leptonic decay of a W boson and a jet misidentified as a τ_h . Its contribution is highly suppressed by requiring the M_T of the lepton and \vec{p}_T^{miss} of Eq. (2) to be < 30 GeV (low- M_T region). The W+jets normalisation is determined from collision data using the yield in the high- M_T (> 70 GeV) sideband, multiplied by an extrapolation factor that is the ratio of the W+jets events in the high- and low- M_T regions in simulated events. The small con-

tribution from other backgrounds in events selected with high- M_T selection is subtracted using the prediction from simulations. The distribution of $m_{\tau\tau}$ for the W+jets background is taken from simulation. A correction to the distribution, measured in a sample enriched in W+jets and as a function of the p_T of the lepton originating from the W boson, is applied to correct the differences between observed and simulated events. In the $e\mu$ final state, the W+jets background is estimated together with the backgrounds that contain at least one jet misidentified as a lepton, such as QCD multijets, as previously described.

The $Z/\gamma^* \rightarrow \mu\mu$ and $Z/\gamma^* \rightarrow ee$ processes contribute, respectively, to the $\mu\tau_h$ and $e\tau_h$ final states, because of the misidentification of a lepton as a τ_h . The normalisation and the distribution of $m_{\tau\tau}$ for these backgrounds are obtained from simulation.

The presence of genuine b jets from top quark decays makes the $t\bar{t}$ background contribution important. The $t\bar{t}$ background has true $\tau_h \approx 70\%$ of the times and misidentified τ_h in $\approx 30\%$ of the times. The distribution of $m_{\tau\tau}$ for $t\bar{t}$ events is taken from simulation, but normalised to the measurement of the $t\bar{t}$ cross section [52]. A reweighting is applied to generated $t\bar{t}$ events to improve the modelling of the top quark p_T spectrum. This reweighting only depends on the simulated p_T of top and antitop quarks [52], and has a negligible impact on the final results. In addition, the $m_{\tau\tau}$ distributions observed in data and predicted by MC simulations are compared in a region with high purity of $t\bar{t}$ events, and depleted in signal, obtained by raising the p_T threshold of the leptons and τ_h , and requiring at least two b-tagged jets with a higher p_T threshold than that used in event selections described in Section 4. Good agreement is found between distributions in data and MC simulation.

Single top quark, diboson (WW, WZ, ZZ), and SM Higgs backgrounds represent a small fraction of the total background, and are taken from simulations and normalised to the NLO cross sections [51, 53, 54].

Scale factors to correct for residual discrepancies between data and MC simulation related to the lepton triggering, identification, and isolation are applied to the signal and the backgrounds estimated from MC simulations. These correction factors are determined using the “tag-and-probe” technique [45, 46, 55], which relies on the presence of two leptons from Z boson decays. No correction factor is applied to the τ_h candidate nor to the selected b jet, as the corrections are found to be consistent with unity. The uncertainties related to these scale factors are described in Section 6.

6 Systematic uncertainties

The results of the analysis are extracted from a fit based on the $m_{\tau\tau}$ distributions in each final state, as discussed in Section 7. Systematic uncertainties in the fit affect the normalisation or the shape of the $m_{\tau\tau}$ distribution for the signal and backgrounds. The normalisation uncertainties are summarised in Table 1.

The uncertainty in normalisation that affects the signal and most of the simulated backgrounds is related to the integrated luminosity at 8 TeV, which is measured with a precision of 2.6% [56]. Uncertainties in muon and electron identification and trigger efficiency, as well as in the τ_h identification efficiency, are determined using the “tag-and-probe” technique [45, 46, 55]. These uncertainties are about 2% for muon and electron and 8% for τ_h . Changes in acceptance due to the uncertainty in the b tagging efficiency and the b mistag rate range from 1 to 9% depending on the process. To estimate the uncertainty in the W+jets normalisation, the uncertainty in the extrapolation factor from the high- M_T sideband to the signal region is obtained by varying

E_T^{miss} and its resolution by their uncertainties, leading to a 30% uncertainty. The uncertainty in the normalisation of QCD multijet background is obtained by adding the statistical uncertainty related to the sample size of the QCD multijet-dominated control region in quadrature with the uncertainty in the extrapolation factor from the control region to the signal region; this amounts to 20%. The normalisation uncertainty for the $t\bar{t}$ background amounts to 10%; it is determined from a control region where both W bosons originating from the top and antitop quarks decay to τ leptons[51]. Uncertainties related to the diboson background cross section amount to 15% [57].

A 30% uncertainty in the signal strength (ratio of observed to expected cross sections) for the SM Higgs boson is applied [51]. Theoretical uncertainties arising from the underlying event and parton showering matching scale, PDF [58] and the dependence on factorisation and normalisation scales are considered for signal. The PDF uncertainty is taken as the difference in the signal acceptance for the signal simulation with CTEQ6L1, MSTW2008NLO [59], and NNPDF2.3NLO [60] PDF sets, leading to a 10% uncertainty. A 20% uncertainty in the signal normalisation is applied to take into account the possible difference in the product of acceptance and efficiency between the LO sample generated with PYTHIA6.4 and the NLO sample generated by the MADGRAPH5_AMC@NLO generator [61].

The τ_h and electron energy scales are among the systematic uncertainties affecting the $m_{\tau\tau}$ distributions. To estimate the effects of these uncertainties, the electron energy scale is changed by 1% or by 2.5% for electrons reconstructed in the barrel or in the endcap regions of the ECAL [40], respectively, while the τ_h energy scale is varied by 3% [46]. The top quark p_T reweighting correction, used for simulated $t\bar{t}$ events to match the observed p_T spectrum in a dedicated control region, is changed between zero and twice the nominal value [52, 62]. The uncertainty in the τ_h misidentification rate correction of the QCD multijet and W +jets background distributions has been taken into account. To estimate this uncertainty, the τ_h misidentification rate correction has been changed between zero and twice its value. An additional trigger uncertainty is applied to the $\mu\tau_h$ and $e\tau_h$ final states to cover possible differences between collision data and simulated events in the low- p_T lepton region, where the trigger efficiency has not yet reached its plateau. These low- p_T leptons are attributed an uncertainty that corresponds to half of the difference between the measured and the plateau efficiencies. Finally, uncertainties due to the limited number of simulated events, or the number of events in the control regions in data, are taken into account. These uncertainties are uncorrelated across the bins in each background distribution [63].

Among all systematic uncertainties, the ones that have the largest impact on the results are the τ_h energy scale, the uncertainties related to the jet to muon, electron or τ_h misidentification rates, and the uncertainties from the limited number of simulated events (or the observed events in data control regions). The impact of these individual uncertainties on the combined expected limit ranges between 5 and 10% depending on $m_{\tau\tau}$.

7 Results

The mass distributions for the $\mu\tau_h$, $e\tau_h$ and $e\mu$ channels are shown in Fig. 1. No significant excess of data is observed on top of the SM backgrounds. A binned maximum likelihood fit has been applied simultaneously to all three distributions, taking into account the systematic uncertainties as nuisance parameters. A log-normal probability distribution function is assumed for the nuisance parameters that affect the event yields of the various background contributions. Systematic uncertainties affecting the $m_{\tau\tau}$ distributions are assumed to have a Gaussian probability distribution function.

Table 1: Systematic uncertainties that affect the normalisation.

	Systematic source	Systematic uncertainty		
		$\mu\tau_h$	$e\tau_h$	$e\mu$
Normalisation	Integrated luminosity	2.6%	2.6%	2.6%
	Muon ID/trigger	2%	—	2%
	Electron ID/trigger	—	2%	2%
	τ_h ID/trigger	8%	8%	—
	Muon to τ_h misidentification rate	30%	—	—
	Electron to τ_h misidentification rate	—	30%	—
	b tagging efficiency	1–4%	1–4%	1–4%
	b mistag rate	1–9%	1–9%	1–9%
	E_T^{miss} scale	1–2%	1–2%	1–2%
	$Z/\gamma^* \rightarrow \tau\tau$ normalisation	3%	3%	3%
	$Z/\gamma^* \rightarrow \tau\tau$ low-mass normalisation	10%	10%	10%
	QCD multijet normalisation	20%	20%	—
	Reducible background normalisation	—	—	30%
	W+jets normalisation	30%	30%	—
	$t\bar{t}$ cross section	10%	10%	10%
	Diboson cross section	15%	15%	15%
	$H \rightarrow \tau\tau$ signal strength	30%	30%	30%
Theory	Underlying event and parton shower	1–5%	1–5%	1–5%
	Scales for A boson production	10%	10%	10%
	PDF for generating signal	10%	10%	10%
	NLO vs. LO	20%	20%	20%

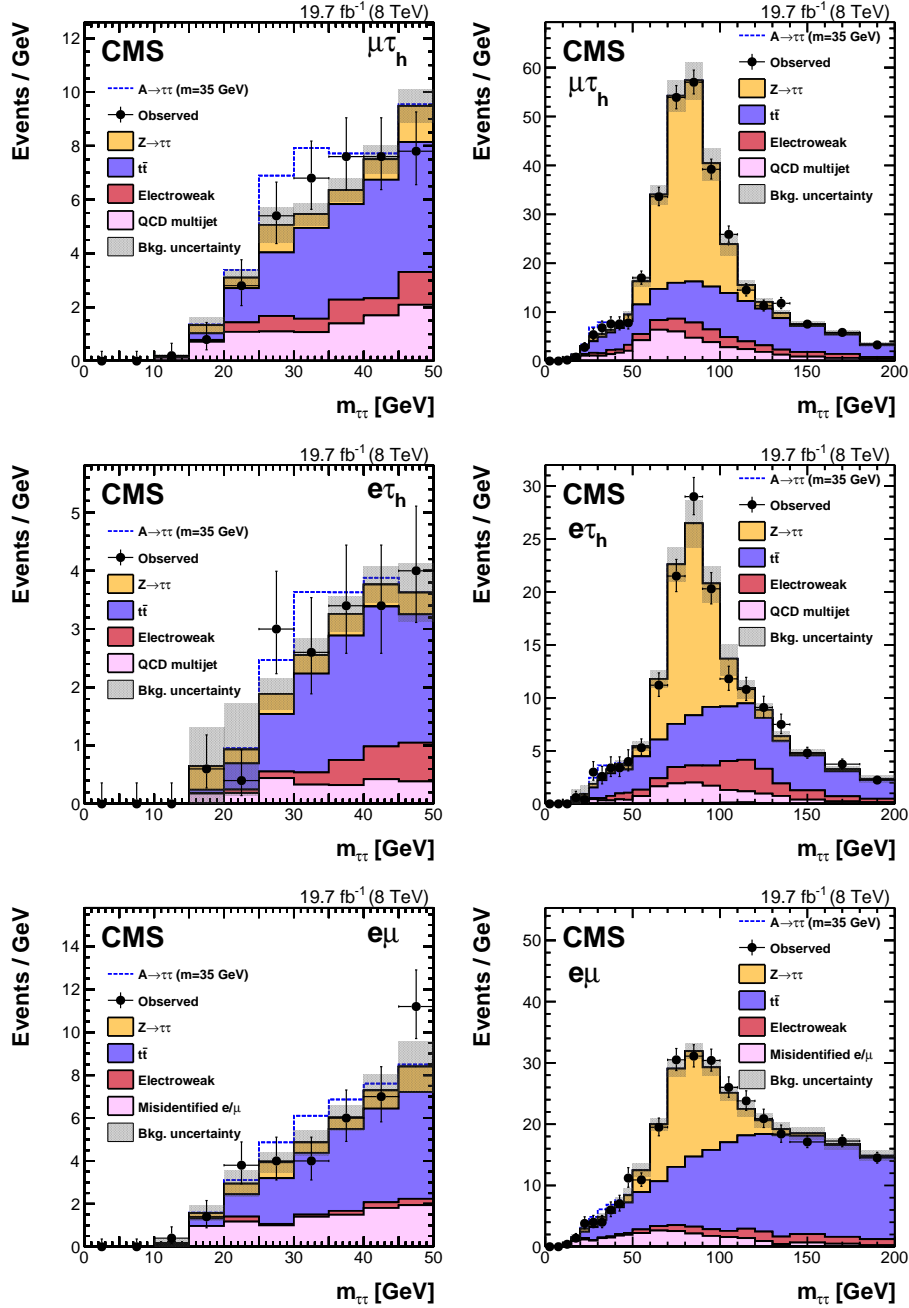


Figure 1: Observed and predicted $m_{\tau\tau}$ distributions in the $\mu\tau_h$ (top), $e\tau_h$ (middle), and $e\mu$ (bottom) channels. The plots on the left are the zoomed-in versions for $m_{\tau\tau}$ distributions below 50 GeV. A signal for a mass of $m_A = 35$ GeV is shown for a cross section of 40 pb. In $\mu\tau_h$ and $e\tau_h$ final states, the electroweak background is composed of $Z \rightarrow ee$, $Z \rightarrow \mu\mu$, W +jets, diboson, and single top quark contributions. In the $e\mu$ final state, the electroweak background is composed of diboson and single top backgrounds, while the misidentified e/μ background is due to QCD multijet and W +jets events. The contribution from the SM Higgs boson is negligible and therefore not shown. Expected background contributions are shown for the values of nuisance parameters (systematic uncertainties) obtained after fitting the signal + background hypothesis to the data.

Upper limits on the product of cross section and branching fraction of the pseudoscalar Higgs boson to $\tau\tau$ are set at 95% confidence level (CL) using the modified frequentist construction CL_s [64, 65] and the procedure is described in Refs. [66, 67]. The observed and expected limits on the $b\bar{b}A \rightarrow b\bar{b}\tau\tau$ process and the one and two standard deviation uncertainties on the expected limits are shown in Fig. 2. Among the three channels, $\mu\tau_h$ is the most sensitive one for the entire mass range because of the higher branching fraction relative to the $e\mu$ channel, lower trigger and offline thresholds on the lepton p_T relative to the $e\tau_h$ channel, and higher muon than electron identification efficiency. Although background yields increase sharply with the mass, the acceptance of the signal grows faster, providing thereby more stringent limits on the cross section at higher masses. The product of signal acceptance and efficiency in the $\mu\tau_h$ channel changes from 1.5×10^{-5} at an A boson mass of 25 GeV to 6×10^{-4} at $m_A = 80$ GeV. In the $e\tau_h$ channel it ranges from 3×10^{-6} at 25 GeV to 2×10^{-4} at 80 GeV, and finally in the $e\mu$ channel, it ranges from 1.3×10^{-5} at 25 GeV to 3.5×10^{-4} at 80 GeV. The trigger requirements and the p_T threshold of the leptons and τ_h s are the main factors in driving the signal acceptance and efficiency, especially at low masses.

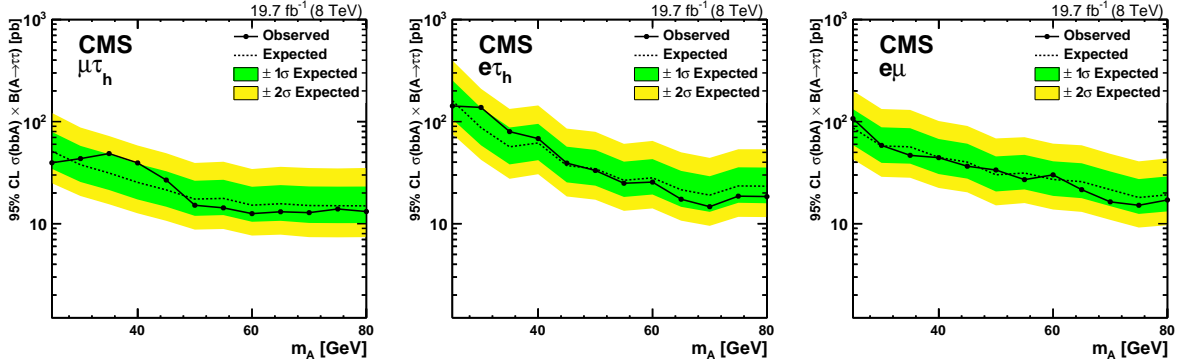


Figure 2: Observed and expected upper limits at 95% CL on the product of cross section and branching fraction for a light pseudoscalar Higgs boson produced in association with two b quarks, that decays to two τ leptons, in the $\mu\tau_h$ (left), $e\tau_h$ (middle), and $e\mu$ (right) channels. The 1σ and 2σ bands represent the 1 and 2 standard deviation uncertainties on the expected limits.

The upper limits from the combination of all final states are presented in Fig. 3, with exact values quoted in Table 2. They range from 7 to 39 pb for A boson masses between 25 and 80 GeV. In addition, superimposed in Fig. 3 are several typical production cross sections for the pseudoscalar Higgs boson produced in association with a pair of b quarks in Type II 2HDM, for m_A less than half of the 125 GeV Higgs boson (h), and for $\mathcal{B}(h \rightarrow AA) < 0.3$ [19]. The points are obtained from a series of scans in the 2HDM parameter space. Points with SM-like Yukawa coupling and small $\tan\beta$ have $\sin(\beta - \alpha) \approx 1$, $\cos(\beta - \alpha) > 0$, and low m_{12}^2 , while points with “wrong sign” Yukawa coupling have $\sin(\beta \pm \alpha) \approx 1$, small $\cos(\beta - \alpha) < 0$, and $\tan\beta > 5$. While the combined results of the current analysis are not sensitive to the SM-like Yukawa coupling, they exclude the “wrong sign” Yukawa coupling for almost the entire mass range, and more generally for $\tan\beta > 5$. For masses greater than $m_h/2$, where the constraint on $\mathcal{B}(h \rightarrow AA) < 0.3$ is automatically satisfied, the production cross section of the pseudoscalar Higgs boson in association with a pair of b quarks is much larger [18]; consequently, the exclusion limit extends to masses up to 80 GeV.

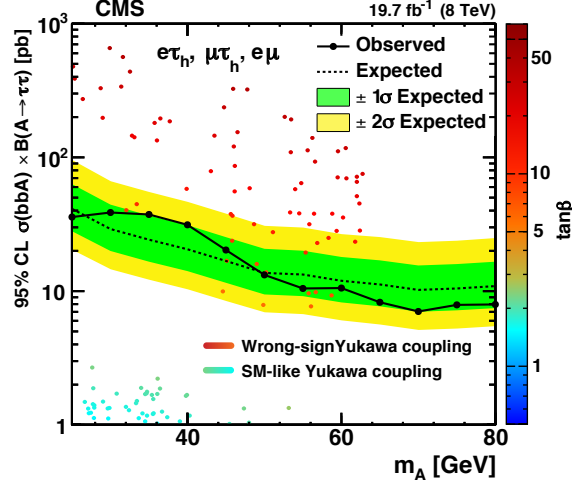


Figure 3: Expected cross sections for Type II 2HDM, superimposed on the expected and observed combined limits from this search. Cyan and green points, indicating small values of $\tan\beta$ as shown in the colour scale, have $\sin(\beta - \alpha) \approx 1$, $\cos(\beta - \alpha) > 0$, and low m_{12}^2 , and correspond to models with SM-like Yukawa coupling, while red and orange points, with large $\tan\beta$, have $\sin(\beta + \alpha) \approx 1$, small $\cos(\beta - \alpha) < 0$, and $\tan\beta > 5$, and correspond to the models with a “wrong sign” Yukawa coupling. Theoretically viable points are shown only up to $m_A = m_h/2$ [19]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2: Expected and observed combined upper limits at 95% CL in pb, along with their 1 and 2 standard deviation uncertainties, in the product of cross section and branching fraction for pseudoscalar Higgs bosons produced in association with $b\bar{b}$ pairs.

m_A (GeV)	Expected limit (pb)					Observed limit (pb)
	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	
25	20.4	28.1	41.3	63.1	95.5	35.8
30	14.6	20.0	29.1	44.3	66.3	38.7
35	12.2	16.6	24.3	36.7	55.1	37.4
40	10.3	14.1	20.6	31.1	46.5	31.3
45	8.4	11.6	16.8	25.3	37.9	20.3
50	7.0	9.5	13.7	20.7	30.8	13.2
55	6.7	9.2	13.3	20.1	29.9	10.5
60	6.1	8.2	12.0	18.0	26.7	10.6
65	5.6	7.7	11.2	17.0	25.4	8.3
70	5.1	7.0	10.2	15.6	23.3	7.1
75	5.3	7.2	10.5	15.9	23.8	7.9
80	5.5	7.5	10.9	16.6	25.0	8.0

8 Summary

A search by the CMS experiment for a light pseudoscalar Higgs boson produced in association with a $b\bar{b}$ pair and decaying to a pair of τ leptons is reported. Three final states: $\mu\tau_h$, $e\tau_h$, and $e\mu$, are used where τ_h represents a hadronic τ decay. The results are based on proton-proton collision data accumulated at a centre-of-mass energy of 8 TeV, corresponding to an integrated luminosity of 19.7 fb^{-1} . Pseudoscalar boson masses between 25 and 80 GeV are probed. No evidence for a pseudoscalar boson is found and upper limits are set on the product of cross section and branching fraction to τ pairs between 7 and 39 pb at the 95% confidence level. This excludes pseudoscalar A bosons with masses between 25 and 80 GeV, with SM-like Higgs boson negative couplings to down-type fermion, produced in association with $b\bar{b}$ pairs, in Type II, two-Higgs-doublet models.

Acknowledgments

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

Individuals have received support from the Marie-Curie programme and the European Research Council and EPLANET (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund; the OPUS programme of the National Science Center (Poland); the Compagnia di San Paolo (Torino); MIUR project 20108T4XTM (Italy); the Thalís and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; the National Priorities Research Program by Qatar National Research Fund; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University (Thailand); and the Welch Foundation, contract C-1845.

References

- [1] ATLAS Collaboration, “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC”, *Phys. Lett. B* **716** (2012) 1, doi:10.1016/j.physletb.2012.08.020, arXiv:1207.7214.
- [2] CMS Collaboration, “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC”, *Phys. Lett. B* **716** (2012) 30, doi:10.1016/j.physletb.2012.08.021, arXiv:1207.7235.
- [3] CMS Collaboration, “Observation of a new boson with mass near 125 GeV in pp collisions at $\sqrt{s} = 7$ and 8 TeV”, *JHEP* **06** (2013) 081, doi:10.1007/JHEP06(2013)081, arXiv:1303.4571.
- [4] ATLAS Collaboration, “Measurement of the Higgs boson mass from the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ channels in pp collisions at center-of-mass energies 7 and 8 TeV with the ATLAS detector”, *Phys. Rev. D* **90** (2014) 052004, doi:10.1103/PhysRevD.90.052004, arXiv:1406.3827.
- [5] CMS Collaboration, “Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV”, *Eur. Phys. J. C* **75** (2015) 212, doi:10.1140/epjc/s10052-015-3351-7, arXiv:1412.8662.
- [6] J. Wess and B. Zumino, “Supergauge transformations in four dimensions”, *Nucl. Phys. B* **70** (1974) 39, doi:10.1016/0550-3213(74)90355-1.
- [7] H.-C. Cheng and I. Low, “TeV symmetry and the little hierarchy problem”, *JHEP* **09** (2003) 051, doi:10.1088/1126-6708/2003/09/051, arXiv:hep-ph/0308199.
- [8] T. Appelquist, H.-C. Cheng, and B. A. Dobrescu, “Bounds on universal extra dimensions”, *Phys. Rev. D* **64** (2001) 035002, doi:10.1103/PhysRevD.64.035002, arXiv:hep-ph/0012100.
- [9] G. Bertone, D. Hooper, and J. Silk, “Particle dark matter: evidence, candidates and constraints”, *Phys. Rept.* **405** (2005) 279, doi:10.1016/j.physrep.2004.08.031, arXiv:hep-ph/0404175.
- [10] T. D. Lee, “A theory of spontaneous T violation”, *Phys. Rev. D* **8** (1973) 1226, doi:10.1103/PhysRevD.8.1226.
- [11] N. G. Deshpande and E. Ma, “Pattern of symmetry breaking with two Higgs doublets”, *Phys. Rev. D* **18** (1978) 2574, doi:10.1103/PhysRevD.18.2574.
- [12] N. G. Deshpande and E. Ma, “The fermion mass scale and possible effects of Higgs bosons on experimental observables”, *Nucl. Phys. B* **161** (1979) 493, doi:10.1016/0550-3213(79)90225-6.
- [13] J. F. Gunion, H. E. Haber, G. L. Kane, and S. Dawson, “The Higgs Hunter’s Guide”, volume 80 of *Frontiers in Physics*. Perseus Books, 2000.
- [14] G. C. Branco et al., “Theory and phenomenology of two-Higgs-doublet models”, *Phys. Rep.* **516** (2012) 1, doi:10.1016/j.physrep.2012.02.002, arXiv:1106.0034.

- [15] S. Glashow and S. Weinberg, “Natural conservation laws for neutral currents”, *Phys. Rev. D* **15** (1958) doi:10.1103/PhysRevD.15.1958.
- [16] H. E. Haber and Y. Nir, “Multi-scalar models with a high-energy scale”, *Nucl. Phys. B* **335** (1990) 363, doi:10.1016/0550-3213(90)90499-4.
- [17] J. F. Gunion and H. E. Haber, “The CP-conserving two-Higgs-doublet model: the approach to the decoupling limit”, *Phys. Rev. D* **67** (2003) 075019, doi:10.1103/PhysRevD.67.075019, arXiv:hep-ph/0207010.
- [18] B. Dumont, J. F. Gunion, Y. Jiang, and S. Kraml, “Constraints on and future prospects for two-Higgs-doublet models in light of the LHC Higgs signal”, *Phys. Rev. D* **90** (2014) 035021, doi:10.1103/PhysRevD.90.035021, arXiv:1405.3584v1.
- [19] J. Bernon, J. F. Gunion, Y. Jiang, and S. Kraml, “Light Higgs bosons in two-Higgs-doublet models”, *Phys. Rev. D* **91** (2015) 075019, doi:10.1103/PhysRevD.91.075019, arXiv:1412.3385.
- [20] ATLAS Collaboration, “Search for neutral Higgs bosons of the minimal supersymmetric standard model in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector”, *JHEP* **11** (2014) 056, doi:10.1007/JHEP11(2014)056, arXiv:1409.6064.
- [21] CMS Collaboration, “Search for neutral MSSM Higgs bosons decaying to a pair of tau leptons in pp collisions”, *JHEP* **10** (2014) 160, doi:10.1007/JHEP10(2014)160, arXiv:1408.3316.
- [22] P. Fayet, “Supergauge invariant extension of the Higgs mechanism and a model for the electron and its neutrino”, *Nucl. Phys. B* **90** (1975) 104, doi:10.1016/0550-3213(75)90636-7.
- [23] P. Fayet, “Supersymmetry and weak, electromagnetic and strong interactions”, *Phys. Lett. B* **64** (1976) 159, doi:10.1016/0370-2693(76)90319-1.
- [24] P. Fayet, “Spontaneously broken supersymmetric theories of weak, electromagnetic and strong interactions”, *Phys. Lett. B* **69** (1977) 489, doi:10.1016/0370-2693(77)90852-8.
- [25] J. Kozaczuk and T. A. W. Martin, “Extending LHC coverage to light pseudoscalar mediators and coy dark sectors”, *JHEP* **04** (2015) 046, doi:10.1007/JHEP04(2015)046, arXiv:1501.07275.
- [26] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [27] F. Maltoni and T. Stelzer, “MadEvent: automatic event generation with MadGraph”, *JHEP* **02** (2003) 027, doi:10.1088/1126-6708/2003/02/027, arXiv:hep-ph/0208156.
- [28] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with parton shower simulations: the POWHEG method”, *JHEP* **11** (2007) 070, doi:10.1088/1126-6708/2007/11/070, arXiv:0709.2092.
- [29] T. Sjöstrand, S. Mrenna, and P. Skands, “PYTHIA 6.4 physics and manual”, *JHEP* **05** (2006) 026, doi:10.1088/1126-6708/2006/05/026, arXiv:hep-ph/0603175.

- [30] Pumplin, J. and Stump, D. R. and Huston, J. and Lai, H.-L. and Nadolsky, P. and Tung, W.-K., “New generation of parton distributions with uncertainties from global QCD analysis”, *JHEP* **07** (2002) 012, doi:10.1088/1126-6708/2002/07/012, arXiv:hep-ph/0201195.
- [31] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [32] CMS Collaboration, “Particle-flow event reconstruction in CMS and performance for jets, taus, and E_T^{miss} ”, CMS Physics Analysis Summary CMS-PAS-PFT-09-001, 2009.
- [33] CMS Collaboration, “Commissioning of the particle-flow event reconstruction with the first LHC collisions recorded in the CMS detector”, CMS Physics Analysis Summary CMS-PAS-PFT-10-001, 2010.
- [34] K. Rose, “Deterministic annealing for clustering, compression, classification, regression and related optimisation problems”, in *Proceedings of the IEEE*, volume 86, p. 22102239. 1998. doi:10.1109/5.726788.
- [35] W. Waltenberger, R. Frühwirth, and P. Vanlaer, “Adaptive vertex fitting”, *J. Phys. G* **34** (2007) N343, doi:10.1088/0954-3899/34/12/N01.
- [36] CMS Collaboration, “Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV”, *JINST* **7** (2012) P10002, doi:10.1088/1748-0221/7/10/P10002, arXiv:1206.4071.
- [37] CMS Collaboration, “Determination of jet energy calibration and transverse momentum resolution in CMS”, *JINST* **6** (2011) P11002, doi:10.1088/1748-0221/6/11/P11002, arXiv:1107.4277.
- [38] W. Adam, R. Frühwirth, A. Strandlie, and T. Todorov, “Reconstruction of electrons with the Gaussian-sum filter in the CMS tracker at the LHC”, *J. Phys. G* **31** (2005) N9, doi:10.1088/0954-3899/31/9/N01, arXiv:physics/0306087.
- [39] H. Voss, A. Höcker, J. Stelzer, and F. Tegenfeldt, “TMVA, the toolkit for multivariate data analysis with ROOT”, in *XIth International Workshop on Advanced Computing and Analysis Techniques in Physics Research (ACAT)*, p. 40. 2007. arXiv:physics/0703039.
- [40] CMS Collaboration, “Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *JINST* **10** (2015) P06005, doi:10.1088/1748-0221/10/06/P06005, arXiv:1502.02701.
- [41] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- k_t jet clustering algorithm”, *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
- [42] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet user manual”, *Eur. Phys. J. C* **72** (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.
- [43] CMS Collaboration, “Pileup jet identification”, CMS Physics Analysis Summary CMS-PAS-JME-13-005, 2013.
- [44] CMS Collaboration, “Identification of b-quark jets with the CMS experiment”, *JINST* **8** (2013) P04013, doi:10.1088/1748-0221/8/04/P04013, arXiv:1211.4462.

- [45] CMS Collaboration, “Performance of tau-lepton reconstruction and identification in CMS”, *JINST* **7** (2012) P01001, doi:10.1088/1748-0221/7/01/P01001, arXiv:1109.6034.
- [46] CMS Collaboration, “Reconstruction and identification of τ lepton decays to hadrons and ν_τ at CMS”, *JINST* **11** (2016), no. 01, P01019, doi:10.1088/1748-0221/11/01/P01019, arXiv:1510.07488.
- [47] CMS Collaboration, “Performance of the CMS missing transverse momentum reconstruction in pp data at $\sqrt{s} = 8$ TeV”, *JINST* **10** (2015) P02006, doi:10.1088/1748-0221/10/02/P02006, arXiv:1411.0511.
- [48] L. Bianchini, J. Conway, E. K. Friis, and C. Veelken, “Reconstruction of the Higgs mass in $H \rightarrow \tau\tau$ events by dynamical likelihood techniques”, *J. Phys. Conf. Ser.* **513** (2014) 022035, doi:10.1088/1742-6596/513/2/022035, arXiv:1603.05910.
- [49] CDF Collaboration, “Search for MSSM Higgs decaying to tau pairs”, CDF Public Note 7161, 2004.
- [50] S. Jadach, Z. Was, R. Decker, and J. H. Kuhn, “The tau decay library Tauola: Version 2.4”, *Comput. Phys. Commun.* **76** (1993) 361, doi:10.1016/0010-4655(93)90061-G.
- [51] CMS Collaboration, “Evidence for the 125 GeV Higgs boson decaying to a pair of τ leptons”, *JHEP* **05** (2014) 104, doi:10.1007/JHEP05(2014)104, arXiv:1401.5041.
- [52] CMS Collaboration, “Measurement of the differential cross section for top quark pair production in pp collisions at $\sqrt{s} = 8$ TeV”, *Eur. Phys. J. C* **75** (2015), no. 11, 542, doi:10.1140/epjc/s10052-015-3709-x, arXiv:1505.04480.
- [53] CMS Collaboration, “Observation of the associated production of a single top quark and a W boson in pp collisions at $\sqrt{s} = 8$ TeV”, *Phys. Rev. Lett.* **112** (2014), no. 23, 231802, doi:10.1103/PhysRevLett.112.231802, arXiv:1401.2942.
- [54] J. M. Campbell, R. K. Ellis, and C. Williams, “Vector boson pair production at the LHC”, *JHEP* **07** (2011) 018, doi:10.1007/JHEP07(2011)018, arXiv:1105.0020.
- [55] CMS Collaboration, “Measurement of the inclusive W and Z production cross sections in pp collisions at $\sqrt{s} = 7$ TeV with the CMS experiment”, *JHEP* **10** (2011) 132, doi:10.1007/JHEP10(2011)132, arXiv:1107.4789.
- [56] CMS Collaboration, “CMS luminosity based on pixel cluster counting — Summer 2013 update”, CMS Physics Analysis Summary CMS-PAS-LUM-13-001, 2013.
- [57] CMS Collaboration, “Measurement of W^+W^- and ZZ production cross sections in pp collisions at $\sqrt{s} = 8$ TeV”, *Phys. Lett. B* **721** (2013) 190, doi:10.1016/j.physletb.2013.03.027, arXiv:1301.4698.
- [58] S. Alekhin et al., “The PDF4LHC Working Group interim report”, (2011). arXiv:1101.0536.
- [59] A. D. Martin, W. J. Stirling, R. S. Thorne, and G. Watt, “Parton distributions for the LHC”, *Eur. Phys. J. C* **63** (2009) 189, doi:10.1140/epjc/s10052-009-1072-5, arXiv:0901.0002.

- [60] R. D. Ball et al., “Parton distributions with LHC data”, *Nucl. Phys. B* **867** (2012) 244, doi:10.1016/j.nuclphysb.2012.10.003, arXiv:1207.1303.
- [61] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.
- [62] CMS Collaboration, “Measurement of differential top-quark pair production cross sections in pp collisions at $\sqrt{s} = 7$ TeV”, *Eur. Phys. J. C* **73** (2013), no. 3, 2339, doi:10.1140/epjc/s10052-013-2339-4, arXiv:1211.2220.
- [63] R. Barlow and C. Beeston, “Fitting using finite Monte Carlo samples”, *Comp. Phys. Comm.* **77** (1993) 219, doi:10.1016/0010-4655(93)90005-W.
- [64] A. L. Read, “Presentation of search results: the CL_s technique”, *J. Phys. G* **28** (2002) 2693, doi:10.1088/0954-3899/28/10/313.
- [65] T. Junk, “Confidence level computation for combining searches with small statistics”, *Nucl. Instrum. Meth. A* **434** (1999) 435, doi:10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.
- [66] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, “Asymptotic formulae for likelihood-based tests of new physics”, *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727. [Erratum: doi:10.1140/epjc/s10052-013-2501-z].
- [67] ATLAS and CMS, LHC Higgs Combination Group, “Procedure for the LHC Higgs boson search combination in Summer 2011”, Technical Report ATL-PHYS-PUB 2011-11, CMS NOTE 2011/005, CERN, 2011.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria

W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth¹, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler¹, V. Knünz, A. König, M. Krammer¹, I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady², B. Rahbaran, H. Rohringer, J. Schieck¹, R. Schöffbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz¹

National Centre for Particle and High Energy Physics, Minsk, Belarus

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

S. Alderweireldt, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, J. Lauwers, S. Luyckx, R. Rougny, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Vrije Universiteit Brussel, Brussel, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, N. Daci, I. De Bruyn, K. Deroover, N. Heracleous, J. Keaveney, S. Lowette, L. Moreels, A. Olbrechts, Q. Python, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Van Parijs

Université Libre de Bruxelles, Bruxelles, Belgium

P. Barria, H. Brun, C. Caillol, B. Clerbaux, G. De Lentdecker, G. Fasanella, L. Favart, A. Grebenyuk, G. Karapostoli, T. Lenzi, A. Léonard, T. Maerschalk, A. Marinov, L. Perniè, A. Randle-conde, T. Reis, T. Seva, C. Vander Velde, P. Vanlaer, R. Yonamine, F. Zenoni, F. Zhang³

Ghent University, Ghent, Belgium

K. Beernaert, L. Benucci, A. Cimmino, S. Crucy, D. Dobur, A. Fagot, G. Garcia, M. Gul, J. Mccartin, A.A. Ocampo Rios, D. Poyraz, D. Ryckbosch, S. Salva, M. Sigamani, N. Strobbe, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

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

S. Basegmez, C. Beluffi⁴, O. Bondu, S. Brochet, G. Bruno, A. Caudron, L. Ceard, G.G. Da Silva, C. Delaere, D. Favart, L. Forthomme, A. Giammanco⁵, J. Hollar, A. Jafari, P. Jez, M. Komm, V. Lemaître, A. Mertens, C. Nuttens, L. Perrini, A. Pin, K. Piotrkowski, A. Popov⁶, L. Quertenmont, M. Selvaggi, M. Vidal Marono

Université de Mons, Mons, Belgium

N. Beliy, G.H. Hammad

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, G.A. Alves, L. Brito, M. Correa Martins Junior, M. Hamer, C. Hensel, C. Mora Herrera, A. Moraes, M.E. Pol, P. Rebello Teles

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

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato⁷, A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, A. Sznajder, E.J. Tonelli Manganote⁷, A. Vilela Pereira

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

S. Ahuja^a, C.A. Bernardes^b, A. De Souza Santos^b, S. Dogra^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, P.G. Mercadante^b, C.S. Moon^{a,8}, S.F. Novaes^a, Sandra S. Padula^a, D. Romero Abad, J.C. Ruiz Vargas

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

University of Sofia, Sofia, Bulgaria

A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, T. Cheng, R. Du, C.H. Jiang, R. Plestina⁹, F. Romeo, S.M. Shaheen, J. Tao, C. Wang, Z. Wang, H. Zhang

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

C. Asawatrangkuldee, Y. Ban, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu, W. Zou

Universidad de Los Andes, Bogota, Colombia

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

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

N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, K. Kadija, J. Luetic, S. Micanovic, L. Sudic

University of Cyprus, Nicosia, Cyprus

A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

Charles University, Prague, Czech Republic

M. Bodlak, M. Finger¹⁰, M. Finger Jr.¹⁰

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

A.A. Abdelalim^{11,12}, A. Awad, A. Mahrous¹¹, A. Radi^{13,14}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

B. Calpas, M. Kadastik, M. Murumaa, M. Raidal, A. Tiko, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

J. Härkönen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland

J. Talvitie, T. Tuuva

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro, F. Ferri,

S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, M. Machet, J. Malcles, J. Rander, A. Rosowsky, M. Titov, A. Zghiche

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, T. Dahms, O. Davignon, N. Filipovic, A. Florent, R. Granier de Cassagnac, S. Lisniak, L. Mastrolorenzo, P. Miné, I.N. Naranjo, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, J.B. Sauvan, Y. Sirois, T. Strebler, Y. Yilmaz, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

J.-L. Agram¹⁵, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte¹⁵, X. Coubez, J.-C. Fontaine¹⁵, D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, J.A. Merlin², K. Skovpen, P. Van Hove

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France

S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

S. Beauceron, C. Bernet, G. Boudoul, E. Bouvier, C.A. Carrillo Montoya, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, J.D. Ruiz Alvarez, D. Sabes, L. Sgandurra, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret

Georgian Technical University, Tbilisi, Georgia

T. Toriashvili¹⁶

Tbilisi State University, Tbilisi, Georgia

Z. Tsamalaidze¹⁰

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

C. Autermann, S. Beranek, M. Edelhoff, L. Feld, A. Heister, M.K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, S. Schael, J.F. Schulte, T. Verlage, H. Weber, B. Wittmer, V. Zhukov⁶

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

M. Ata, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, S. Knutzen, P. Kreuzer, M. Merschmeyer, A. Meyer, P. Millet, M. Olschewski, K. Padeken, P. Papacz, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, L. Sonnenschein, D. Teyssier, S. Thüer

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

V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Künsken, J. Lingemann², A. Nehr Korn, A. Nowack, I.M. Nugent, C. Pistone, O. Pooth, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, I. Asin, N. Bartosik, O. Behnke, U. Behrens, A.J. Bell, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, S. Choudhury, F. Costanza, C. Diez Pardos, G. Dolinska, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flucke, E. Gallo¹⁷, J. Garay Garcia, A. Geiser, A. Gizhko, P. Gunnellini, J. Hauk, M. Hempel¹⁸, H. Jung,

A. Kalogeropoulos, O. Karacheban¹⁸, M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann¹⁸, R. Mankel, I. Marfin¹⁸, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, S. Naumann-Emme, A. Nayak, E. Ntomari, H. Perrey, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M.Ö. Sahin, P. Saxena, T. Schoerner-Sadenius, M. Schröder, C. Seitz, S. Spannagel, K.D. Trippkewitz, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany

V. Blobel, M. Centis Vignali, A.R. Draeger, J. Erfle, E. Garutti, K. Goebel, D. Gonzalez, M. Görner, J. Haller, M. Hoffmann, R.S. Höing, A. Junkes, R. Klanner, R. Kogler, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, M. Meyer, D. Nowatschin, J. Ott, F. Pantaleo², T. Peiffer, A. Perieanu, N. Pietsch, J. Poehlsen, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, J. Schwandt, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

M. Akbiyik, C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, F. Colombo, W. De Boer, A. Descroix, A. Dierlamm, S. Fink, F. Frensch, M. Giffels, A. Gilbert, F. Hartmann², S.M. Heindl, U. Husemann, I. Katkov⁶, A. Kornmayer², P. Lobelle Pardo, B. Maier, H. Mildner, M.U. Mozer, T. Müller, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, M. Weber, T. Weiler, C. Wöhrmann, R. Wolf

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

G. Anagnostou, G. Daskalakis, T. Gerasis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, A. Psallidas, I. Topsis-Giotis

University of Athens, Athens, Greece

A. Agapitos, S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

University of Ioánnina, Ioánnina, Greece

I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Loukas, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, A. Hazi, P. Hidas, D. Horvath¹⁹, F. Sikler, V. Veszpremi, G. Vesztergombi²⁰, A.J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi²¹, J. Molnar, Z. Szillasi

University of Debrecen, Debrecen, Hungary

M. Bartók²², A. Makovec, P. Raics, Z.L. Trocsanyi, B. Ujvari

National Institute of Science Education and Research, Bhubaneswar, India

P. Mal, K. Mandal, D.K. Sahoo, N. Sahoo, S.K. Swain

Panjab University, Chandigarh, India

S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, R. Gupta, U. Bhawandeep, A.K. Kalsi, A. Kaur, M. Kaur, R. Kumar, A. Mehta, M. Mittal, J.B. Singh, G. Walia

University of Delhi, Delhi, India

Ashok Kumar, A. Bhardwaj, B.C. Choudhary, R.B. Garg, A. Kumar, S. Malhotra, M. Naimuddin, N. Nishu, K. Ranjan, R. Sharma, V. Sharma

Saha Institute of Nuclear Physics, Kolkata, India

S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutta, Sa. Jain, N. Majumdar, A. Modak, K. Mondal, S. Mukherjee, S. Mukhopadhyay, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan

Bhabha Atomic Research Centre, Mumbai, India

A. Abdulsalam, R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty², L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research, Mumbai, India

T. Aziz, S. Banerjee, S. Bhowmik²³, R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu²⁴, G. Kole, S. Kumar, B. Mahakud, M. Maity²³, G. Majumder, K. Mazumdar, S. Mitra, G.B. Mohanty, B. Parida, T. Sarkar²³, K. Sudhakar, N. Sur, B. Sutar, N. Wickramage²⁵

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

S. Chauhan, S. Dube, S. Sharma

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

H. Bakhshiansohi, H. Behnamian, S.M. Etesami²⁶, A. Fahim²⁷, R. Goldouzian, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh²⁸, M. Zeinali

University College Dublin, Dublin, Ireland

M. Felcini, M. Grunewald

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

M. Abbrescia^{a,b}, C. Calabria^{a,b}, C. Caputo^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, G. Maggi^{a,c}, M. Maggi^a, G. Miniello^{a,b}, S. My^{a,c}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^{a,b}, A. Ranieri^a, G. Selvaggi^{a,b}, L. Silvestris^{a,2}, R. Venditti^{a,b}, P. Verwilligen^a

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

G. Abbiendi^a, C. Battilana², A.C. Benvenuti^a, D. Bonacorsi^{a,b}, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, S.S. Chhibra^{a,b}, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,b}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, S. Marcellini^a, G. Masetti^a, A. Montanari^a, F.L. Navarria^{a,b}, A. Perrotta^a, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, N. Tosi^{a,b}, R. Travaglini^{a,b}

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

G. Cappello^a, M. Chiorboli^{a,b}, S. Costa^{a,b}, F. Giordano^{a,b}, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

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

G. Barbagli^a, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, S. Gonzi^{a,b}, V. Gori^{a,b}, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, A. Tropiano^{a,b}, L. Viliani^{a,b}

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera

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

V. Calvelli^{a,b}, F. Ferro^a, M. Lo Vetere^{a,b}, M.R. Monge^{a,b}, E. Robutti^a, S. Tosi^{a,b}

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

L. Brianza, M.E. Dinardo^{a,b}, S. Fiorendi^{a,b}, S. Gennai^a, R. Gerosa^{a,b}, A. Ghezzi^{a,b}, P. Govoni^{a,b},

S. Malvezzi^a, R.A. Manzoni^{a,b}, B. Marzocchi^{a,b,2}, 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}

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, N. Cavallo^{a,c}, S. Di Guida^{a,d,2}, M. Esposito^{a,b}, F. Fabozzi^{a,c}, A.O.M. Iorio^{a,b}, G. Lanza^a, L. Lista^a, S. Meola^{a,d,2}, M. Merola^a, P. Paolucci^{a,2}, C. Sciacca^{a,b}, F. Thyssen

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

P. Azzi^{a,2}, N. Bacchetta^a, M. Bellato^a, L. Benato^{a,b}, D. Bisello^{a,b}, A. Boletti^{a,b}, A. Branca^{a,b}, R. Carlin^{a,b}, P. Checchia^a, M. Dall'Osso^{a,b,2}, T. Dorigo^a, U. Dosselli^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, S. Lacaprara^a, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, J. Pazzini^{a,b}, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, M. Tosi^{a,b}, S. Ventura^a, M. Zanetti, P. Zotto^{a,b}, A. Zucchetta^{a,b,2}, G. Zumerle^{a,b}

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

A. Braghieri^a, A. Magnani^a, 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

L. Alunni Solestizi^{a,b}, M. Biasini^{a,b}, G.M. Bilei^a, D. Ciangottini^{a,b,2}, L. Fanò^{a,b}, P. Lariccia^{a,b}, G. Mantovani^{a,b}, M. Menichelli^a, A. Saha^a, A. Santocchia^{a,b}, A. Spiezia^{a,b}

INFN Sezione di Pisa ^a, Università di Pisa ^b, Scuola Normale Superiore di Pisa ^c, Pisa, Italy

K. Androsov^{a,29}, P. Azzurri^a, G. Bagliesi^a, J. Bernardini^a, T. Boccali^a, G. Broccolo^{a,c}, R. Castaldi^a, M.A. Ciocci^{a,29}, R. Dell'Orso^a, S. Donato^{a,c,2}, G. Fedi, L. Foà^{a,c†}, A. Giassi^a, M.T. Grippo^{a,29}, F. Ligabue^{a,c}, T. Lomtadze^a, L. Martini^{a,b}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, A. Savoy-Navarro^{a,30}, A.T. Serban^a, P. Spagnolo^a, P. Squillacioti^{a,29}, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verdini^a

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

L. Barone^{a,b}, F. Cavallari^a, G. D'imperio^{a,b,2}, D. Del Re^{a,b}, M. Diemoz^a, S. Gelli^{a,b}, C. Jorda^a, E. Longo^{a,b}, F. Margaroli^{a,b}, P. Meridiani^a, G. Organtini^{a,b}, R. Paramatti^a, F. Preiato^{a,b}, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{a,b}, P. Traczyk^{a,b,2}

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,2}, S. Argiro^{a,b}, M. Arneodo^{a,c}, R. Bellan^{a,b}, C. Biino^a, N. Cartiglia^a, M. Costa^{a,b}, R. Covarelli^{a,b}, A. Degano^{a,b}, N. Demaria^a, L. Finco^{a,b,2}, B. Kiani^{a,b}, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, E. Monteil^{a,b}, M. Musich^a, M.M. Obertino^{a,b}, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G.L. Pinna Angioni^{a,b}, F. Ravera^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, A. Solano^{a,b}, A. Staiano^a, U. Tamponi^a

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

S. Belforte^a, V. Candelise^{a,b,2}, M. Casarsa^a, F. Cossutti^a, G. Della Ricca^{a,b}, B. Gobbo^a, C. La Licata^{a,b}, M. Marone^{a,b}, A. Schizzi^{a,b}, A. Zanetti^a

Kangwon National University, Chunchon, Korea

A. Kropivnitskaya, S.K. Nam

Kyungpook National University, Daegu, Korea

D.H. Kim, G.N. Kim, M.S. Kim, D.J. Kong, S. Lee, Y.D. Oh, A. Sakharov, D.C. Son

Chonbuk National University, Jeonju, Korea

J.A. Brochero Cifuentes, H. Kim, T.J. Kim, M.S. Ryu

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

S. Song

Korea University, Seoul, Korea

S. Choi, Y. Go, D. Gyun, B. Hong, M. Jo, H. Kim, Y. Kim, B. Lee, K. Lee, K.S. Lee, S. Lee, S.K. Park, Y. Roh

Seoul National University, Seoul, Korea

H.D. Yoo

University of Seoul, Seoul, Korea

M. Choi, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park, G. Ryu

Sungkyunkwan University, Suwon, Korea

Y. Choi, J. Goh, D. Kim, E. Kwon, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania

A. Juodagalvis, J. Vaitkus

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

I. Ahmed, Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali³¹, F. Mohamad Idris³², W.A.T. Wan Abdullah, M.N. Yusli

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

E. Casimiro Linares, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz³³, A. Hernandez-Almada, R. Lopez-Fernandez, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

I. Pedraza, H.A. Salazar Ibarguen

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

A. Morelos Pineda

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

P.H. Butler

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

A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, T. Khurshid, M. Shoaib

National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

G. Brona, K. Bunkowski, A. Byszuk³⁴, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, M. Walczak

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

P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, N. Leonardo, L. Lloret Iglesias, F. Nguyen, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadrucio, J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Konoplyanikov, A. Lanev, A. Malakhov, V. Matveev³⁵, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

V. Golovtsov, Y. Ivanov, V. Kim³⁶, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Epshteyn, V. Gavrillov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, E. Vlasov, A. Zhokin

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia

A. Bylinkin

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin³⁷, I. Dremin³⁷, M. Kirakosyan, A. Leonidov³⁷, G. Mesyats, S.V. Rusakov, A. Vinogradov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin³⁸, L. Dudko, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Myagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

P. Adzic³⁹, M. Ekmedzic, J. Milosevic, V. Rekovic

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

J. Alcaraz Maestre, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, E. Navarro De Martino, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, J.F. de Trocóniz, M. Missiroli, D. Moran

Universidad de Oviedo, Oviedo, Spain

J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, J.M. Vizan Garcia

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

I.J. Cabrillo, A. Calderon, J.R. Castiñeiras De Saa, P. De Castro Manzano, J. Duarte Campderros, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, A. Benaglia, J. Bendavid, L. Benhabib, J.F. Benitez, G.M. Berruti, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, R. Castello, G. Cerminara, S. Colafranceschi⁴⁰, M. D'Alfonso, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, F. De Guio, A. De Roeck, S. De Visscher, E. Di Marco, M. Dobson, M. Dordevic, B. Dorney, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, G. Franzoni, W. Funk, D. Gigi, K. Gill, D. Giordano, M. Girone, F. Glege, R. Guida, S. Gundacker, M. Guthoff, J. Hammer, P. Harris, J. Hegeman, V. Innocente, P. Janot, H. Kirschenmann, M.J. Kortelainen, K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenço, M.T. Lucchini, N. Magini, L. Malgeri, M. Mannelli, A. Martelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, M.V. Nemallapudi, H. Neugebauer, S. Orfanelli⁴¹, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, D. Piparo, A. Racz, G. Rolandi⁴², M. Rovere, M. Ruan, H. Sakulin, C. Schäfer, C. Schwick, A. Sharma, P. Silva, M. Simon, P. Sphicas⁴³, D. Spiga, J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Triossi, A. Tsiros, G.I. Veres²⁰, N. Wardle, H.K. Wöhri, A. Zagozdinska³⁴, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, D. Renker, T. Rohe

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

F. Bachmair, L. Bäni, L. Bianchini, M.A. Buchmann, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, P. Eller, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, W. Lustermann, B. Mangano, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, L. Perrozzi, M. Quittnat, M. Rossini, A. Starodumov⁴⁴, M. Takahashi, V.R. Tavolaro, K. Theofilatos, R. Wallny

Universität Zürich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler⁴⁵, L. Caminada, M.F. Canelli, V. Chiochia, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, J. Ngadiuba, D. Pinna, P. Robmann, F.J. Ronga, D. Salerno, Y. Yang

National Central University, Chung-Li, Taiwan

M. Cardaci, K.H. Chen, T.H. Doan, Sh. Jain, R. Khurana, M. Konyushikhin, C.M. Kuo, W. Lin, Y.J. Lu, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

Arun Kumar, R. Bartek, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, F. Fiori, U. Grundler, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, M. Miñano Moya, E. Petrakou, J.f. Tsai, Y.M. Tzeng

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

B. Asavapibhop, K. Kovitanggoon, G. Singh, N. Srimanobhas, N. Suwonjandee

Cukurova University, Adana, Turkey

A. Adiguzel, M.N. Bakirci⁴⁶, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal⁴⁷, G. Onengut⁴⁸, K. Ozdemir⁴⁹, A. Polatoz, D. Sunar Cerci⁵⁰, H. Topakli⁴⁶, M. Vergili, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

I.V. Akin, B. Bilin, S. Bilmis, B. Isildak⁵¹, G. Karapinar⁵², M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

E.A. Albayrak⁵³, E. Gülmez, M. Kaya⁵⁴, O. Kaya⁵⁵, T. Yetkin⁵⁶

Istanbul Technical University, Istanbul, Turkey

K. Cankocak, S. Sen⁵⁷, F.I. Vardarli

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, P. Sorokin

University of Bristol, Bristol, United Kingdom

R. Aggleton, F. Ball, L. Beck, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, Z. Meng, D.M. Newbold⁵⁸, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, D. Smith, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell, A. Belyaev⁵⁹, C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley, S.D. Worm

Imperial College, London, United Kingdom

M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, S. Casasso, M. Citron, D. Colling, L. Corpe, N. Cripps, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, P. Dunne, A. Elwood, W. Ferguson, J. Fulcher, D. Futyan, G. Hall, G. Iles, M. Kenzie, R. Lane, R. Lucas⁵⁸, L. Lyons, A.-M. Magnan, S. Malik, J. Nash, A. Nikitenko⁴⁴, J. Pela, M. Pesaresi, K. Petridis, D.M. Raymond, A. Richards, A. Rose, C. Seez, A. Tapper, K. Uchida, M. Vazquez Acosta⁶⁰, T. Virdee, S.C. Zenz

Brunel University, Uxbridge, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, USA

A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, A. Kasmi, H. Liu, N. Pastika

The University of Alabama, Tuscaloosa, USA

O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio

Boston University, Boston, USA

A. Avetisyan, T. Bose, C. Fantasia, D. Gastler, P. Lawson, D. Rankin, C. Richardson, J. Rohlf, J. St. John, L. Sulak, D. Zou

Brown University, Providence, USA

J. Alimena, E. Berry, S. Bhattacharya, D. Cutts, N. Dhingra, A. Ferapontov, A. Garabedian, J. Hakala, U. Heintz, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Piperov, S. Sagir, T. Sinthuprasith, R. Syarif

University of California, Davis, Davis, USA

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, M. Gardner, J. Gunion, Y. Jiang, W. Ko, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, F. Ricci-Tam, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

University of California, Los Angeles, USA

R. Cousins, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, D. Saltzberg, E. Takasugi, V. Valuev, M. Weber

University of California, Riverside, Riverside, USA

K. Burt, R. Clare, J. Ellison, J.W. Gary, G. Hanson, J. Heilman, M. Ivova PANEVA, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, A. Luthra, M. Malberti, M. Olmedo Negrete, A. Shrinivas, H. Wei, S. Wimpenny, B. R. Yates

University of California, San Diego, La Jolla, USA

J.G. Branson, G.B. Cerati, S. Cittolin, R.T. D'Agnolo, A. Holzner, R. Kelley, D. Klein, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech⁶¹, C. Welke, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara, Santa Barbara, USA

D. Barge, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Gran, J. Incandela, C. Justus, N. Mccoll, S.D. Mullin, J. Richman, D. Stuart, I. Suarez, W. To, C. West, J. Yoo

California Institute of Technology, Pasadena, USA

D. Anderson, A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, J. Duarte, A. Mott, H.B. Newman, C. Pena, M. Pierini, M. Spiropulu, J.R. Vlimant, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA

M.B. Andrews, V. Azzolini, A. Calamba, B. Carlson, T. Ferguson, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev

University of Colorado Boulder, Boulder, USA

J.P. Cumalat, W.T. Ford, A. Gaz, F. Jensen, A. Johnson, M. Krohn, T. Mulholland, U. Nauenberg, K. Stenson, S.R. Wagner

Cornell University, Ithaca, USA

J. Alexander, A. Chatterjee, J. Chaves, J. Chu, S. Dittmer, N. Eggert, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, W. Sun, S.M. Tan, W.D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, P. Wittich

Fermi National Accelerator Laboratory, Batavia, USA

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir, V.D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, D. Hare, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, S. Jindariani, M. Johnson, U. Joshi, A.W. Jung, B. Klima, B. Kreis, S. Kwan[†], S. Lammel, J. Linacre, D. Lincoln, R. Lipton, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, J.M. Marraffino, V.I. Martinez Outschoorn,

S. Maruyama, D. Mason, P. McBride, P. Merkel, K. Mishra, S. Mrenna, S. Nahn, C. Newman-Holmes, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, H.A. Weber, A. Whitbeck, F. Yang

University of Florida, Gainesville, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Carnes, M. Carver, D. Curry, S. Das, G.P. Di Giovanni, R.D. Field, I.K. Furic, J. Hugon, J. Konigsberg, A. Korytov, J.F. Low, P. Ma, K. Matchev, H. Mei, P. Milenovic⁶², G. Mitselmakher, D. Rank, R. Rossin, L. Shchutska, M. Snowball, D. Sperka, N. Terentyev, L. Thomas, J. Wang, S. Wang, J. Yelton

Florida International University, Miami, USA

S. Hewamanage, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, USA

A. Ackert, J.R. Adams, T. Adams, A. Askew, J. Bochenek, B. Diamond, J. Haas, S. Hagopian, V. Hagopian, K.F. Johnson, A. Khatiwada, H. Prosper, V. Veeraraghavan, M. Weinberg

Florida Institute of Technology, Melbourne, USA

M.M. Baarmand, V. Bhopatkar, M. Hohlmann, H. Kalakhety, D. Noonan, T. Roy, F. Yumiceva

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

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, P. Kurt, C. O'Brien, I.D. Sandoval Gonzalez, C. Silkworth, P. Turner, N. Varelas, Z. Wu, M. Zakaria

The University of Iowa, Iowa City, USA

B. Bilki⁶³, W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya⁶⁴, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok⁵³, A. Penzo, C. Snyder, P. Tan, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, USA

I. Anderson, B.A. Barnett, B. Blumenfeld, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, C. Martin, M. Osherson, M. Swartz, M. Xiao, Y. Xin, C. You

The University of Kansas, Lawrence, USA

P. Baringer, A. Bean, G. Benelli, C. Bruner, R.P. Kenny III, D. Majumder, M. Malek, M. Murray, S. Sanders, R. Stringer, Q. Wang

Kansas State University, Manhattan, USA

A. Ivanov, K. Kaadze, S. Khalil, M. Makouski, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

Lawrence Livermore National Laboratory, Livermore, USA

D. Lange, F. Rebassoo, D. Wright

University of Maryland, College Park, USA

C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, J.A. Gomez, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Kolberg, J. Kunkle, Y. Lu, A.C. Mignerey, Y.H. Shin, A. Skuja, M.B. Tonjes, S.C. Tonwar

Massachusetts Institute of Technology, Cambridge, USA

A. Apyan, R. Barbieri, A. Baty, K. Bierwagen, S. Brandt, W. Busza, I.A. Cali, Z. Demiragli, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Gulhan, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, A.C. Marini, C. Mcginn,

C. Mironov, X. Niu, C. Paus, D. Ralph, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephans, K. Sumorok, M. Varma, D. Velicanu, J. Veverka, J. Wang, T.W. Wang, B. Wyslouch, M. Yang, V. Zhukova

University of Minnesota, Minneapolis, USA

B. Dahmes, A. Evans, A. Finkel, A. Gude, P. Hansen, S. Kalafut, S.C. Kao, K. Klapoetke, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, N. Tambe, J. Turkewitz

University of Mississippi, Oxford, USA

J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA

E. Avdeeva, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, J. Keller, D. Knowlton, I. Kravchenko, J. Lazo-Flores, F. Meier, J. Monroy, F. Ratnikov, J.E. Siado, G.R. Snow

State University of New York at Buffalo, Buffalo, USA

M. Alyari, J. Dolen, J. George, A. Godshalk, C. Harrington, I. Iashvili, J. Kaisen, A. Kharchilava, A. Kumar, S. Rappoccio

Northeastern University, Boston, USA

G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, R.-J. Wang, D. Wood, J. Zhang

Northwestern University, Evanston, USA

K.A. Hahn, A. Kubik, N. Mucia, N. Odell, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA

A. Brinkerhoff, N. Dev, M. Hildreth, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, S. Lynch, N. Marinelli, F. Meng, C. Mueller, Y. Musienko³⁵, T. Pearson, M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, N. Valls, M. Wayne, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA

L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, A. Hart, C. Hill, R. Hughes, W. Ji, K. Kotov, T.Y. Ling, B. Liu, W. Luo, D. Puigh, M. Rodenburg, B.L. Winer, H.W. Wulsin

Princeton University, Princeton, USA

O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S.A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, C. Palmer, P. Piroué, X. Quan, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

University of Puerto Rico, Mayaguez, USA

S. Malik

Purdue University, West Lafayette, USA

V.E. Barnes, D. Benedetti, D. Bortoletto, L. Gutay, M.K. Jha, M. Jones, K. Jung, M. Kress, D.H. Miller, N. Neumeister, B.C. Radburn-Smith, X. Shi, I. Shipsey, D. Silvers, J. Sun, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu

Purdue University Calumet, Hammond, USA

N. Parashar, J. Stupak

Rice University, Houston, USA

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

University of Rochester, Rochester, USA

B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, A. Harel, O. Hindrichs, A. Khukhunaishvili, G. Petrillo, M. Verzetti

The Rockefeller University, New York, USA

L. Demortier

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

S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, A. Lath, K. Nash, S. Panwalkar, M. Park, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, USA

M. Foerster, G. Riley, K. Rose, S. Spanier, A. York

Texas A&M University, College Station, USA

O. Bouhali⁶⁵, A. Castaneda Hernandez⁶⁵, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon⁶⁶, V. Krutelyov, R. Mueller, I. Osipenkov, Y. Pakhotin, R. Patel, A. Perloff, A. Rose, A. Safonov, A. Tatarinov, K.A. Ulmer²

Texas Tech University, Lubbock, USA

N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Duderu, J. Faulkner, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, S. Undleeb, I. Volobouev

Vanderbilt University, Nashville, USA

E. Appelt, A.G. Delannoy, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, Y. Mao, A. Melo, H. Ni, P. Sheldon, B. Snook, S. Tuo, J. Velkovska, Q. Xu

University of Virginia, Charlottesville, USA

M.W. Arenton, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Lin, C. Neu, X. Sun, Y. Wang, E. Wolfe, J. Wood, F. Xia

Wayne State University, Detroit, USA

C. Clarke, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, J. Sturdy

University of Wisconsin - Madison, Madison, WI, USA

D.A. Belknap, D. Carlsmith, M. Cepeda, A. Christian, S. Dasu, L. Dodd, S. Duric, E. Friis, B. Gomber, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, T. Ruggles, T. Sarangi, A. Savin, A. Sharma, N. Smith, W.H. Smith, D. Taylor, N. Woods

†: Deceased

1: Also at Vienna University of Technology, Vienna, Austria

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

3: Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

4: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

5: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

6: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University,

Moscow, Russia

- 7: Also at Universidade Estadual de Campinas, Campinas, Brazil
- 8: Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France
- 9: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
- 10: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 11: Also at Helwan University, Cairo, Egypt
- 12: Now at Zewail City of Science and Technology, Zewail, Egypt
- 13: Also at British University in Egypt, Cairo, Egypt
- 14: Now at Ain Shams University, Cairo, Egypt
- 15: Also at Université de Haute Alsace, Mulhouse, France
- 16: Also at Tbilisi State University, Tbilisi, Georgia
- 17: Also at University of Hamburg, Hamburg, Germany
- 18: Also at Brandenburg University of Technology, Cottbus, Germany
- 19: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 20: Also at Eötvös Loránd University, Budapest, Hungary
- 21: Also at University of Debrecen, Debrecen, Hungary
- 22: Also at Wigner Research Centre for Physics, Budapest, Hungary
- 23: Also at University of Visva-Bharati, Santiniketan, India
- 24: Now at King Abdulaziz University, Jeddah, Saudi Arabia
- 25: Also at University of Ruhuna, Matara, Sri Lanka
- 26: Also at Isfahan University of Technology, Isfahan, Iran
- 27: Also at University of Tehran, Department of Engineering Science, Tehran, Iran
- 28: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 29: Also at Università degli Studi di Siena, Siena, Italy
- 30: Also at Purdue University, West Lafayette, USA
- 31: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
- 32: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
- 33: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
- 34: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- 35: Also at Institute for Nuclear Research, Moscow, Russia
- 36: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 37: Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- 38: Also at California Institute of Technology, Pasadena, USA
- 39: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 40: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
- 41: Also at National Technical University of Athens, Athens, Greece
- 42: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 43: Also at University of Athens, Athens, Greece
- 44: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 45: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
- 46: Also at Gaziosmanpasa University, Tokat, Turkey
- 47: Also at Mersin University, Mersin, Turkey
- 48: Also at Cag University, Mersin, Turkey
- 49: Also at Piri Reis University, Istanbul, Turkey
- 50: Also at Adiyaman University, Adiyaman, Turkey
- 51: Also at Ozyegin University, Istanbul, Turkey
- 52: Also at Izmir Institute of Technology, Izmir, Turkey

- 53: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 54: Also at Marmara University, Istanbul, Turkey
- 55: Also at Kafkas University, Kars, Turkey
- 56: Also at Yildiz Technical University, Istanbul, Turkey
- 57: Also at Hacettepe University, Ankara, Turkey
- 58: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 59: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 60: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
- 61: Also at Utah Valley University, Orem, USA
- 62: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 63: Also at Argonne National Laboratory, Argonne, USA
- 64: Also at Erzincan University, Erzincan, Turkey
- 65: Also at Texas A&M University at Qatar, Doha, Qatar
- 66: Also at Kyungpook National University, Daegu, Korea