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Searches for a heavy scalar boson H decaying to a pair of 125 GeV Higgs bosons hh or for a heavy pseudoscalar boson A decaying to Zh, in the final states with $h \to \tau\tau$

CMS Collaboration *

CERN, Switzerland

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ABSTRACT

A search for a heavy scalar boson H decaying into a pair of lighter standard-model-like 125 GeV Higgs bosons hh and a search for a heavy pseudoscalar boson A decaying into a Z and an h boson are presented. The searches are performed on a data set corresponding to an integrated luminosity of 19.7 fb^{-1} of pp collision data at a centre-of-mass energy of 8 TeV, collected by CMS in 2012. A final state consisting of two τ leptons and two b jets is used to search for the $H \to hh$ decay. A final state consisting of two τ leptons from the h boson decay, and two additional leptons from the Z boson decay, is used to search for the decay $A \to Zh$. The results are interpreted in the context of two-Higgs-doublet models. No excess is found above the standard model expectation and upper limits are set on the heavy boson production cross sections in the mass ranges $260 < m_H < 350$ GeV and $220 < m_A < 350$ GeV.

1. Introduction

The discovery of additional Higgs bosons at the LHC would provide direct evidence of physics beyond the standard model (SM). There are several types of models that require two Higgs doublets [1–3]. For example the minimal supersymmetric extension of the SM (MSSM) requires the introduction of an additional Higgs doublet, where one Higgs doublet couples to up-type quarks and the other to down-type quarks [4–11]. This leads to the prediction of five Higgs particles: one light and one heavy CP-even Higgs boson, h and H, one CP-odd Higgs boson A, and two charged Higgs bosons $H^{\pm}$ [2,12]. The masses and couplings of these bosons are interrelated and, at tree level, can be described by two parameters, which are often chosen to be the mass of the pseudoscalar boson m_A and the ratio of the vacuum expectation values of the neutral components of the two Higgs doublets $\tan\beta$. However, radiative corrections [13–17] introduce dependencies on other parameters namely the mass of the top quark m_t, the scale of the soft supersymmetry breaking masses M_{SUSY}, the higgsino mass parameter μ, the wino mass parameter M_2, the third-generation trilinear couplings, A_t, A_b, and A_τ, the mass of the gluino $m_{\tilde{g}}$, and the third-generation slepton mass parameter $M_{\tilde{\ell}_3}$.

Direct searches for the neutral MSSM Higgs bosons have been performed by the CMS and ATLAS Collaborations [18–20] using the benchmark scenarios proposed in Ref. [21]. In these scenarios the parameters involved in the radiative corrections for the Higgs boson masses and couplings have been fixed, and only the two parameters m_A and $\tan\beta$ remain free. The value of M_{SUSY} was fixed at around 1 TeV, which produces a lightest CP-even Higgs boson with a mass m_h lower than the observed Higgs boson mass of $125.09 \pm 0.21\,(\text{stat}) \pm 0.11\,(\text{syst})$ GeV [22], for values of $\tan\beta \lesssim 6$.

If, however, M_{SUSY} is much larger than 1 TeV, as suggested by the non-observations of SUSY partner particles at the LHC so far, low values of $\tan\beta$ can produce an h boson with $m_h \simeq 125$ GeV [23,24]. The interpretation of the Higgs boson measurements in the framework of the recently developed MSSM benchmark scenarios [24–27] suggests that the mass of the CP-odd Higgs boson, m_A, can be smaller than $2m_t$. In the mass region below $2m_t$ and at low values of $\tan\beta$, the decay mode of the heavy scalar $H \to hh$ and that of the pseudoscalar $A \to Zh$ can have sizeable branching fractions.

This encourages a programme of searches in the so-called “low $\tan\beta$” channels [23,28]:

- for 220 GeV $< m_A < 2m_t$: $A \to Zh$;
- for 260 GeV $< m_A < 2m_t$: $H \to hh$;
- for $m_A > 2m_t$: $A/H \to t\bar{t}$.

* *E-mail address:* cms-publication-committee-chair@cern.ch.

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The decay modes $H \to hh$ and $A \to Zh$, studied in this paper, are also present in other types of two-Higgs-doublet models (2HDM) [2,3]. There are different types of 2HDM with those most similar to the MSSM (i.e. where up-type fermions couple to one doublet and down-type fermions to the other) being "Type II" 2HDM. The discovery of a Higgs boson at the LHC [29–31] with a mass around 125 GeV pushes the 2HDM parameter space towards either the alignment or decoupling limits [24]. In these limits the properties of h are SM-like.

In the alignment limit of 2HDM when $\cos(\beta - \alpha) \ll 1$ (where α is the mixing angle between the two neutral scalar fields), the Hhh and AZh couplings vanish at Born level [32]. However, in the MSSM, the Hhh and AZh couplings do not vanish, even in the alignment limit, because of the large radiative corrections that arise in the model. In the decoupling limit of 2HDM the scalar Higgs boson H has a very large mass and the decay $H \to t\bar{t}$ dominates [32].

This paper reports the results of searches for the decays $H \to hh \to bb\tau\tau$ and $A \to Zh \to \ell\ell\tau\tau$ (where $\ell\ell$ denotes $\mu\mu$ or ee). The choice of τ pair final state was driven by its quite clean signature and by the most recent results, which gave stronger evidence of the 125 Higgs boson coupling to the fermions [33]. This analysis exploits similar techniques as used for the search for the SM Higgs boson at 125 GeV [34] and several different $\tau\tau$ signatures are studied. For the channel $H \to hh \to bb\tau\tau$, the $\mu\tau_h$, $e\tau_h$, and $\tau_h\tau_h$ final states are used, where τ_h denotes the visible products of a hadronically decaying τ, whereas for the channel $A \to Zh \to \ell\ell\tau\tau$, the $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$, and $e\mu$ final states are selected.

Searches for the decays $H \to hh$, and $A \to Zh$ have already been performed by the ATLAS [35–38] and CMS Collaborations [39–41] in di-photon, multilepton and bb final states.

This analysis has the power to bring important results in the low $\tan\beta$ region for the m_A range, which has been previously discussed and where these processes have an enhanced sensitivity [23]. This region has not yet been excluded by the direct or indirect searches for a heavy scalar or pseudoscalar Higgs boson, that have been mentioned above, therefore the described decay modes look to be quite promising.

For simplicity of the paper, we are neither indicating the charge of the leptons nor the particle–antiparticle nature of quarks.

2. The CMS detector, simulation and data samples

A detailed description of the CMS detector can be found in Ref. [42]. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter providing a field of 3.8 T. Within the field volume are a silicon pixel and strip tracker, a crystal electromagnetic calorimeter (ECAL), and a brass/scintillator hadron calorimeter. Muons are measured in gas-ionisation detectors embedded in the steel return yoke of the magnet.

The CMS coordinate system has the origin centred at the nominal collision point and is oriented such that the x-axis points to the centre of the LHC ring, the y-axis points vertically upward and the z-axis is in the direction of the beam. The azimuthal angle ϕ is measured from the x-axis in the xy plane and the radial coordinate in this plane is denoted by r. The polar angle θ is defined in the rz plane and the pseudorapidity is $\eta = -\ln[\tan(\theta/2)]$ [42]. The momentum component transverse to the beam direction, denoted by p_T, is computed from the x- and y-components.

The first level (L1) of the CMS trigger system, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select the most interesting events in a fixed time interval of less than 4 μs. The high-level Trigger processor farm decreases the L1 accept rate from around 100 kHz to less than 1 kHz before data storage.

The data used for this search were recorded with the CMS detector in proton–proton collisions at the CERN LHC and correspond to an integrated luminosity of 19.7 fb^{-1} at a centre-of-mass energy of $\sqrt{s} = 8$ TeV. The $H \to hh$ signals are modelled with the PYTHIA 6.4.26 [43] event generator while the $A \to Zh$ signals were modelled with MadGraph 5.1 [44]. When modelling background processes, the MadGraph 5.1 generator is used for Z+jets, W+jets, $t\bar{t}$, and diboson production, and POWHEG 1.0 [45–48] for single top quark production. The POWHEG and MadGraph generators are interfaced with PYTHIA for parton showering and fragmentation using the Z2* tune [49]. All generators are interfaced with TAUOLA [50] for the simulation of the τ decays. All generated events are processed through a detailed simulation of the CMS detector based on Geant4 [51] and are reconstructed with the same algorithms as the data. Parton distribution functions (PDFs) CT10 [52] or CTEQ6L1 [53] for the proton are used, depending on the generator in question, together with MSTW2008 [54] according to PDF4LHC prescriptions [55].

3. Event reconstruction

During the 2012 LHC run there were an average of 21 proton–proton interactions per bunch crossing. The collision vertex that maximises the sum of the squares of momenta components perpendicular to the beamline (transverse momenta) of all tracks associated with it, $\sum p_T^2$, is taken to be the vertex of the primary hard interaction. The other vertices are categorised as pileup vertices.

A particle-flow algorithm [56,57] is used to reconstruct individual particles, i.e. muons, electrons, photons, charged hadrons and neutral hadrons, using information from all CMS subdetectors. Composite objects such as jets, hadronically decaying τ leptons, and missing transverse energy are then constructed using the lists of individual particles.

Muons are reconstructed by performing a simultaneous global track fit to hits in the silicon tracker and the muon system [58]. Electrons are reconstructed from clusters of ECAL energy deposits matched to hits in the silicon tracker [59]. Muons and electrons assumed to originate from W or Z boson decays are required to be spatially isolated from other particles [59,60]. The presence of charged and neutral particles from pileup vertices is taken into account in the isolation requirement of both muons and electrons. Muon and electron identification and isolation efficiencies are measured via the tag-and-probe technique [61] using inclusive samples of $Z \to \ell\ell$ events from data and simulation. Correction factors are applied to account for differences between data and simulation.

Jets are reconstructed from all particles using the anti-k_T jet clustering algorithm implemented in FASTJET [62,63] with a distance parameter of 0.5. The contribution to the jet energy from particles originating from pileup vertices is removed following a procedure based on the effective jet area described in Ref. [64]. Furthermore, jet energy corrections are applied as a function of jet p_T and η correcting jet energies to the generator level response of the jet, on average. Jets originating from pileup interactions are removed by a multivariate pileup jet identification algorithm [65].

The missing transverse momentum vector $\vec{p}_T^{\text{miss}}$ is defined as the negative vector sum of the transverse momenta of all reconstructed particles in the volume of the detector (electrons, muons, photons, and hadrons). Its magnitude is referred to as E_T^{miss}. The E_T^{miss} reconstruction is improved by taking into account the jet energy scale corrections and the ϕ modulation, due to collisions not being at the nominal centre of CMS [66]. A multivariate regression correction of E_T^{miss}, where the contributing particles are separated into those coming from the primary vertex and those that are not, mitigates the effect of pileup [66].

Jets from the hadronisation of b-quarks (b jets) are identified with the combined secondary vertex (CSV) b tagging algorithm [67], which exploits the information on the decay vertices of long-lived mesons and the transverse impact parameter measurements of charged particles. This information is combined in a likelihood discriminant. The medium value of the CSV discriminator, corresponding to a b jet misidentification probability of 1%, has been used in this analysis.

Hadronically decaying τ leptons are reconstructed using the hadron-plus-strips algorithm [68], which considers candidates with one charged pion and up to two neutral pions, or three charged pions. The neutral pions are reconstructed as "strips" of electromagnetic particles taking into account possible broadening of calorimeter energy depositions in the ϕ direction from photon conversions. The τ_h candidates that are also compatible with muons or electrons are rejected. Jets originating from the hadronisation of quarks and gluons are suppressed by requiring the τ_h candidate to be isolated. The contribution of charged and neutral particles from pileup interactions is removed when computing the isolation.

4. Event selection

The events are selected with a combination of electron, muon and τ trigger objects [34,59,60,69]. The identification criteria of these objects were progressively tightened and their transverse momentum thresholds raised as the LHC instantaneous luminosity increased over the data taking period. A tag-and-probe method was used to measure the efficiencies of these triggers in data and simulation, and correction factors are applied to the simulation.

Electrons, muons, and τ_h are selected using the criteria defined in the CMS search for the SM Higgs boson at 125 GeV [34]. Specific requirements for the selection of the $\mathrm{H} \to \mathrm{hh} \to \mathrm{bb}\tau\tau$ and the $\mathrm{A} \to \mathrm{Zh} \to \ell\ell\tau\tau$ channels are described below.

4.1. Event selection of $\mathrm{H} \to \mathrm{hh} \to \mathrm{bb}\tau\tau$

In the $\mathrm{H} \to \mathrm{hh} \to \mathrm{bb}\tau\tau$ channel, the three most sensitive final states are analysed, distinguished by the decay mode of the two τ leptons originating from the h boson ($\mu\tau_h$, $\mathrm{e}\tau_h$ and $\tau_h\tau_h$).

In the $\mu\tau_h$ and $\mathrm{e}\tau_h$ final states, events are selected with a muon with $p_T > 20$ GeV and $|\eta| < 2.1$ or an electron of $p_T > 24$ GeV and $|\eta| < 2.1$, and an oppositely charged τ_h of $p_T > 20$ GeV and $|\eta| < 2.3$. To reduce the $\mathrm{Z} \to \mu\mu, \mathrm{ee}$ contamination, events with two muons or electrons of $p_T > 15$ GeV, of opposite charges, and passing loose isolation criteria are rejected.

In the $\mu\tau_h$ and $\mathrm{e}\tau_h$ final states, the transverse mass of the muon or electron and $\vec{p}_T^{\,\mathrm{miss}}$

$$m_T = \sqrt{2 p_T E_T^{\mathrm{miss}} (1 - \cos \Delta\phi)}, \quad (1)$$

where p_T is the lepton transverse momentum and $\Delta\phi$ is the difference in the azimuthal angle between the lepton momentum and $\vec{p}_T^{\,\mathrm{miss}}$, is required to be less than 30 GeV to reject events coming from W+jets and $\mathrm{t\bar{t}}$ backgrounds. The m_T distribution for the $\mu\tau_h$ final state is shown in Fig. 1.

In the $\tau_h\tau_h$ final state, events with two oppositely charged hadronically decaying τ leptons with $p_T > 45$ GeV and $|\eta| < 2.1$ are selected.

In addition to the $\tau\tau$ selection, each selected event must contain at least two jets with $p_T > 20$ GeV and $|\eta| < 2.4$. These p_T and η requirements are necessary to select jets that have a well defined value of the CSV discriminator (Section 3), which is important for categorising signal-like events with two b jet candidates coming from the 125 GeV Higgs boson decaying to bb.

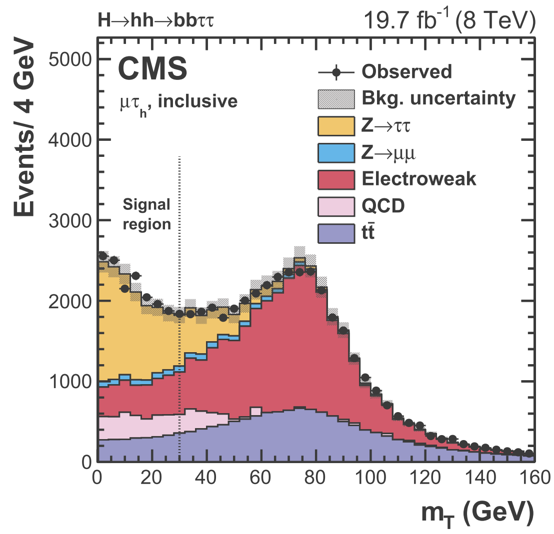

Fig. 1. Distribution of m_T for events in the $\mu\tau_h$ final state, containing at least two additional jets. The W+jets background is included in the "electroweak" category. Multijet events are indicated as QCD. The $\mathrm{H} \to \mathrm{hh} \to \mathrm{bb}\tau\tau$ selection requires $m_T <$ 30 GeV for the $\mu\tau_h$ and $\mathrm{e}\tau_h$ final states.

Simulation studies show that the majority of signal events will have at least one jet passing the medium working point of the CSV discriminator. The jets are ordered by CSV discriminator value, such that the leading and subleading jets are defined as those with the two highest CSV values. Then the events are separated into categories, defined as:

- 2jet–0tag when neither the leading nor subleading jet passes the medium CSV working point. Only a small amount of signal is collected in this category, which is background-dominated.
- 2jet–1tag when only the leading but not the subleading jet passes the medium CSV working point.
- 2jet–2tag when both the leading and subleading jets pass the medium CSV working point.

The signal extraction is performed using the distribution of the reconstructed mass of the H boson candidate.

4.2. Event selection of $\mathrm{A} \to \mathrm{Zh} \to \ell\ell\tau\tau$

In the $\mathrm{A} \to \mathrm{Zh} \to \ell\ell\tau\tau$ channel eight final states are analysed. These are categorised according to the decay mode of the Z boson and the decay mode of the τ leptons originating from the h boson.

The Z boson is reconstructed from two same-flavour, isolated, and oppositely charged electrons or muons. In the $\mathrm{Z} \to \mu\mu$ (ee) final state the muons (electrons) are required to have $|\eta| < 2.4$ (2.5) with $p_T > 20$ GeV for the leading lepton and $p_T > 10$ GeV for the subleading lepton. The invariant mass of the two leptons is required to be between 60 GeV and 120 GeV. When more than one pair of leptons satisfy these criteria, the pair with an invariant mass closest to the Z boson mass is selected.

After the Z candidate has been chosen, the $\mathrm{h} \to \tau\tau$ decay is selected by combining the decay products of the two τ leptons in the four final states $\mu\tau_h, \mathrm{e}\tau_h, \tau_h\tau_h, \mathrm{e}\mu$. The combination of the large contribution from the irreducible ZZ background and of the small branching fractions of leptonic tau decays makes the $\mu\mu$ and ee final states less sensitive to the signal, and therefore they are not used in the analysis. Depending on the final state, a muon with $p_T > 10$ GeV and $|\eta| < 2.4$, or an electron of $p_T > 10$ GeV and $|\eta| < 2.5$, or a τ_h of $p_T > 21$ GeV and $|\eta| < 2.3$ are combined to

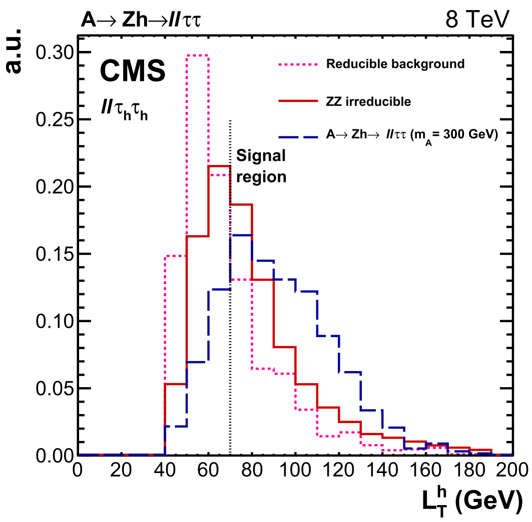

Fig. 2. Distribution of the variable L_T^h for events in the $\ell\ell\tau_h\tau_h$ final state. The reducible background is estimated from data, instead the ZZ irreducible background from simulation.

form an oppositely charged pair. Events with additional light leptons satisfying these requirements are rejected.

A requirement on L_T^h, which is the scalar sum of the visible transverse momenta of the two τ candidates originating from the h boson, is applied to lower the reducible background from misidentified leptons as well as the irreducible background from ZZ production. The thresholds of this requirement depend on the final state and have been chosen in such a way as to optimise the sensitivity of the analysis to the presence of an A $\to$ Zh signal for A masses between 220 and 350 GeV. The distribution of L_T^h for events in the $\ell\ell\tau_h\tau_h$ final state can be seen in Fig. 2.

In order to reduce the $t\bar{t}$ background, events containing a jet with $p_T > 20$ GeV, $|\eta| < 2.4$ and passing the medium working point of the CSV b tagging discriminator are removed.

The four final objects are further required to be separated from each other by $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2}$ larger than 0.5 (where φ is in radians), and to come from the same primary vertex.

In this channel the signal extraction is performed using the distribution of the reconstructed mass of the A boson candidate.

5. Background estimation

5.1. Background estimation for H $\to$ hh $\to$ bb$\tau\tau$

The backgrounds to the H $\to$ hh $\to$ bb$\tau\tau$ final state consist predominantly of $t\bar{t}$ events, followed by Z $\to\tau\tau$+jets events, W+jets events, and QCD multijet events, with other small contributions from Z $\to\ell\ell$, diboson, and single top quark production. The estimation of the shapes of the reconstructed H mass and of the yields of the major backgrounds is obtained from data wherever possible.

The Z $\to\tau\tau$ process constitutes an irreducible background due to its final state involving two τ leptons, which only differ from the h $\to\tau\tau$ signal by having an invariant mass closer to the mass of the Z boson instead of the Higgs boson. Requiring two jets in the event greatly reduces this background and the b tagging requirements reduce it even further. Nevertheless, it still remains an important source of background events, in particular in the 2jet–1tag and 2jet–0tag categories. This background is estimated using a sample of Z $\to\mu\mu$ events from data, obtained by requiring two oppositely charged isolated muons, where the reconstructed

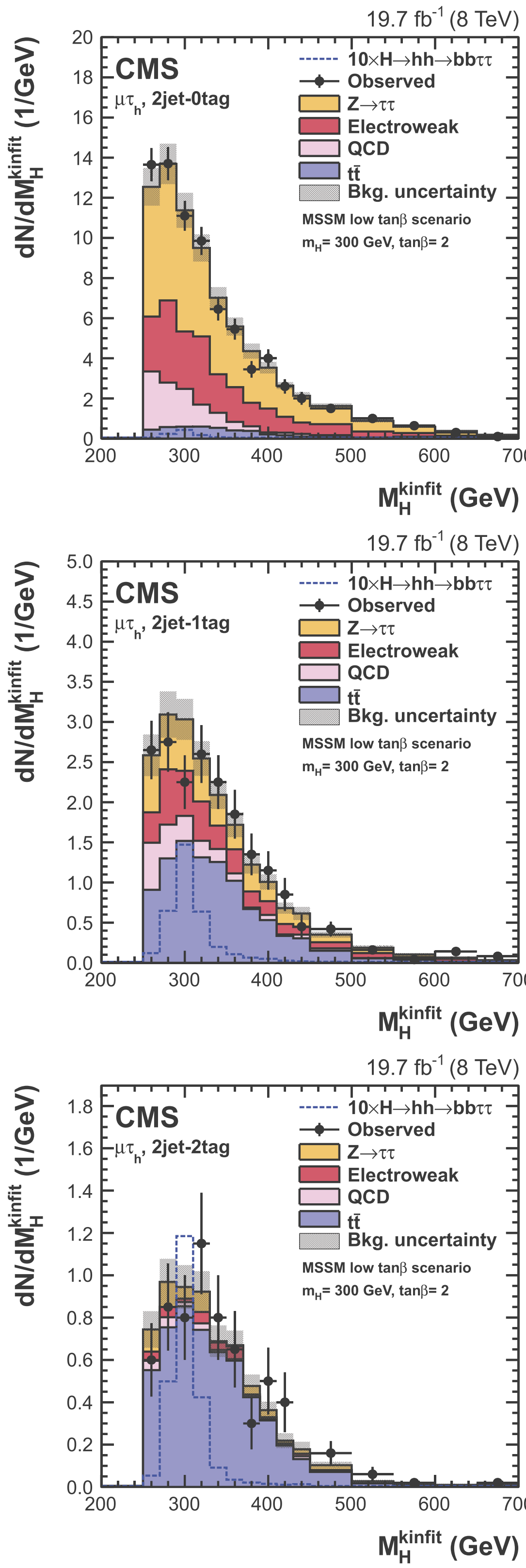

Fig. 3. Distributions of the reconstructed four-body mass with the kinematic fit after applying mass selections on $m_{\tau\tau}$ and m_{bb} in the $\mu\tau_h$ channel. The plots are shown for events in the 2jet–0tag (top), 2jet–1tag (middle), and 2jet–2tag (bottom) categories. The expected signal scaled by a factor 10 is shown superimposed as an open dashed histogram for $\tan\beta = 2$ and $m_H = 300$ GeV in the low $\tan\beta$ scenario of the MSSM. Expected background contributions are shown for the values of nuisance parameters (systematic uncertainties) obtained after fitting the signal plus background hypothesis to the data.

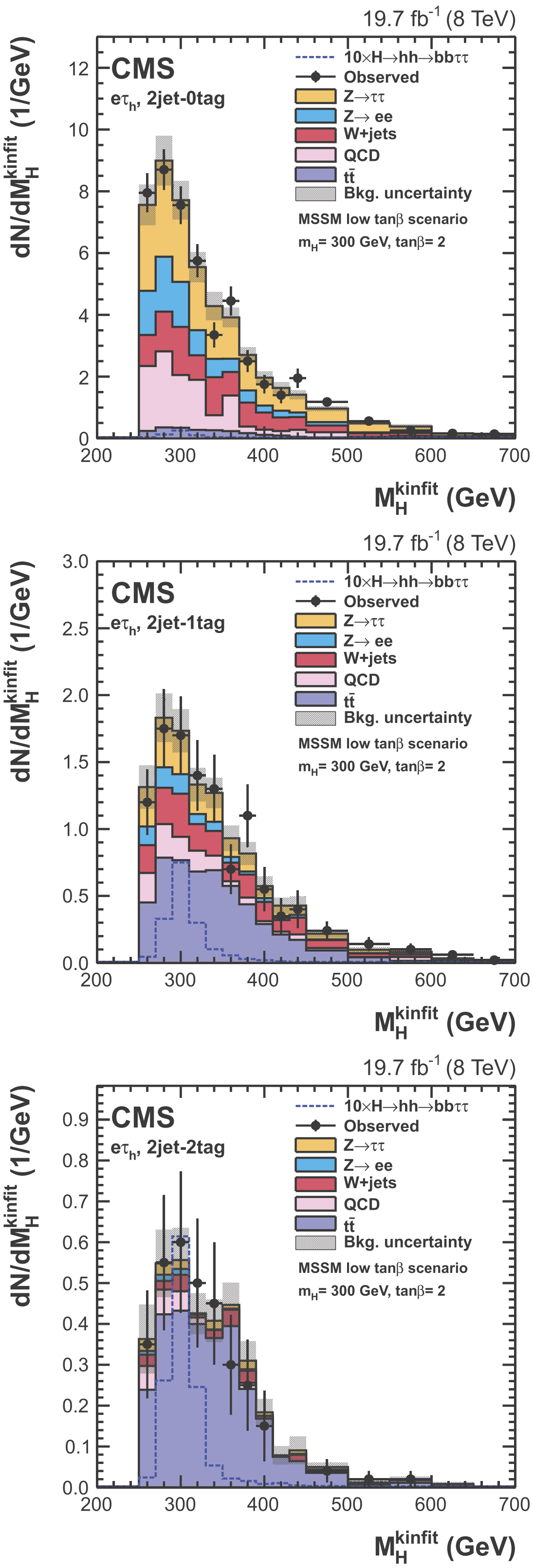

Fig. 4. Distributions of the reconstructed four-body mass with the kinematic fit after applying mass selections on $m_{\tau\tau}$ and m_{bb} in the $e\tau_{\mathrm{h}}$ channel. The plots are shown for events in the 2jet–0tag (top), 2jet–1tag (middle), and 2jet–2tag (bottom) categories. The expected signal scaled by a factor 10 is shown superimposed as an open dashed histogram for $\tan\beta = 2$ and $m_{\mathrm{H}} = 300$ GeV in the low $\tan\beta$ scenario of the MSSM. Expected background contributions are shown for the values of nuisance parameters (systematic uncertainties) obtained after fitting the signal plus background hypothesis to the data.

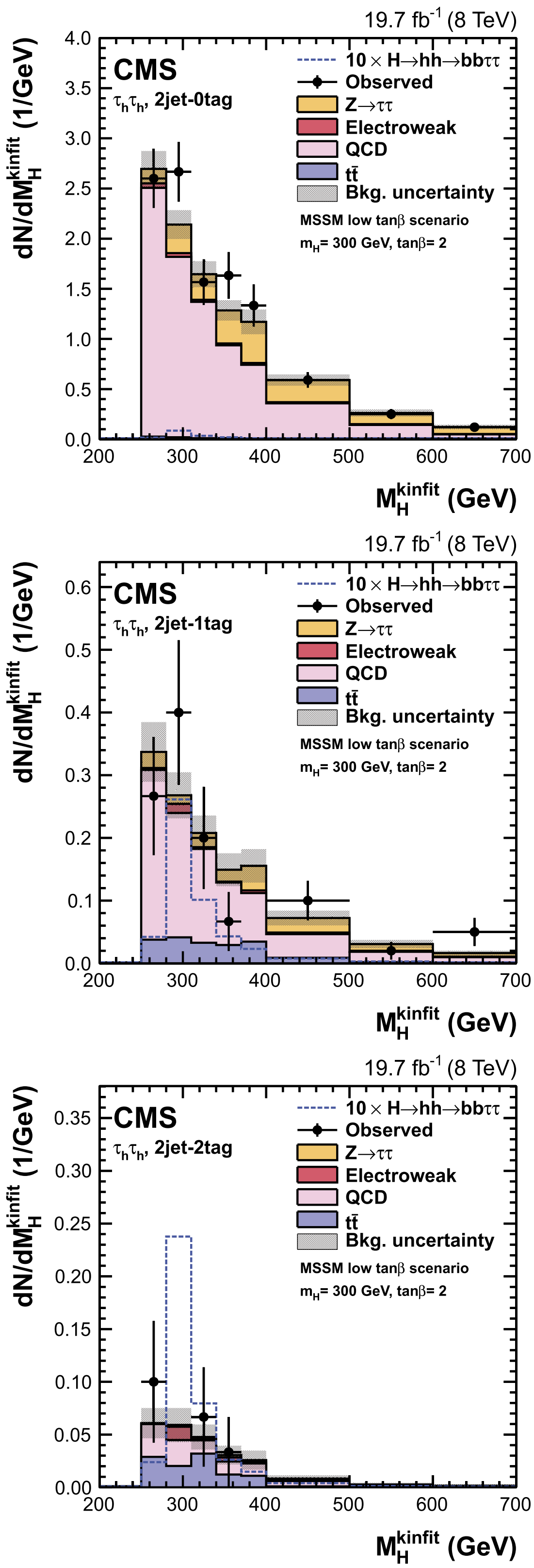

Fig. 5. Distributions of the reconstructed four-body mass with the kinematic fit after applying mass selections on $m_{\tau\tau}$ and m_{bb} in the $\tau_{\mathrm{h}}\tau_{\mathrm{h}}$ channel. The plots are shown for events in the 2jet–0tag (top), 2jet–1tag (middle), and 2jet–2tag (bottom) categories. The expected signal scaled by a factor 10 is shown superimposed as an open dashed histogram for $\tan\beta = 2$ and $m_{\mathrm{H}} = 300$ GeV in the low $\tan\beta$ scenario of the MSSM. Expected background contributions are shown for the values of nuisance parameters (systematic uncertainties) obtained after fitting the signal plus background hypothesis to the data.

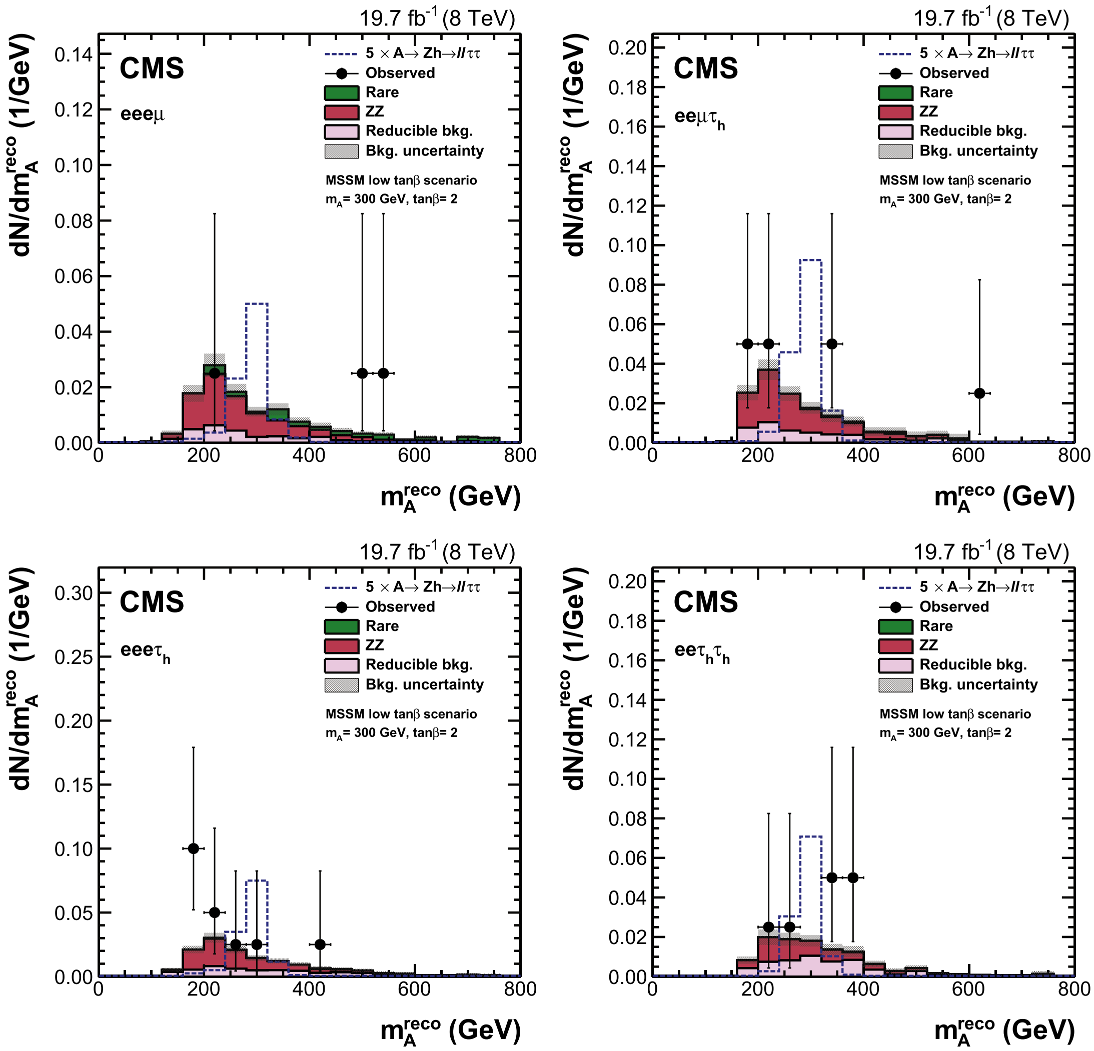

Fig. 6. Invariant mass distributions for different final states of the $A \to Zh$ process where Z decays to ee. The expected signal scaled by a factor 5 is shown superimposed as an open dashed histogram for $\tan\beta = 2$ and $m_A = 300$ GeV in the low $\tan\beta$ scenario of MSSM. Expected background contributions are shown for the values of nuisance parameters (systematic uncertainties) obtained after fitting the signal plus background hypothesis to the data. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

muons are replaced by the reconstructed particles from simulated τ decays. A correction for a contamination from $t\bar{t}$ events is applied to the $Z \to \mu\mu$ selection. This technique substantially reduces the systematic uncertainties due to the jet energy scale and the missing transverse energy, as these quantities are modelled with data.

For the $t\bar{t}$ background, both shape and normalisation are taken from Monte Carlo simulation (MC), and the results are checked against data in a control region where the presence of $t\bar{t}$ events is enhanced by requiring $e\mu$ in the final state instead of a ditau, and at least one b tagged jet.

Another significant source of background is from QCD multijet events, which can mimic the signal in various ways, e.g. where one or more jets are misidentified as τ_h. In the $\mu\tau_h$ and $e\tau_h$ channels, the shape of the QCD background is estimated using an observed sample of same-sign (SS) $\tau\tau$ events. The yield is obtained by scaling the observed number of SS events by the ratio of the opposite-sign (OS) to SS event yields obtained in a QCD-enriched region with relaxed lepton isolation. In the $\tau_h\tau_h$ channel, the shape is obtained from OS events with relaxed τ isolation. The yield is obtained by scaling these events by the ratio of SS events with tighter and relaxed τ isolation.

In the $\mu\tau_h$ and $e\tau_h$ channels, W+jets events in which there is a jet misidentified as a τ_h are another sizeable source of background. The W+jets shape is modelled using MC simulation and the yield is estimated using a control region of events with large m_T close to the W mass. In the $\tau_h\tau_h$ channel this background has been found to be less relevant and its shape and yield are taken from MC simulation.

The contribution of Drell–Yan production of muon and electron pairs is estimated from simulation after rescaling the simulated yield to that measured from observed $Z \to \mu\mu$ events. In the $e\tau_h$ channel, the $Z \to ee$ simulation is further corrected using the $e \to \tau_h$ misidentification rate measured in data using a tag-and-probe technique [61] on $Z \to ee$ events.

Finally the contributions of other minor backgrounds such as diboson and single top quark events are estimated from simulation. Possible contributions from SM Higgs boson production are estimated and found to have a negligible effect on the final result.

5.2. Background estimation for $A \to Zh \to \ell\ell\tau\tau$

The backgrounds to the $A \to Zh$ channel can be divided into a reducible component and an irreducible component which contribute in equal parts.

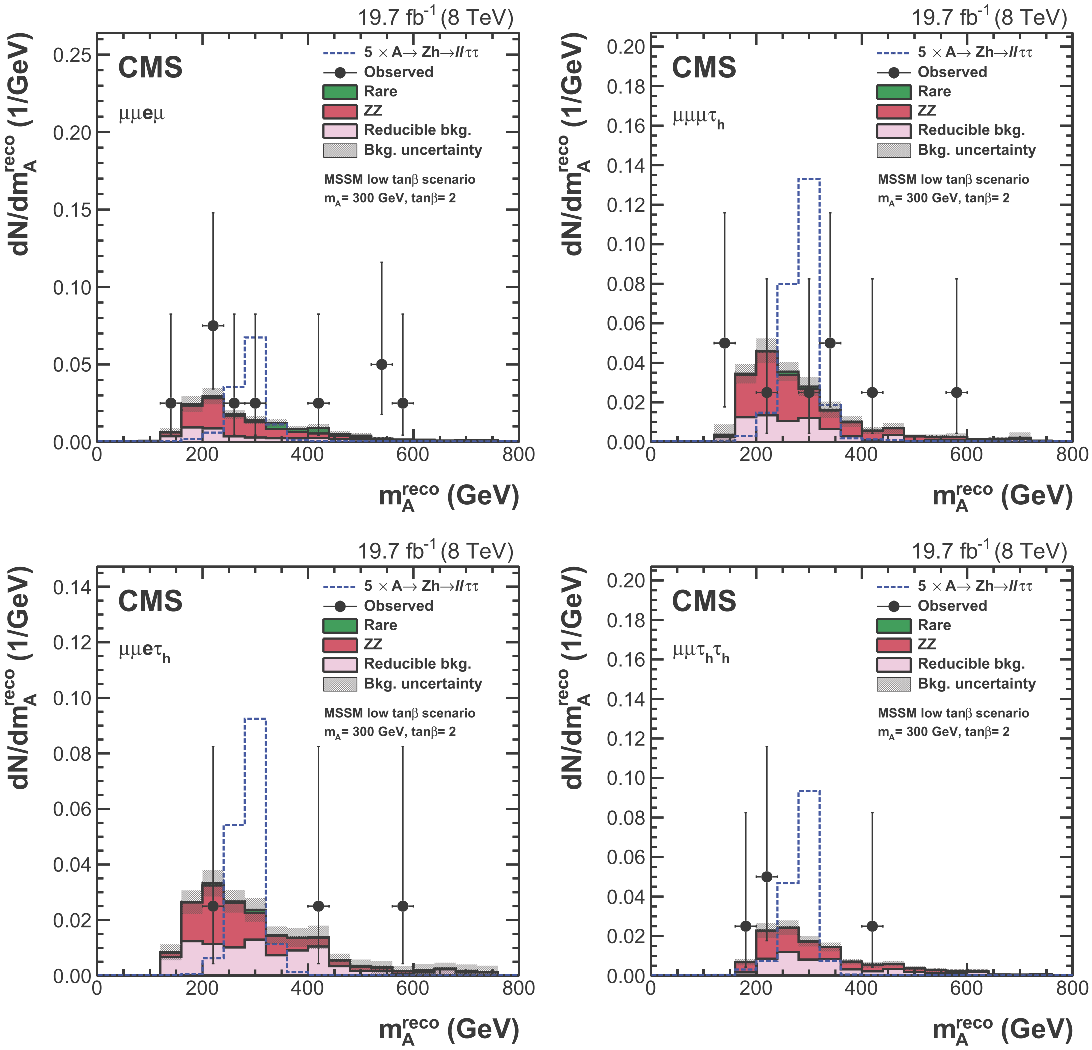

Fig. 7. Invariant mass distributions for different final states of the A → Zh process where Z decays to $\mu\mu$. The expected signal scaled by a factor 5 is shown superimposed as an open dashed histogram for $\tan\beta = 2$ and $m_A = 300$ GeV in the low $\tan\beta$ scenario of MSSM. Expected background contributions are shown for the values of nuisance parameters (systematic uncertainties) obtained after fitting the signal plus background hypothesis to the data. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

The predominant source of irreducible background is from ZZ production that yields exactly the same final states as the expected signal. Other "rare" sources of irreducible background are SM Higgs boson associated production with a Z boson, $t\bar{t}Z$ production where the Z boson decays into a muon or an electron pair and both top quarks decay leptonically (to e, μ, or τ_h), and triboson events (WWZ, WZZ, ZZZ). The contributions of all the irreducible backgrounds after the final selection are estimated from simulation.

The reducible backgrounds have at least one lepton in the final state that is due to a misidentified jet that passes the lepton identification. In $\ell\ell\tau_h\tau_h$ final states, the reducible background is essentially composed of Z+jets events with at least two jets, whereas in $\ell\ell\mu\tau_h$ and $\ell\ell e\tau_h$ final states, the main contribution to the reducible background comes from WZ+jets with three light leptons. The contribution from these processes to the final selected events is estimated using control samples in data.

The probabilities for a jet that passes relaxed lepton selection criteria to pass the final identification and isolation criteria of electrons, muons, and τ leptons are measured in a signal-free region as a function of the transverse momentum of the object closest to the candidate, $f(p_T^{\text{fake}})$. In this region, events are required to pass all the final state selections, except that the reconstructed τ candidates are required to have the same sign and to pass relaxed identification and isolation criteria. This effectively eliminates any possible signal, while maintaining roughly the same proportion of reducible background events.

In order to use the misidentification probabilities $f(p_T^{\text{fake}})$, sidebands are defined for each channel, where, unlike the relaxed criterion, the final identification or isolation criterion is not satisfied for one or more of the final state lepton candidates. The number of reducible background events due to a lepton being misidentified in the final selection is estimated by applying the weight $f(p_T^{\text{fake}})/(1 - f(p_T^{\text{fake}}))$ to the observed events with lepton candidates in the sideband that satisfy the relaxed but not the final identification or isolation criterion. Finally, the reducible background shape of the reconstructed A mass is obtained from a SS signal-free region where the τ candidates have the same charge and relaxed isolation criteria. Possible contributions from SM Higgs boson production are estimated and found to have a negligible effect on the final result.

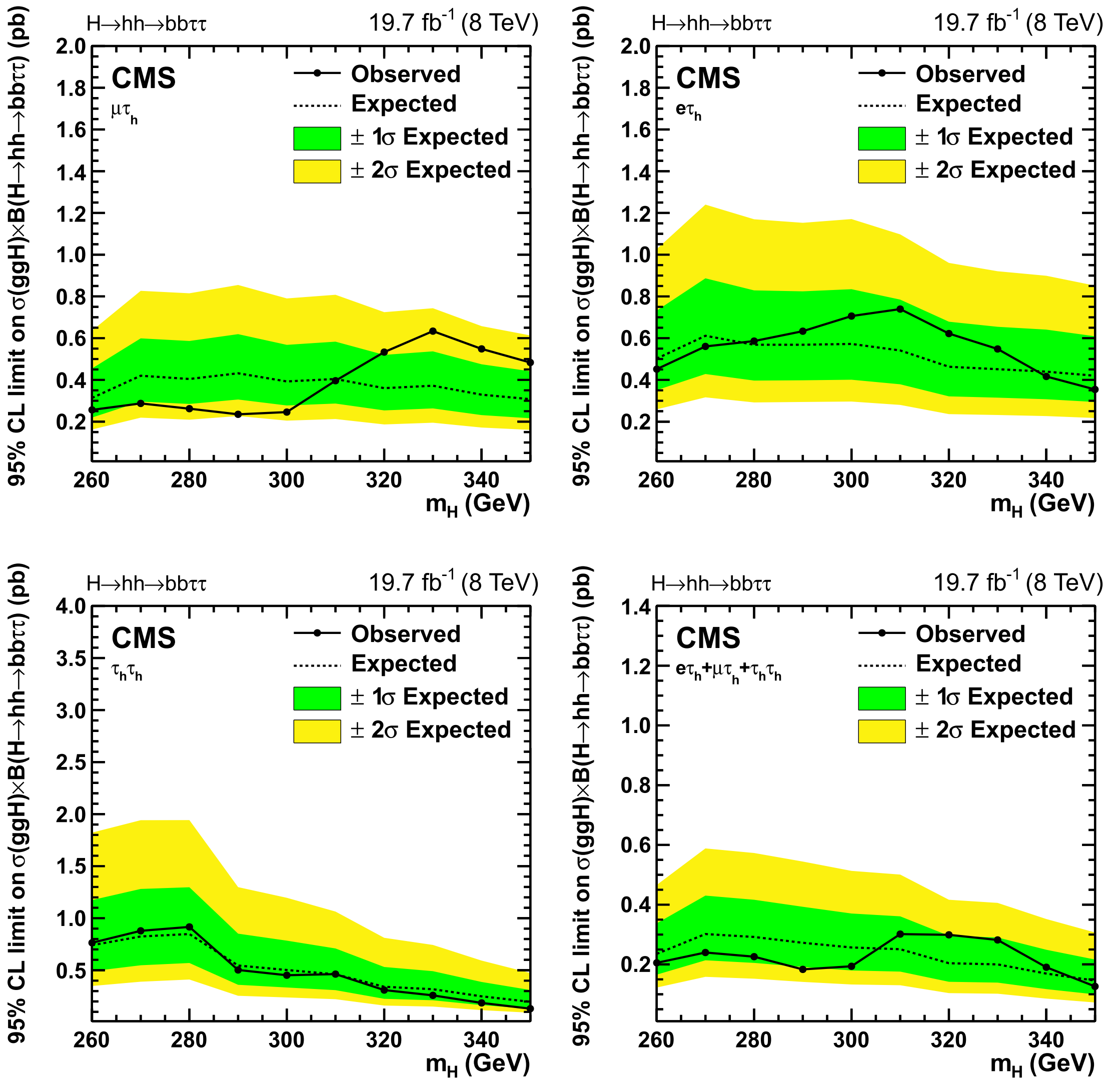

Fig. 8. Upper limits at 95% CL on the $H \to hh \to bb\tau\tau$ cross section times branching fraction for the $\mu\tau_h$ (top left), $e\tau_h$ (top right), $\tau_h\tau_h$ (bottom left), and for final states combined (bottom right).

6. Systematic uncertainties

The shape of the reconstructed mass of the A and H boson candidates, used for signal extraction, and the normalisation are sensitive to various systematic uncertainties.

The main contributions to the normalisation uncertainty that affect the signal and the simulated backgrounds include the uncertainty in the total integrated luminosity, which amounts to 2.6% [70], and the identification and trigger efficiencies of muons (2%) and electrons (2%). The τ_h identification efficiency has a 6% uncertainty (8% in the $\tau_h\tau_h$ channel), which is measured in $Z/\gamma^* \to \tau\tau \to \mu\tau_h$ events using a tag-and-probe technique. There is a 3% uncertainty in the efficiency on the hadronic part of the $\mu\tau_h$ and $e\tau_h$ triggers, and a 4.5% uncertainty on each of the two τ_h candidates required by the $\tau_h\tau_h$ trigger. The b tagging efficiency has an uncertainty of 2–7%, and the mistag rate for light-flavour partons is accurate to 10–20% depending on η and p_T [67]. The background normalisation uncertainties from the estimation methods discussed in Section 5 are also considered. In the $H \to hh \to bb\tau\tau$ channel this uncertainties amount to 2–40% depending on the event category and on the final state. The uncertainties of reducible backgrounds to the $A \to Zh$ channel are estimated by evaluating an individual uncertainty for each lepton misidentification rate and applying it to the background calculation. This amounts to 15–50% depending on the final $\ell\ell\tau\tau$ state considered. The main uncertainty in the estimation of the ZZ background arises from the theoretical uncertainty in the ZZ production cross section.

Uncertainties that contribute to variations in the shape of the mass spectrum include the jet energy scale, which varies with jet p_T and jet η [71], and the τ lepton (3%) energy scale [34].

Theoretical uncertainties on the cross section for signal derive from PDF and QCD scale uncertainties and depend on the choice of signal hypothesis. For model independent results no choice of cross section is made and hence no theoretical uncertainties are considered. For the MSSM interpretation the uncertainties depend on m_A and $\tan\beta$ and amount to 2–3% for PDF uncertainties and 5–9% for scale uncertainties, evaluated as described in [27] and using the PDF4LHC recommendations [55]. No theoretical uncertainties are considered in the 2HDM interpretation.

7. Results and interpretation

The ditau ($m_{\tau\tau}$) mass is reconstructed using a dedicated algorithm called SVFit [72], which combines the visible four-vectors of

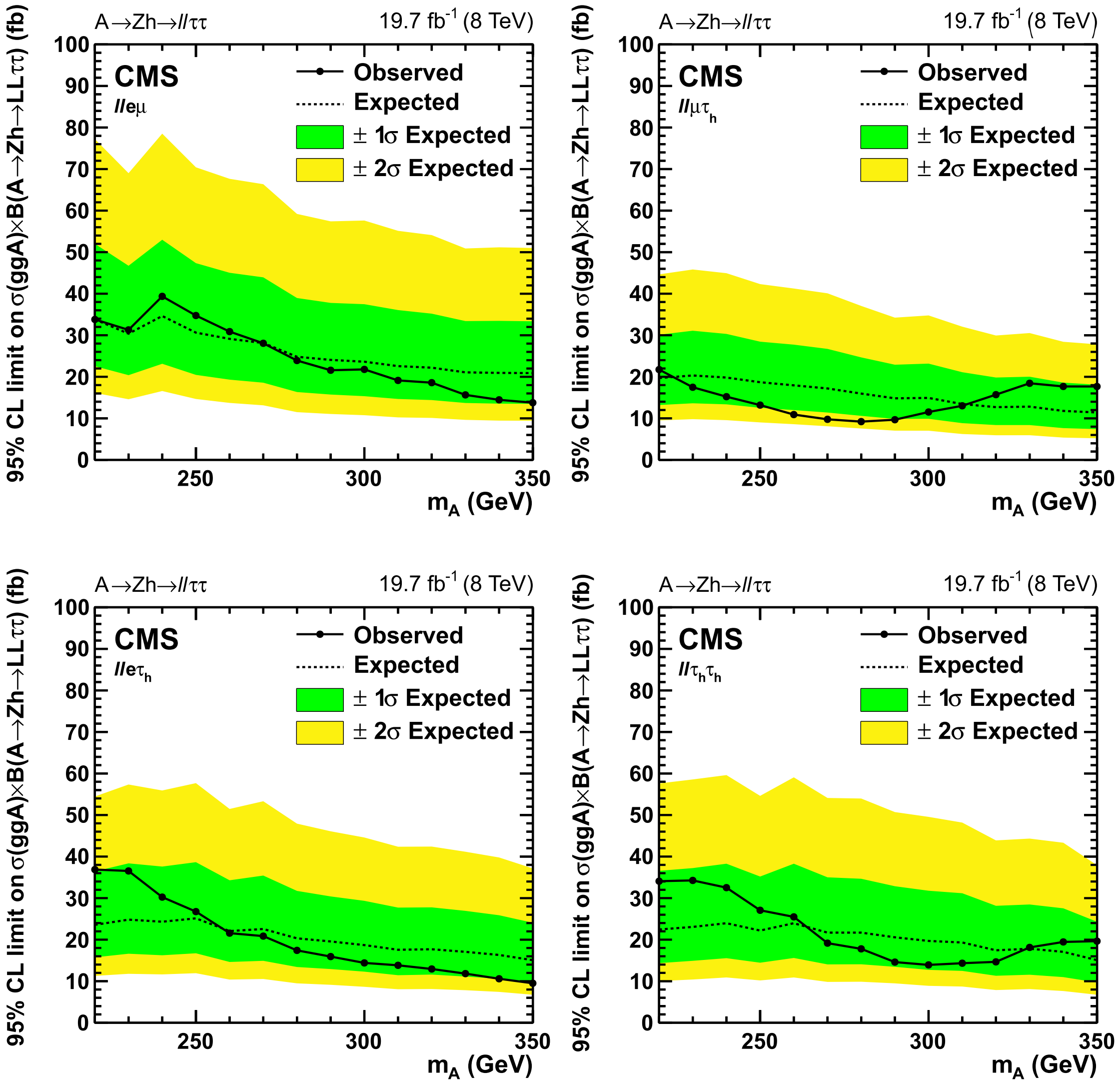

Fig. 9. Upper limits at 95% CL on cross section times branching fraction on $A \to Zh \to LL\tau\tau$ for $\ell\ell e\mu$ (top left), $\ell\ell\mu\tau_h$ (top right), $\ell\ell e\tau_h$ (bottom left), and $\ell\ell\tau_h\tau_h$ (bottom right) final states.

the τ lepton candidates as well as the E_T^{miss} and its experimental resolution in a maximum likelihood estimator.

For the $H \to hh \to bb\tau\tau$ process, the chosen distribution for signal extraction is the four-body mass. The decay products of the two h bosons need to fulfill stringent kinematic constraints, due to the small natural width of the h. These constraints can be used in a kinematic fit in order to improve the event reconstruction and to better separate signal events from background. The collinear approximation for the decay products of the τ leptons is assumed in the fit, since the τ leptons are highly boosted as they originate from an object that is heavy when compared to their own mass. Furthermore, it is assumed that the reconstruction of the directions of all final state objects is accurate and the uncertainties can be neglected compared to the uncertainties on the energy reconstruction. In the decay of the two τ leptons, at least two neutrinos are involved and there is no precise measurement of the original τ lepton energies. For this reason, the τ lepton energies are constrained from the balance of the fitted H boson transverse momentum and the reconstructed transversal recoil determined from E_T^{miss} reconstruction algorithms, as described in Sec. 3. The reconstructed mass obtained with the kinematic fit is denoted by m_H^{kinfit} (see the Supplementary material for a detailed description).

The signal-to-background ratio is greatly improved by selecting events that are consistent with a mass of 125 GeV for both the dijet (m_{bb}) mass and the ditau mass ($m_{\tau\tau}$) reconstructed with SVFit. The mass windows of the selections are optimised to collect as much signal as possible while rejecting a large part of the background. They correspond to $70 < m_{bb} < 150$ GeV and $90 < m_{\tau\tau} < 150$ GeV. The invariant mass distributions of the H boson in different final states are shown in Figs. 3, 4 and 5.

For the $A \to Zh \to \ell\ell\tau\tau$ process, the A boson mass is reconstructed from the four-vector information of the Z boson candidate and the four-vector information of the h boson candidate as obtained from SVFit. The invariant mass distributions of the A boson in the different final states are shown in Figs. 6 and 7. The $\ell\ell\tau_h\tau_h$ final states have a comparable contribution from reducible and irreducible backgrounds, while the $\ell\ell e\mu$ final states are dominated by the irreducible ZZ production. The background labelled as "rare" collects together the smaller contributions from the triboson processes as discussed in the previous section.

In neither search do the invariant mass spectra show any evidence of a signal. Model independent upper limits at 95% confidence level (CL) on the cross section times branching fraction are

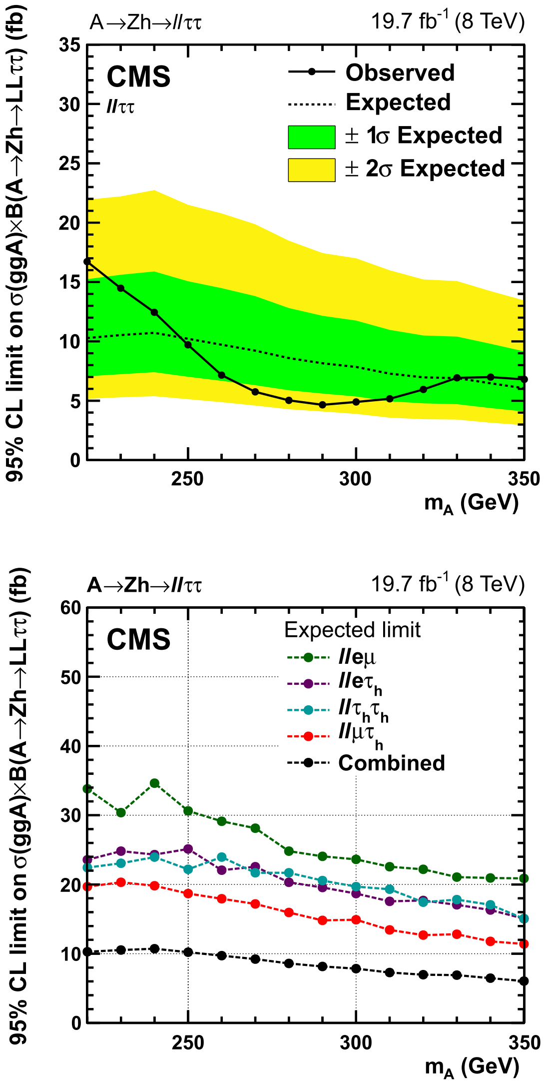

Fig. 10. Upper limits at 95% CL on cross section times branching fraction on $A \to Zh \to LL\tau\tau$ for all $\ell\ell\tau\tau$ final states combined (top) and comparison of the different final states (bottom).

set using a binned maximum likelihood fit for the *signal plus background* and *background-only* hypotheses. The limits are determined using the CL_s method [73,74] and the procedure is described in Refs. [75,76].

Systematic uncertainties are taken into account as nuisance parameters in the fit procedure: normalisation uncertainties affect the signal and background yields. Uncertainties on the τ energy scale and jet energy scale are propagated as shape uncertainties.

The model independent expected and observed cross section times branching fraction limits for the $H \to hh \to bb\tau\tau$ process are shown in Fig. 8 and for the $A \to Zh \to LL\tau\tau$ process in Figs. 9 and 10 where $L = e, \mu$ or τ in order to reflect the small $Z \to \tau\tau$ contribution to the signal acceptance.

We interpret the observed limits on the cross section times branching fraction in the MSSM and 2HDM frameworks, discussed in Section 1.

In the MSSM we interpret them in the "low $\tan\beta$" scenario [27,78] in which the value of M_{SUSY} is increased until the mass of the lightest Higgs boson is consistent with 125 GeV over a range of low $\tan\beta$ and m_A values. The exclusion region in the m_A–$\tan\beta$ plane for the combination of the $H \to hh \to bb\tau\tau$ and $A \to Zh \to \ell\ell\tau\tau$ analyses, in such a scenario, is shown in Fig. 11. The limit falls off rapidly as m_A approaches 350 GeV because decays of the A to two top quarks are becoming kinematically allowed.

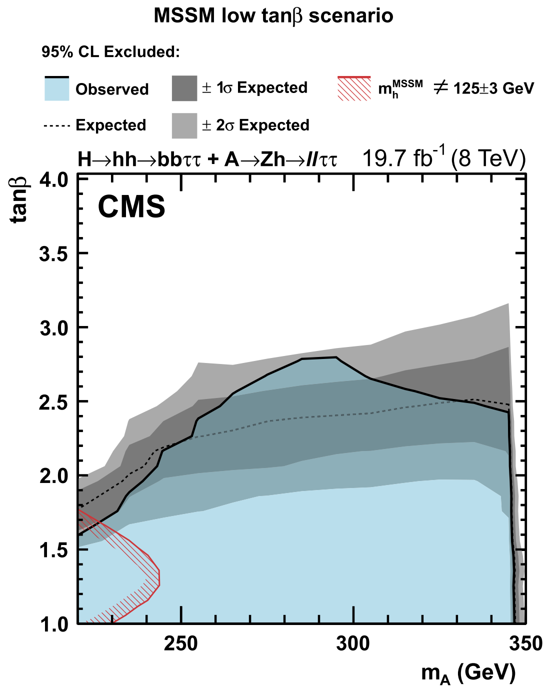

Fig. 11. The 95% CL exclusion region in the m_A–$\tan\beta$ plane for the low $\tan\beta$ scenario as discussed in the introduction, combining the results of the $H \to hh \to bb\tau\tau$ and the $A \to Zh \to \ell\ell\tau\tau$ analysis. The area highlighted in blue below the black curve marks the observed exclusion. The dashed curve and the grey bands show the expected exclusion limit with the relative uncertainty. The red area with the back-slash lines at the lower-left corner of the plot indicates the region excluded by the mass of the SM-like scalar boson being 125 GeV. The limit falls off rapidly as m_A approaches 350 GeV because decays of the A to two top quarks are becoming kinematically allowed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The interpretation of the observed limits in a Type II 2HDM is performed in the "physics basis". The inputs to this interpretation are the physical Higgs boson masses (m_h, m_H, m_A, $m_{H^\pm}$), the ratio of the vacuum expectation energies ($\tan\beta$), the CP-even Higgs mixing angle (α) and $m_{12}^2 = m_A^2[\tan\beta/(1+\tan\beta^2)]$. For simplicity we assume that $m_H = m_A = m_{H^\pm}$.

The cross sections and branching fractions in the 2HDM were calculated as described by the LHC Higgs Cross Section Working Group [77,78]. The exclusion regions, calculated using the combination of the $H \to hh \to bb\tau\tau$ and $A \to Zh \to \ell\ell\tau\tau$ analyses, in the $\cos(\beta - \alpha)$ vs. $\tan\beta$ plane for such a Type II 2HDM scenario with a heavy Higgs boson mass of 300 GeV are shown in Fig. 12. This can be compared to Fig. 5 in Ref. [41].

8. Summary

A search for a heavy scalar Higgs boson (H) decaying into a pair of SM-like Higgs bosons (hh) and a search for a heavy neutral pseudoscalar Higgs boson (A) decaying into a Z boson and a SM-like Higgs boson (h), have been performed using events recorded by the CMS experiment at the LHC. The data set corresponds to an integrated luminosity of 19.7 fb^{-1}, recorded at 8 TeV centre-of-mass energy in 2012. No evidence for a signal has been found and exclusion limits on the production cross section times branching fraction for the processes $H \to hh \to bb\tau\tau$ and $A \to Zh \to LL\tau\tau$ are presented. The results are also interpreted in the context of the MSSM and 2HDM models.

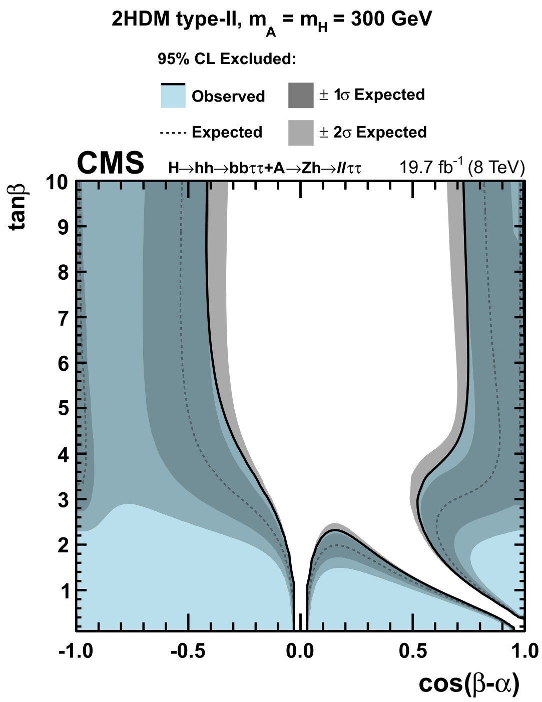

Fig. 12. The 95% CL exclusion regions in the $\cos(\beta-\alpha)$ vs. $\tan\beta$ plane of 2HDM Type II model for $m_A = m_H = 300$ GeV, combining the results of the $H \to hh \to bb\tau\tau$ and $A \to Zh \to \ell\ell\tau\tau$ analysis. The areas highlighted in blue bounded by the black curves mark the observed exclusion. The dashed curves and the grey bands show the expected exclusion limit with the relative uncertainty. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.physletb.2016.01.056.

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G. Cowan, K. Cranmer, E. Gross, O. Vitells, Eur. Phys. J. C 75 (2013) 2501, http://dx.doi.org/10.1140/epjc/s10052-013-2501-z (Erratum).

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CMS Collaboration

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

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth [1], V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler [1], V. Knünz, A. König, M. Krammer [1], I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady [2], B. Rahbaran, H. Rohringer, J. Schieck [1], R. Schöfbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz [1]

Institut für Hochenergiephysik der OeAW, Wien, Austria

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

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

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

Universiteit Antwerpen, Antwerpen, 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

Vrije Universiteit Brussel, Brussel, Belgium

P. Barria, H. Brun, C. Caillol, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart, A.P.R. Gay, 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. Zhang [3]

Université Libre de Bruxelles, Bruxelles, 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

Ghent University, Ghent, Belgium

S. Basegmez, C. Beluffi [4], O. Bondu, S. Brochet, G. Bruno, R. Castello, A. Caudron, L. Ceard, G.G. Da Silveira, C. Delaere, D. Favart, L. Forthomme, A. Giammanco [5], J. Hollar, A. Jafari, P. Jez, M. Komm, V. Lemaitre, A. Mertens, C. Nuttens, L. Perrini, A. Pin, K. Piotrzkowski, A. Popov [6], L. Quertenmont, M. Selvaggi, M. Vidal Marono

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

N. Beliy, G.H. Hammad

Université de Mons, Mons, Belgium

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

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato [7], 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 Manganote [7], A. Vilela Pereira

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

[a] *Universidade Estadual Paulista, São Paulo, Brazil*
[b] *Universidade Federal do ABC, São Paulo, Brazil*

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

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

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

University of Sofia, Sofia, Bulgaria

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, T. Cheng, R. Du, C.H. Jiang, R. Plestina [9], F. Romeo, S.M. Shaheen, J. Tao, C. Wang, Z. Wang, H. Zhang

Institute of High Energy Physics, Beijing, China

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

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

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

Universidad de Los Andes, Bogota, Colombia

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

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

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

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

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

M. Bodlak, M. Finger [10], M. Finger Jr. [10]

Charles University, Prague, Czech Republic

A.A. Abdelalim [11,12], A. Awad, M. El Sawy [13,14], A. Mahrous [11], A. Radi [14,15]

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

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

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, J. Pekkanen, M. Voutilainen

Department of Physics, University of Helsinki, 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

Helsinki Institute of Physics, Helsinki, Finland

J. Talvitie, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

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

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

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

J.-L. Agram [16], J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte [16], X. Coubez, J.-C. Fontaine [16], D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, J.A. Merlin [2], K. Skovpen, P. Van Hove

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

S. Gadrat

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

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

T. Toriashvili [17]

Georgian Technical University, Tbilisi, Georgia

Z. Tsamalaidze [10]

Tbilisi State University, Tbilisi, Georgia

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. Zhukov [6]

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

V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Künsken, J. Lingemann [2], A. Nehrkorn, A. Nowack, I.M. Nugent, C. Pistone, O. Pooth, A. Stahl

RWTH Aachen University, III. Physikalisches Institut B, Aachen, 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. Gallo [18], J. Garay Garcia, A. Geiser, A. Gizhko, P. Gunnellini, J. Hauk, M. Hempel [19], H. Jung, A. Kalogeropoulos, O. Karacheban [19], M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann [19], R. Mankel, I. Marfin [19], 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

Deutsches Elektronen-Synchrotron, 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. Pantaleo [2], 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

University of Hamburg, Hamburg, 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. Hartmann [2], S.M. Heindl, U. Husemann, I. Katkov [6], A. Kornmayer [2], 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

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

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

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

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

University of Athens, Athens, Greece

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

University of Ioánnina, Ioánnina, Greece

G. Bencze, C. Hajdu, A. Hazi, P. Hidas, D. Horvath [20], F. Sikler, V. Veszpremi, G. Vesztergombi [21], A.J. Zsigmond

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi [22], J. Molnar, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

M. Bartók [23], A. Makovec, P. Raics, Z.L. Trocsanyi, B. Ujvari

University of Debrecen, Debrecen, Hungary

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

National Institute of Science Education and Research, Bhubaneswar, 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

Panjab University, Chandigarh, 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

University of Delhi, Delhi, India

S. Banerjee, 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

Saha Institute of Nuclear Physics, Kolkata, India

A. Abdulsalam, R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty [2], L.M. Pant, P. Shukla, A. Topkar

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Banerjee, S. Bhowmik [24], R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu [25], G. Kole, S. Kumar, B. Mahakud, M. Maity [24], G. Majumder, K. Mazumdar, S. Mitra, G.B. Mohanty, B. Parida, T. Sarkar [24], K. Sudhakar, N. Sur, B. Sutar, N. Wickramage [26]

Tata Institute of Fundamental Research, Mumbai, India

S. Chauhan, S. Dube, S. Sharma

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

H. Bakhshiansohi, H. Behnamian, S.M. Etesami [27], A. Fahim [28], R. Goldouzian, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh [29], M. Zeinali

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

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]

[a] *INFN Sezione di Bari, Bari, Italy*
[b] *Università di Bari, Bari, Italy*
[c] *Politecnico di Bari, Bari, Italy*

G. Abbiendi [a], C. Battilana [2], 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]

[a] *INFN Sezione di Bologna, Bologna, Italy*
[b] *Università di Bologna, Bologna, 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]

[a] *INFN Sezione di Catania, Catania, Italy*
[b] *Università di Catania, Catania, 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]

[a] *INFN Sezione di Firenze, Firenze, Italy*
[b] *Università di Firenze, Firenze, Italy*

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

INFN Laboratori Nazionali di Frascati, Frascati, 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]

[a] *INFN Sezione di Genova, Genova, Italy*
[b] *Università di Genova, Genova, Italy*

L. Brianza, M.E. Dinardo [a,b], P. Dini [a], 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], S. Ragazzi [a,b], N. Redaelli [a], T. Tabarelli de Fatis [a,b]

[a] *INFN Sezione di Milano-Bicocca, Milano, Italy*
[b] *Università di Milano-Bicocca, Milano, 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

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

P. Azzi [a,2], N. Bacchetta [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], F. Montecassiano [a], M. Passaseo [a], J. Pazzini [a,b], N. Pozzobon [a,b], P. Ronchese [a,b], F. Simonetto [a,b], E. Torassa [a], M. Tosi [a,b], M. Zanetti, P. Zotto [a,b], A. Zucchetta [a,b,2], G. Zumerle [a,b]

[a] *INFN Sezione di Padova, Padova, Italy*
[b] *Università di Padova, Padova, Italy*
[c] *Università di Trento, Trento, 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]

[a] *INFN Sezione di Pavia, Pavia, Italy*
[b] *Università di Pavia, Pavia, 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]

[a] *INFN Sezione di Perugia, Perugia, Italy*
[b] *Università di Perugia, Perugia, Italy*

K. Androsov [a,30], P. Azzurri [a], G. Bagliesi [a], J. Bernardini [a], T. Boccali [a], G. Broccolo [a,c], R. Castaldi [a], M.A. Ciocci [a,30], R. Dell'Orso [a], S. Donato [a,c,2], G. Fedi, L. Foà [a,c,†], A. Giassi [a], M.T. Grippo [a,30],

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,31], A.T. Serban [a], P. Spagnolo [a], P. Squillacioti [a,30], R. Tenchini [a], G. Tonelli [a,b], A. Venturi [a], P.G. Verdini [a]

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

[a] INFN Sezione di Roma, Roma, Italy
[b] Università di Roma, Roma, 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]

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

[a] INFN Sezione di Trieste, Trieste, Italy
[b] Università di Trieste, Trieste, Italy

A. Kropivnitskaya, S.K. Nam

Kangwon National University, Chunchon, Republic of Korea

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

Kyungpook National University, Daegu, Republic of Korea

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

Chonbuk National University, Jeonju, Republic of Korea

S. Song

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Republic of 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

Korea University, Seoul, Republic of Korea

H.D. Yoo

Seoul National University, Seoul, Republic of Korea

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

University of Seoul, Seoul, Republic of Korea

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

Sungkyunkwan University, Suwon, Republic of Korea

A. Juodagalvis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

I. Ahmed, Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali [32], F. Mohamad Idris [33], W.A.T. Wan Abdullah, M.N. Yusli

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

E. Casimiro Linares, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz [34], A. Hernandez-Almada, R. Lopez-Fernandez, A. Sanchez-Hernandez

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

S. Carrillo Moreno, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

I. Pedraza, H.A. Salazar Ibarguen

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

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

D. Krofcheck

University of Auckland, Auckland, New Zealand

P.H. Butler

University of Canterbury, Christchurch, New Zealand

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

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

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

National Centre for Nuclear Research, Swierk, Poland

G. Brona, K. Bunkowski, A. Byszuk [35], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, M. Walczak

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

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. Vadruccio, J. Varela, P. Vischia

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

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Konoplyanikov, A. Lanev, A. Malakhov, V. Matveev [36], P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

V. Golovtsov, Y. Ivanov, V. Kim [37], E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

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

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

Institute for Nuclear Research, Moscow, Russia

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

Institute for Theoretical and Experimental Physics, Moscow, Russia

A. Bylinkin

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

V. Andreev, M. Azarkin [38], I. Dremin [38], M. Kirakosyan, A. Leonidov [38], G. Mesyats, S.V. Rusakov, A. Vinogradov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin [39], L. Dudko, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Myagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

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

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

P. Adzic [40], M. Ekmedzic, J. Milosevic, V. Rekovic

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

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

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

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

Universidad Autónoma de Madrid, Madrid, Spain

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

Universidad de Oviedo, Oviedo, 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

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

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, G. Cerminara, S. Colafranceschi [41], 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. Orfanelli [42], L. Orsini, L. Pape,

E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, D. Piparo, A. Racz, G. Rolandi [43], M. Rovere, M. Ruan, H. Sakulin, C. Schäfer, C. Schwick, A. Sharma, P. Silva, M. Simon, P. Sphicas [44], D. Spiga, J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Triossi, A. Tsirou, G.I. Veres [21], N. Wardle, H.K. Wöhri, A. Zagozdzinska [35], W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

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

Paul Scherrer Institut, Villigen, 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. Starodumov [45], M. Takahashi, V.R. Tavolaro, K. Theofilatos, R. Wallny

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler [46], 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

Universität Zürich, Zurich, Switzerland

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 Central University, Chung-Li, 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

National Taiwan University (NTU), Taipei, Taiwan

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

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

A. Adiguzel, M.N. Bakirci [47], Z.S. Demiroglu, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal [48], G. Onengut [49], K. Ozdemir [50], A. Polatoz, D. Sunar Cerci [51], B. Tali [51], M. Vergili, C. Zorbilmez

Cukurova University, Adana, Turkey

I.V. Akin, B. Bilin, S. Bilmis, B. Isildak [52], G. Karapinar [53], M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E.A. Albayrak [54], E. Gülmez, M. Kaya [55], O. Kaya [56], T. Yetkin [57]

Bogazici University, Istanbul, Turkey

K. Cankocak, S. Sen [58], F.I. Vardarlı

Istanbul Technical University, Istanbul, Turkey

B. Grynyov

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

L. Levchuk, P. Sorokin

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

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. Newbold [59], S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, D. Smith, V.J. Smith

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev [60], 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, L. Thomas, I.R. Tomalin, T. Williams, W.J. Womersley, S.D. Worm

Rutherford Appleton Laboratory, Didcot, 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. Lucas [59], L. Lyons, A.-M. Magnan, S. Malik, J. Nash, A. Nikitenko [45], J. Pela, M. Pesaresi, K. Petridis, D.M. Raymond, A. Richards, A. Rose, C. Seez, A. Tapper, K. Uchida, M. Vazquez Acosta [61], T. Virdee, S.C. Zenz

Imperial College, London, 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

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, USA

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

The University of Alabama, Tuscaloosa, USA

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

Boston University, Boston, 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

Brown University, Providence, 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, 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, Davis, Davis, USA

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

University of California, Los Angeles, 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, Riverside, Riverside, 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. Wasserbaech [62], C. Welke, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, San Diego, La Jolla, 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

University of California, Santa Barbara, Santa Barbara, 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

California Institute of Technology, Pasadena, USA

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

Carnegie Mellon University, Pittsburgh, USA

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

University of Colorado Boulder, Boulder, 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

Cornell University, Ithaca, USA

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, 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, 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

Fermi National Accelerator Laboratory, Batavia, 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. Milenovic [63], G. Mitselmakher, D. Rank, R. Rossin, L. Shchutska, M. Snowball, D. Sperka, N. Terentyev, J. Wang, S. Wang, J. Yelton

University of Florida, Gainesville, USA

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

Florida International University, Miami, 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 State University, Tallahassee, USA

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

Florida Institute of Technology, Melbourne, 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

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

B. Bilki [64], W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya [65], A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok [54], A. Penzo, C. Snyder, P. Tan, E. Tiras, J. Wetzel, K. Yi

The University of Iowa, Iowa City, 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

Johns Hopkins University, Baltimore, 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

The University of Kansas, Lawrence, USA

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

Kansas State University, Manhattan, USA

D. Lange, F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, 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

University of Maryland, College Park, 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

Massachusetts Institute of Technology, Cambridge, 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 Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, 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

University of Nebraska-Lincoln, Lincoln, USA

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

State University of New York at Buffalo, Buffalo, 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

Northeastern University, Boston, USA

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

Northwestern University, Evanston, 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. Musienko [36], T. Pearson, M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, N. Valls, M. Wayne, M. Wolf, A. Woodard

University of Notre Dame, Notre Dame, 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

The Ohio State University, Columbus, 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

Princeton University, Princeton, USA

S. Malik

University of Puerto Rico, Mayaguez, 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, West Lafayette, USA

N. Parashar, J. Stupak

Purdue University Calumet, Hammond, 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

Rice University, Houston, 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

University of Rochester, Rochester, USA

L. Demortier

The Rockefeller University, New York, 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

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

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

University of Tennessee, Knoxville, USA

O. Bouhali [66], A. Castaneda Hernandez [66], M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon [67], V. Krutelyov, R. Mueller, I. Osipenkov, Y. Pakhotin, R. Patel, A. Perloff, A. Rose, A. Safonov, A. Tatarinov, K.A. Ulmer [2]

Texas A&M University, College Station, USA

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

Texas Tech University, Lubbock, 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

Vanderbilt University, Nashville, USA

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

University of Virginia, Charlottesville, USA

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

Wayne State University, Detroit, USA

D.A. Belknap, D. Carlsmith, M. Cepeda, 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

University of Wisconsin, Madison, USA

† 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 Beni-Suef University, Bani Sweif, Egypt.
14 Now at British University in Egypt, Cairo, Egypt.
15 Now at Ain Shams University, Cairo, Egypt.
16 Also at Université de Haute Alsace, Mulhouse, France.
17 Also at Tbilisi State University, Tbilisi, Georgia.
18 Also at University of Hamburg, Hamburg, Germany.
19 Also at Brandenburg University of Technology, Cottbus, Germany.
20 Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
21 Also at Eötvös Loránd University, Budapest, Hungary.
22 Also at University of Debrecen, Debrecen, Hungary.
23 Also at Wigner Research Centre for Physics, Budapest, Hungary.
24 Also at University of Visva-Bharati, Santiniketan, India.

[25] Now at King Abdulaziz University, Jeddah, Saudi Arabia.
[26] Also at University of Ruhuna, Matara, Sri Lanka.
[27] Also at Isfahan University of Technology, Isfahan, Iran.
[28] Also at University of Tehran, Department of Engineering Science, Tehran, Iran.
[29] Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
[30] Also at Università degli Studi di Siena, Siena, Italy.
[31] Also at Purdue University, West Lafayette, USA.
[32] Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
[33] Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
[34] Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.
[35] Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
[36] Also at Institute for Nuclear Research, Moscow, Russia.
[37] Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
[38] Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
[39] Also at California Institute of Technology, Pasadena, USA.
[40] Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
[41] Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.
[42] Also at National Technical University of Athens, Athens, Greece.
[43] Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
[44] Also at University of Athens, Athens, Greece.
[45] Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
[46] Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
[47] Also at Gaziosmanpasa University, Tokat, Turkey.
[48] Also at Mersin University, Mersin, Turkey.
[49] Also at Cag University, Mersin, Turkey.
[50] Also at Piri Reis University, Istanbul, Turkey.
[51] Also at Adiyaman University, Adiyaman, Turkey.
[52] Also at Ozyegin University, Istanbul, Turkey.
[53] Also at Izmir Institute of Technology, Izmir, Turkey.
[54] Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
[55] Also at Marmara University, Istanbul, Turkey.
[56] Also at Kafkas University, Kars, Turkey.
[57] Also at Yildiz Technical University, Istanbul, Turkey.
[58] Also at Hacettepe University, Ankara, Turkey.
[59] Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
[60] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[61] Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.
[62] Also at Utah Valley University, Orem, USA.
[63] Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
[64] Also at Argonne National Laboratory, Argonne, USA.
[65] Also at Erzincan University, Erzincan, Turkey.
[66] Also at Texas A&M University at Qatar, Doha, Qatar.
[67] Also at Kyungpook National University, Daegu, Republic of Korea.