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Search for the Higgs boson decay to a pair of electrons in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

A search is presented for the Higgs boson decay to a pair of electrons (e^+e^-) in proton-proton collisions at $\sqrt{s} = 13$ TeV. The data set was collected with the CMS experiment at the LHC between 2016 and 2018, corresponding to an integrated luminosity of 138 fb^{-1} . The analysis uses event categories targeting Higgs boson production via gluon fusion and vector boson fusion. The observed upper limit on the Higgs boson branching fraction to an electron pair is 3.0×10^{-4} (3.0×10^{-4} expected) at the 95% confidence level, which is the most stringent limit on this branching fraction to date.

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1 Introduction

Since the discovery of the Higgs boson by the ATLAS and CMS Collaborations in 2012 [1–3], various measurements of its interactions with standard model (SM) particles have been performed. In particular, the interactions of the Higgs boson with the third-generation fermions have been observed, with coupling strengths found to be in agreement with the expectations of the SM [4–9]. More recently, the CMS Collaboration has also presented first evidence for the decay of the Higgs boson to the second-generation fermions, in a search for $H \rightarrow \mu^+\mu^-$ decays [10]. Such measurements of Yukawa couplings to light fermions are experimentally challenging at the LHC, given that the SM predicts the coupling strengths to be proportional to the fermion mass [11–13]. Consequently, couplings of the Higgs boson to the first-generation fermions have yet to be confirmed experimentally.

For the Higgs boson decay to an electron pair, $H \rightarrow e^+e^-$, the SM predicted branching fraction of $\mathcal{B}(H \rightarrow e^+e^-) \approx 5 \times 10^{-9}$ [14] is extremely small and inaccessible with the current LHC data set. Higher-order corrections included in the branching fraction prediction introduce diagrams which do not contain the Higgs boson Yukawa coupling to the electron. These contributions are expected to dominate in the SM, but are still much smaller than present sensitivity. Therefore, a search for this decay channel currently provides the only direct probe of the Higgs boson Yukawa coupling to the electron, which is enhanced in several scenarios beyond the SM. The simplest of these are models postulating two Higgs doublets [15]; other extensions include the addition of higher order operators to the SM Lagrangian, including dimension 10 operators that could modify the coupling by a factor of ≈ 10 [16, 17]. These enhancements are, however, still smaller than present sensitivity could detect.

This Letter describes a search for $H \rightarrow e^+e^-$ decays in proton-proton (pp) collisions at $\sqrt{s} = 13$ TeV, using data recorded with the CMS detector in 2016–2018, corresponding to an integrated luminosity of 138 fb^{-1} . The most recent search from the CMS Collaboration for this decay was performed using pp collision data collected at $\sqrt{s} = 8$ TeV with an integrated luminosity of 19.7 fb^{-1} [18]. A 95% confidence level (CL) upper limit on $\mathcal{B}(H \rightarrow e^+e^-)$ of 1.9×10^{-3} was determined. The most sensitive search for $H \rightarrow e^+e^-$ decays from the ATLAS Collaboration was performed using pp data with an integrated luminosity of 139 fb^{-1} , collected at $\sqrt{s} = 13$ TeV. A 95% CL upper limit on $\mathcal{B}(H \rightarrow e^+e^-)$ was set at 3.6×10^{-4} [19].

The analysis presented in this Letter primarily targets Higgs boson production by gluon fusion (ggH) and vector boson fusion (VBF). Rarer Higgs boson production processes, including production in association with top quarks ($t\bar{t}H$) and a vector boson (VH), are also considered, although no dedicated selection is applied to target them. The final states of interest comprise a pair of two prompt, oppositely charged electrons, potentially produced in association with hadronic jets. The sensitivity to each production mode is increased by dividing events into analysis categories, giving an improved signal to background ratio (S/B). Each analysis category is defined by a selection on a dedicated multivariate (MVA) discriminant. The MVA-based classifiers are trained to separate Higgs boson signal events from the dominant Drell–Yan (DY) background and smaller background contributions from $t\bar{t}$ decays. A simultaneous fit to the dielectron invariant mass distribution (m_{ee}) in each category is then used to extract an upper limit on $\mathcal{B}(H \rightarrow e^+e^-)$.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and

strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. The pseudorapidity (η) coverage provided by the barrel and endcap detectors is extended by the forward hadron calorimeter, which uses steel as an absorber and quartz fibres as the sensitive material. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid.

Events of interest are selected using a two-tiered trigger system [20, 21]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about 4 μ s. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage.

The global event reconstruction (also called particle-flow (PF) event reconstruction [22]) aims to reconstruct individual particles (photons, charged and neutral hadrons, muons, and electrons) by optimally combining information from the various elements of the CMS detector. In the case of electrons, the energy is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the charged electron track. The momentum resolution for electrons with transverse momentum $p_T \approx 45$ GeV from $Z \rightarrow e^+e^-$ decays ranges from 1.6–5.0% [23, 24]. The candidate vertex with the largest value of summed physics-object p_T^2 is taken to be the primary pp interaction vertex. The physics objects used for this determination are the jets, clustered using the infrared- and collinear-safe anti- k_T algorithm [25, 26] with the tracks assigned to candidate vertices as inputs, and the associated missing transverse momentum, taken as the negative vector p_T sum of those jets.

For charged hadrons, the energy is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for the response function of the calorimeters to hadronic showers. The energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies. Hadronic jets are built from PF candidates using the anti- k_T algorithm [25] with a distance parameter of 0.4. The momentum of a jet is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be, on average, within 5–10% of the true momentum over the whole p_T spectrum and detector acceptance. Charged hadrons originating from additional pp interactions are removed from the analysis.

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [27].

3 Analysis strategy

The analysis strategy is similar to that used in the SM $H \rightarrow \gamma\gamma$ analysis [28]. In this case, however, events are selected using a dielectron trigger with asymmetric electron p_T thresholds of 23 and 12 GeV, and loose isolation requirements. Offline, all events entering the analysis are required to pass a loose selection placed on the electron kinematics and an electron identification (ID) criterion. Simulated signal and background events are then used to train MVA-based classifiers designed to reduce the number of background events entering the selection. This is performed independently for the ggH and VBF channels, with classifiers trained on simulated samples corresponding to the three data-taking years, combined in accordance with their

integrated luminosities.

In both ggH and VBF channels, the dominant background consists of DY events, with smaller contributions from $t\bar{t}$ processes with dilepton or lepton + jets final states. In the VBF channel, electroweak Z boson production in association with two jets (EW $Z \rightarrow e^+e^-$) is also considered. These events closely mimic the VBF signal process and are included as a background during MVA training. Although the cross section for VBF production is roughly an order of magnitude smaller than for ggH production, the VBF final state provides a distinct signature in the detector, in which the Higgs boson is produced in association with two forward jets with a large η difference and high dijet invariant mass. These features are exploited by the VBF classifier to enhance the expected S/B ratio, allowing the sensitivity of the VBF categories to become comparable to those targeting ggH.

The output scores of the classifiers are used to define analysis categories. The number and location of category boundaries is chosen to optimize the expected significance of all resulting categories combined. The categories are non-overlapping by construction, with events first being considered for the VBF categories, as these have both a higher S/B and a distinctive topology. If an event fails the VBF requirements, it is then considered for the ggH analysis categories.

Once the analysis categories are defined, a maximum likelihood fit is performed to the m_{ee} distribution in each category simultaneously. The smoothly-falling background spectrum, consisting mostly of DY events, is modelled directly from data using the discrete profiling method [29]. The signal model is derived from simulated Higgs boson events independently for each production mode and analysis category. The fit is used to extract 95% CL upper limits on $\mathcal{B}(H \rightarrow e^+e^-)$.

4 Data and simulated events

This analysis uses pp collision data corresponding to an integrated luminosity of 138 fb^{-1} , of which 36.3, 41.5, and 59.8 fb^{-1} were collected during 2016, 2017, and 2018, respectively.

A Monte Carlo (MC) simulated sample is generated for each of the ggH, VBF, VH, and $t\bar{t}H$ signal processes using MADGRAPH5_aMC@NLO v2.6.5 [30] at next-to-leading order (NLO) accuracy in perturbative quantum chromodynamics (QCD). For the ggH process, up to three additional partons are considered in the matrix element calculation; for VBF production, up to one additional parton is considered, excluding the quark-initiated jets produced in the leading order process. In addition, events from ggH production are weighted to match the predictions of the NNLOPS program [31], as a function of the Higgs boson transverse momentum and the number of jets in the event. Simulated DY and electroweak $Z \rightarrow e^+e^-$ background processes are also generated at NLO using MADGRAPH5_aMC@NLO, while $t\bar{t}$ events are produced using the POWHEG v2.0 [32–35] NLO generator. All parton-level simulated samples are interfaced with PYTHIA v8.230 [36] for parton showering and hadronization, using the CP5 underlying event tune [37]. Parton distribution functions (PDFs) are taken from the NNPDF 3.1 [38] set for the simulation of all years. The ggH, VBF, VH, and $t\bar{t}H$ production cross sections used to normalize the signal samples are taken from the LHC Higgs Working Group recommendations [39], at the highest available order. Additional pp interactions occurring in both the same and adjacent bunch crossings (pileup) are simulated as a set of minimum bias interactions that are mixed with the hard scattering event. In the analysis of each data-taking year, the simulated events are weighted based on the number of pileup events to match the distribution measured in data. Finally, the response of the CMS detector is simulated using the GEANT4 package [40].

5 Event selection

A loose preselection on the events is applied to ensure they are consistent with a Higgs boson decaying to two electrons. The two electrons with the highest and next-highest p_T are referred to as the leading and subleading electrons, respectively, and define the dielectron system. Each event must contain at least two oppositely charged electrons fulfilling the following requirements:

- $p_T > 35$ (25) GeV for the leading (subleading) electron;
- a tight working point on an electron ID, designed to have a 90% signal selection efficiency. The ID combines descriptions of the shape and isolation of energy deposits in the ECAL, the quality of associated tracks, and the compatibility of measurements from the tracker and ECAL, in an MVA-based discriminator [24];
- pseudorapidity within the ECAL acceptance ($|\eta| < 2.5$), and not in the barrel-endcap transition region ($1.44 < |\eta| < 1.57$); and
- $110 < m_{ee} < 150$ GeV, chosen to limit contributions from DY events, and to ensure the m_{ee} sideband regions have sufficient events to constrain the background expectation in the signal region.

All jets entering the analysis are required to have $p_T > 25$ GeV and $|\eta| < 4.7$. Jets are required to pass a tight pileup identification criterion [41] that uses the topology of the jet shape, the number of charged and neutral jet constituents, and information on any associated tracks, to reject jets resulting from pileup. A tight requirement is also placed on an additional jet ID, which rejects spurious jets resulting from detector noise [41]. Finally, a selection is applied to suppress the observed noise in the ECAL endcaps for low- p_T jets in the 2017 data; this selection vetoes jets with $p_T < 50$ GeV within the region $2.7 < |\eta| < 3.1$.

Scale factors are applied to simulated samples to correct for differences between simulation and data. These include corrections for differences in the electron reconstruction and identification efficiencies, as well as in the trigger efficiency.

6 Event categorization

The categorization targeting VBF events is based on a boosted decision tree (BDT) trained to discriminate between signal and background events, referred to as the VBF BDT. Prior to training the BDT, an additional selection is applied on top of the loose preselection in order to target VBF events. This is referred to as the VBF preselection and comprises the following:

- $p_T > 40$ (25) GeV for the leading (subleading) jet;
- dijet invariant mass > 350 GeV.

All simulated VBF events passing the VBF preselection are considered as signal when training the BDT. The largest background process in the VBF phase space consists of DY events, with a smaller but significant contribution from $t\bar{t}$ production. Although small in yield, the electroweak Z boson production process is also considered, since such events typically have signal-like characteristics and thus are assigned high VBF BDT scores.

Many observables characterising the VBF event topology are leveraged in the BDT in order to significantly increase the S/B in each analysis category, including information related to the kinematics of the individual electrons, the dielectron system, the three leading jets individually, the dijet system, and the dielectron plus dijet system. Inputs with good discriminating power

include the invariant mass of the dijet object, the difference in η between the two leading jets, and a centrality variable [42] defined as $\exp[-4(|\eta_{ee} - \frac{1}{2}(\eta_{j_1} + \eta_{j_2})|/|\eta_{j_1} - \eta_{j_2}|)^2]$, where η_{ee} is the dielectron pseudorapidity, and $j_{1(2)}$ labels the leading (subleading) jet. Other jet variables such as a quark-gluon identification score [43] are also included. The score is based on quantities such as the p_T and multiplicity of PF candidates reconstructed within a jet in a likelihood discriminant to separate gluon and quark-initiated jets. Finally, it was verified that information related to the dielectron system was not sufficient for the Higgs boson mass (m_H) to be inferred by the classifier. The output score for the VBF BDT is shown for both simulation and data in Fig. 1 (left).

In this analysis, the background model is taken directly from data, whereas the signal modelling uses simulated samples. Therefore, it is necessary to ensure there is reasonable agreement between data and simulation for input observables to the VBF classifier as well as the output score. This is checked using $Z \rightarrow e^+e^-$ events from a control region, defined to be non-overlapping with the analysis category phase space. The VBF preselection is also applied, with the exception of the m_{ee} requirements which are shifted to approximately centre on the Z boson mass ($80 < m_{ee} < 100$ GeV). Drell-Yan events are chosen for this validation since the final state mimics that of the $H \rightarrow e^+e^-$ process and is relatively free from contaminating backgrounds. The distribution of the classifier output score is shown in Fig. 1 (right). Agreement between data and simulation is observed to be within the uncertainty given by the combined systematic and statistical variations, for the range of output scores in which the analysis categories are constructed.

Analysis categories targeting VBF events are defined using the output score of the BDT. The analysis defines only two VBF categories, since the sensitivity to VBF events is observed to saturate at numbers larger than two. The expected signal and background yields for both VBF categories are shown in Table 1.

Table 1: The total expected number of signal events for $m_H = 125.38$ GeV in analysis categories targeting ggH and VBF events, for an integrated luminosity of 138 fb^{-1} . The fractional contribution from each production mode to each category is also shown. The σ_{eff} , defined as the smallest interval containing 68.3% of the m_{ee} distribution, is listed for each analysis category. The final column shows the expected ratio of signal to background, where S and B are the numbers of expected signal and background events in a $\pm 1\sigma_{\text{eff}}$ window centred on m_H . The expected background event yields are extrapolated from data sidebands.

Analysis categories	SM 125.38 GeV expected $H \rightarrow e^+e^-$ signal yields						Bkg. per GeV	S/B
	Yield ($\times 10^{-4}$)	Production mode fractions				σ_{eff} (GeV)		
		ggH	VBF	VH	t \bar{t} H			
ggH Tag 0	4.7	81.0%	12.1%	5.0%	1.9%	1.65	250	7.7×10^{-7}
ggH Tag 1	18	86.5%	8.4%	4.2%	0.9%	1.84	2340	2.8×10^{-7}
ggH Tag 2	35	91.7%	4.8%	3.1%	0.5%	2.02	8760	1.4×10^{-7}
ggH Tag 3	61	92.6%	3.5%	3.2%	0.7%	2.52	30500	5.4×10^{-8}
VBF Tag 0	2.2	19.8%	80.0%	0.1%	0.1%	2.04	25.9	2.8×10^{-6}
VBF Tag 1	1.7	40.3%	58.5%	0.8%	0.4%	2.26	81.7	6.3×10^{-7}

The categorization for ggH events is also based on a BDT trained to discriminate between simulated signal and background events, referred to as the ggH BDT. All simulated signal and background events passing the basic preselection are considered when training. The largest background contribution in this channel consists of DY events, the kinematics of which are typ-

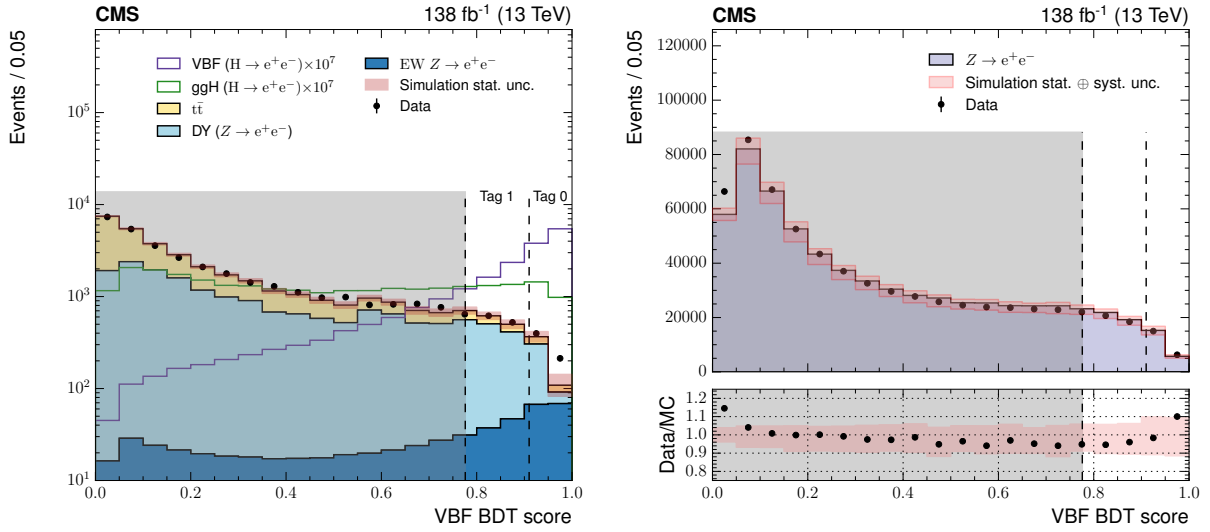


Figure 1: Distribution of the output score of the VBF BDT in all simulated background and signal events, and data (left), passing VBF preselection. The ggH and VBF signals are scaled for better visibility. Category boundaries targeting VBF production are denoted with dashed lines. The shaded region defines events which are not selected to enter VBF analysis categories, but may populate those targeting ggH. A small excess in data with respect to the MC background prediction is observed in the most signal-like bin; however, these events are not found to peak around the signal region of the m_{ee} distribution. The right plot shows the distribution of the output score of the VBF BDT in a control region around the Z boson mass. The simulated samples include both DY and EW $Z \rightarrow e^+e^-$ events. The combined impact of the statistical and systematic uncertainties in simulation is shown by the red shaded band, where the systematic component includes uncertainties in the jet energy scale and resolution corrections, alongside the electron energy scale corrections. Uncertainties in the efficiency of electron identification, reconstruction, and trigger selection are also included, as well as the uncertainty in the integrated luminosity, presented in Section 7. Good agreement is observed between the DY simulation (filled histogram) and data (black markers), within the phase space in which the analysis categories are constructed.

ically similar to the ggH signal. Hence, the classification task is nontrivial and many features are leveraged to improve the separation power of the BDT. These features include kinematic properties of the individual electrons, the dielectron system, and up to two jets, if present. Although these inputs are broadly similar between simulated ggH signal and background events, quantities such as the dielectron p_T provide reasonable discriminating power, where the average dielectron p_T for ggH events is higher than in background. Similarly to the VBF BDT, it is checked that information related to the dielectron system is not sufficient for m_H to be inferred by the classifier. The output score for the ggH BDT is shown for both simulation and data in Fig. 2 (left).

The validation procedure for the ggH BDT is identical to that for the VBF BDT, described above, and is performed in the Z boson mass control region designed to be non-overlapping with the ggH analysis categories. The basic analysis preselection is also applied, with the exception of the m_{ee} requirements. The distribution of the classifier output score in this region is shown in Fig. 2 (right). The agreement between data and simulation is typically within the uncertainty permitted by the combined systematic and statistical variations; any residual differences are smaller than the theoretical uncertainty in the ggH production cross section, presented in Section 7.

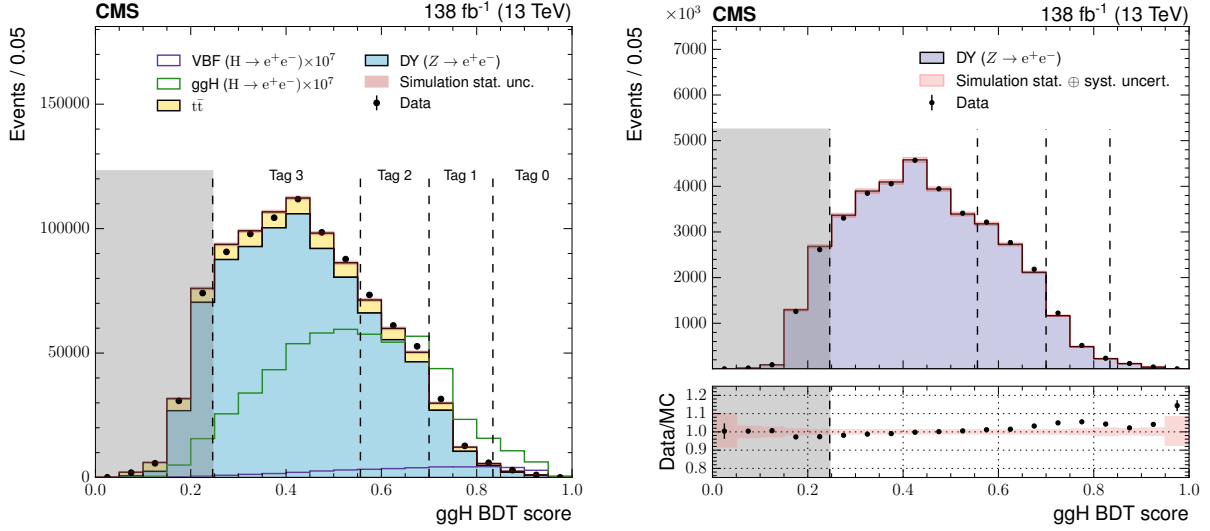


Figure 2: Distribution of the output score of the ggH BDT in simulated background and signal events, and data (left). The ggH and VBF signals are scaled such that they are visible. Category boundaries targeting ggH Higgs boson production are denoted with dashed lines. Events with scores in the grey shaded region are discarded from the analysis. The right plot shows the distribution of the output score of the ggH BDT in a control region around the Z boson mass. Agreement is compared between the DY simulation (filled histogram) and data (black points). The combined impact of the statistical and systematic uncertainties in simulation is shown by the red shaded band, where the sources contributing to the systematic component are identical to those included in Fig. 1. Residual differences between data and simulation are smaller than the theory uncertainties in the ggH cross section and event kinematics, which are included in the final maximum likelihood fit.

Four analysis categories targeting ggH events are defined using the output score of the ggH BDT. It is checked that going beyond four categories offers no improvement in sensitivity. The expected signal and background yields in each ggH category are shown in Table 1.

7 Systematic uncertainties

In this analysis, the systematic uncertainty associated with the background estimation from data is handled using the discrete profiling method, as described in Section 8. Systematic uncertainties that affect the signal model are implemented in one of the following two ways. Uncertainties that modify the shape of the m_{ee} distribution are incorporated into the signal model as nuisance parameters. These are typically experimental uncertainties related to the energy measurement of the individual electrons. Conversely, if the shape of the m_{ee} distribution is unaffected, the uncertainty is treated as a log-normal constrained variation in the event yield.

7.1 Theoretical uncertainties

The sources of theoretical uncertainty considered in this analysis are listed below. The effects of theoretical uncertainties are taken to be correlated across years.

- *Renormalization and factorization scale uncertainty*: the uncertainty arising from variations of the renormalization (μ_R) and factorization (μ_F) scales used when computing the expected SM cross section and event kinematics. These account for the missing higher-order terms in perturbative calculations. The recommendations provided by

the Higgs Cross Section Working Group quoted in Ref. [39] are followed. The uncertainties in the signal acceptance due to the μ_R and μ_F scales are estimated using three sources: varying the μ_R scale by a factor of 2 and 0.5, varying the μ_F scale by a factor of 2 and 0.5, and varying both in the same direction simultaneously. The impacts of the signal acceptance uncertainties are evaluated keeping the overall normalization of each signal process constant, and are at largest (for the ggH production mode) 10%.

- *PDF uncertainties*: these account for the uncertainty due to imperfect knowledge of the composition of the proton, that affects which partons are most likely to initiate high energy events. The normalization uncertainties are computed following the PDF4LHC prescription [14, 44]. The impact on the normalization ranges between 1.9 and 3%.
- *Uncertainty in the strong force coupling constant*: the uncertainty in the value of the strong force coupling constant α_S is included in the treatment of the PDF uncertainties, following the PDF4LHC [14, 44] prescription. The impact on the normalization is largest for ggH production, with a value of 2.6%.
- *Underlying event and parton shower uncertainties*: these uncertainties are obtained using dedicated simulated samples which vary the PYTHIA tune from that used in the nominal simulation samples, and vary the renormalization scale for QCD emissions in both initial-state and final-state radiation by a factor of 2 and 0.5. These uncertainties are treated as migrations of events from a given production mode into and out of the VBF and ggH analysis categories. The largest effect comes from the parton shower uncertainty in VBF events, which can change the signal yield in the VBF analysis categories by up to 5%.

The total impact on the $\mathcal{B}(H \rightarrow e^+e^-)$ measurement from theoretical systematic uncertainties is ${}^{+0.2}_{-0.1} \times 10^{-4}$, with dominant contributions from uncertainties affecting the ggH production cross section.

7.2 Experimental uncertainties

The uncertainties that affect the shape of the signal m_{ee} distribution are listed below.

- *Electron energy scale*: the uncertainty associated with the corrections applied to the electron energy scale in simulated events [24], derived using a sample of $Z \rightarrow e^+e^-$ tag-and-probe (T&P) events [45]. Four nuisance parameters are defined for the possible combinations of low R_9 , high R_9 , electrons in the endcap, and electrons in the barrel region of the ECAL, where R_9 is defined as the energy sum of the 3×3 crystals centred on the most energetic crystal in the candidate electromagnetic cluster divided by the sum of the crystal energies assigned to that electromagnetic cluster.
- *Electron energy scale nonlinearity*: a further source of uncertainty to cover possible differences between the linearity of the electron energy scale between data and simulation, estimated on a sample of $Z \rightarrow e^+e^-$ T&P events. An uncertainty of 0.1% is assigned for electrons with $p_T < 80$ GeV, and 0.2% for those above.

The uncertainties that only modify the event yield include:

- *Integrated luminosity*: the integrated luminosities for the 2016, 2017, and 2018 data-taking years have individual uncertainties of 1.2, 2.3, and 2.5%, respectively [46–48]. The total uncertainty for the 2016–2018 period is 1.6%. These are partially correlated across the different data sets to account for common sources of uncertainty in the

luminosity measurement schemes.

- *Electron identification and reconstruction*: uncertainties in the scale factors derived to correct for differences in simulation and data for the electron identification and reconstruction efficiency. For both sources, the size of the uncertainty is approximately 1% in each category.
- *Jet energy scale and resolution corrections*: the energy scale of jets is measured using the p_T balance of jets with Z bosons and photons in $Z \rightarrow e^+e^-$, $Z \rightarrow \mu^+\mu^-$ and γ +jets events, as well as the p_T balance between jets in dijet and multijet events [43]. The uncertainty in the jet energy scale is a few percent and depends on p_T and η . The impact of jet energy scale uncertainties in event yields is evaluated by varying the jet energy corrections within their uncertainties and propagating the effect to the final result. The impact of the scale uncertainties on the category yields is largest for those targeting VBF, and can be as high as 15%, but is less than 3% for the resolution. The effect of the scale uncertainties is observed in Fig. 1 (right), where the combined uncertainty has large contributions from the jet energy scale uncertainty.
- *Trigger efficiency*: the uncertainty in the efficiency of the trigger selection is measured with $Z \rightarrow e^+e^-$ events using the T&P technique. The size of its uncertainty is less than 1%. An additional uncertainty is introduced to account for a gradual shift in the timing of the inputs of the ECAL L1 trigger in the region at $|\eta| > 2.0$, which caused a specific trigger inefficiency during 2016–2017 data taking [20].

The total impact on the $\mathcal{B}(H \rightarrow e^+e^-)$ measurement from experimental systematic uncertainties is $\pm 0.2 \times 10^{-4}$, with the largest contributions arising from uncertainties affecting the electron energy scale.

8 Results

This section describes the construction of the statistical model used in the maximum likelihood fit, and presents the results of the analysis.

8.1 Signal models

The shape of the m_{ee} distribution for simulated signal is parameterized independently for each production process entering each event category, and for each year separately. Each signal model is constructed from a sum of up to five independent Gaussian functions. To allow for the extraction of limits on $\mathcal{B}(H \rightarrow e^+e^-)$ as a function of m_H , signal models are constructed from a simultaneous fit to samples at $m_H = 120, 125, \text{ and } 130 \text{ GeV}$. Each parameter for each Gaussian is a linear function of m_H . The optimal number of Gaussian functions is chosen by performing an F-test [49], to avoid overfitting to statistical fluctuations resulting from the limited size of the simulated samples. The sum of models for each production process is shown for the highest S/B analysis categories targeting VBF and ggH production in Fig. 3, for a nominal m_H of 125 GeV.

8.2 Background models

The discrete profiling method [29] is used to account for the uncertainty related to mismodelling of the background. This method treats the choice of the function used to model the background, which is unknown a priori, as a discrete nuisance parameter. For each category, a range of analytical functions are used as candidates to fit the m_{ee} distribution. These include generic smoothly-falling functions such as sums of exponential functions, Laurent se-

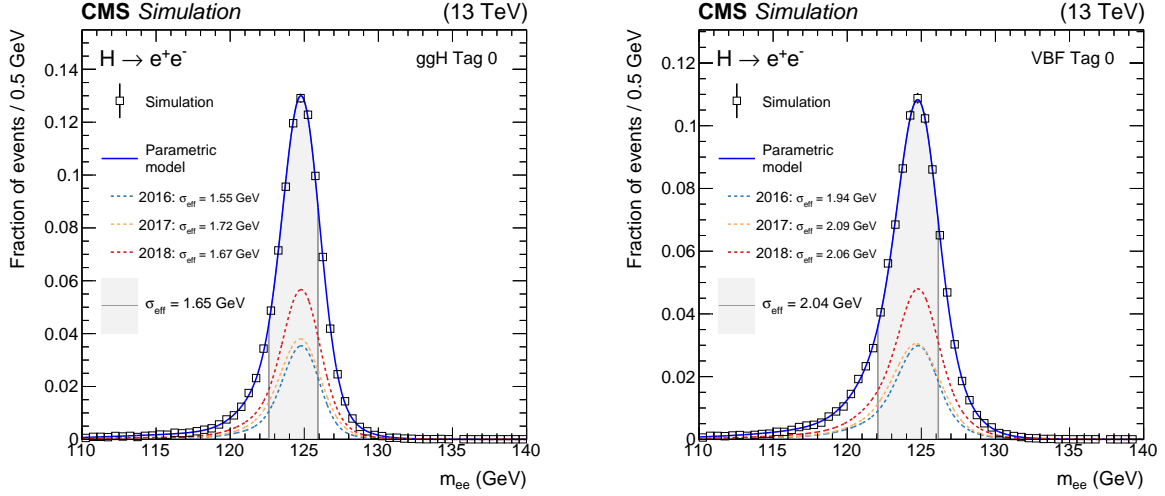


Figure 3: Signal models for the highest S/B categories targeting ggH and VBF processes, integrated over production processes, for Higgs boson events simulated at $m_H = 125$ GeV. Contributions from each of the three years are shown by the dashed lines. The models are normalized to unit area. The σ_{eff} is the smallest interval containing 68.3% of the m_{ee} signal distribution.

ries', and Bernstein polynomials, as well as physics-inspired models chosen to fit the dominant DY component of the background, which comprise modified Breit–Wigner functions. These functions have been used successfully to fit similar background processes in previous CMS analyses [10, 28]. The final set of functions considered is chosen by performing an F-test for each candidate, with a loose requirement on the goodness-of-fit.

Each candidate function is considered in the final signal-plus-background (S+B) fit to data. The function that results in the best overall fit is chosen for each value of the parameter of interest. In the fit, the normalization and shape parameters for the background functions are allowed to vary freely. The resulting confidence intervals therefore account for possible changes in the preferred function choice. The bias on $\mathcal{B}(H \rightarrow e^+e^-)$ resulting from a particular choice of background function was also checked for each category and found to be negligible.

Finally, background events resulting from both SM $H \rightarrow \gamma\gamma$ production, where the photons are misreconstructed as electrons, and from the Dalitz decay [50] ($H \rightarrow e^+e^-\gamma$), where the photon is included in the electron reconstruction, were studied with simulated events. Each process was found to contribute around 0.1% and 0.2% to the inclusive analysis categories, respectively, for a $\mathcal{B}(H \rightarrow e^+e^-)$ at the expected limit. These processes are, therefore, neglected in this analysis.

8.3 Limits on $\mathcal{B}(H \rightarrow e^+e^-)$

A simultaneous maximum likelihood fit is performed across all analysis categories. The (S+B) m_{ee} distributions are shown for the highest S/B analysis categories targeting ggH and VBF production in Fig. 4. Upper limits are set on $\mathcal{B}(H \rightarrow e^+e^-)$ using the CL_s modified frequentist criterion [51–53] for m_H hypotheses between 120–130 GeV. This construction uses the profile-likelihood ratio as the test statistic [54], under the asymptotic approximation. Limits for a range of m_H hypotheses, along with the associated uncertainty intervals, are shown in Fig. 5. At the current best measured value of $m_H = 125.38$ GeV [55], the observed (expected) 95% CL limit is $\mathcal{B}(H \rightarrow e^+e^-) < 3.0 \times 10^{-4}$ (3.0×10^{-4}). Assuming that the only deviation from the SM prediction is from a modified Yukawa coupling to the electron, the limit translates into

an upper bound on the Higgs boson effective coupling modifier to electrons of $|\kappa_e| < 240$. A breakdown of the expected and observed limits on $\mathcal{B}(H \rightarrow e^+e^-)$ is shown per analysis category in Fig. 6. Tabulated results are provided in the HEPData record for this analysis [56].

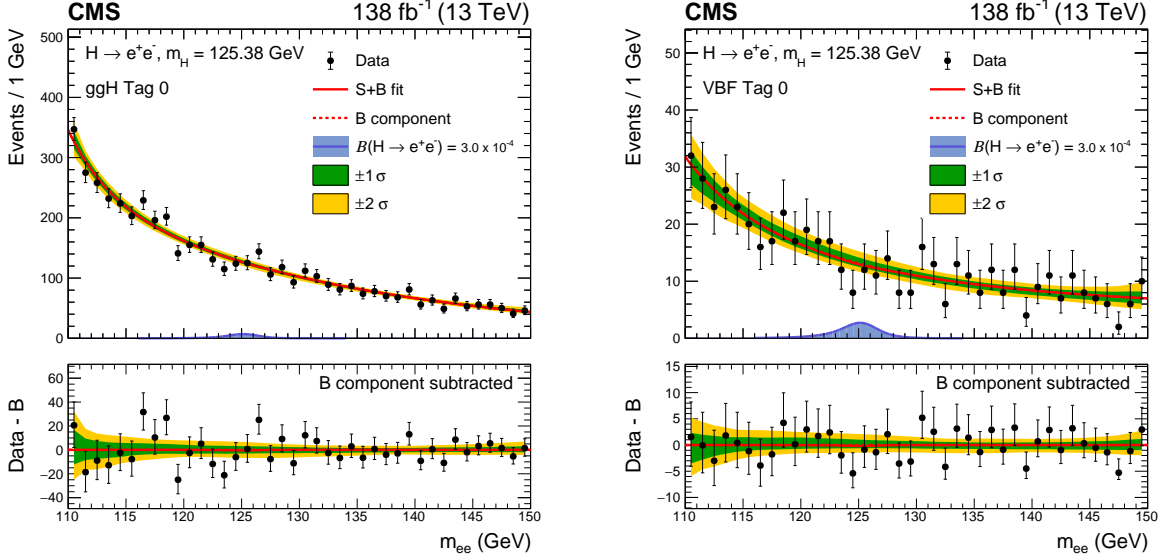


Figure 4: The signal-plus-background model fit to the m_{ee} distribution for the highest S/B analysis categories targeting the ggH (left) and VBF (right) processes. The signal model for each category is also shown, scaled to the observed limit at $m_H = 125.38$ GeV. The one (green) and two (yellow) standard deviation bands show the uncertainties in the background component of the fit. The lower panel shows the residuals after subtraction of this background component. The background functions describe the data well, with no excess observed.

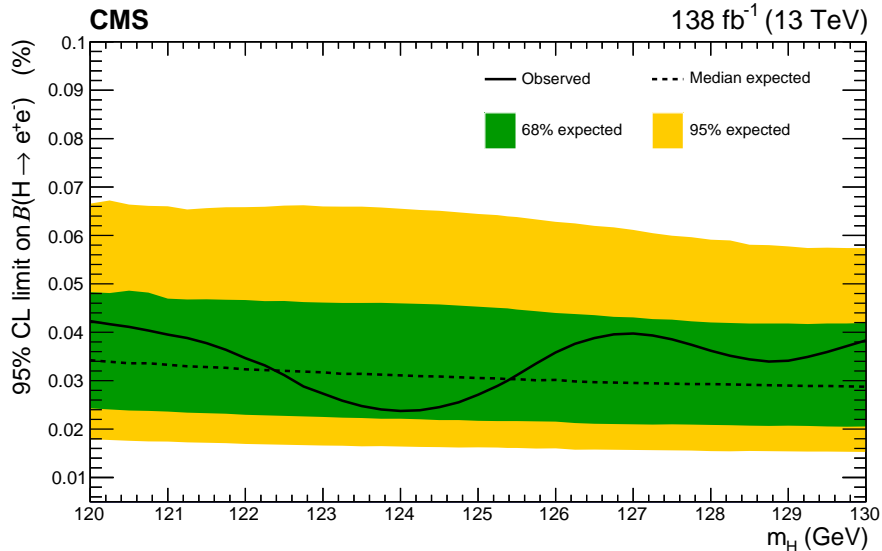


Figure 5: Expected and observed limits on $\mathcal{B}(H \rightarrow e^+e^-)$ for a Higgs boson mass between 120–130 GeV.

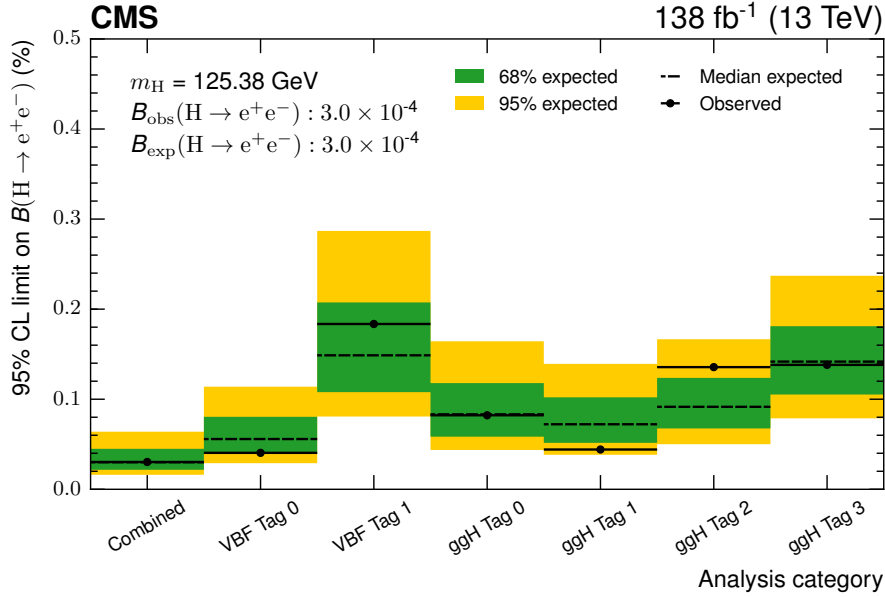


Figure 6: Expected and observed limits on $\mathcal{B}(H \rightarrow e^+e^-)$ for each analysis category, and all categories combined. The results here are computed for $m_H = 125.38$ GeV.

9 Summary

A search for the Higgs boson decaying to an e^+e^- pair is performed using proton-proton collision data collected at $\sqrt{s} = 13$ TeV with the CMS experiment at the LHC between 2016–2018, corresponding to an integrated luminosity of 138 fb^{-1} . The analysis uses categories targeting Higgs boson production via gluon fusion and vector boson fusion, with dedicated boosted decision tree classifiers trained for each production mode to enhance the sensitivity of the resulting categories. A maximum likelihood fit to the dielectron mass distribution is performed simultaneously in each analysis category to extract an upper limit on the Higgs boson to electron pair branching fraction; the resulting observed (expected) limit at the 95% confidence level on the branching fraction for $H \rightarrow e^+e^-$ decays is 3.0×10^{-4} (3.0×10^{-4}). This is the most stringent limit on the Higgs boson branching fraction to an e^+e^- pair to date. When compared with the previous best limit from the CMS Collaboration [18], where analysis categories were constructed using a selection on electron and jet kinematics, the improvement in sensitivity presented in this Letter is attributed primarily to the use of BDT classifiers, which significantly improve the S/B ratio of analysis categories. Accounting both for the increase in integrated luminosity and centre-of-mass energy, the use of BDT classifiers further improves the limit on $\mathcal{B}(H \rightarrow e^+e^-)$ by a factor of approximately 1.5.

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













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A The CMS Collaboration


Yerevan Physics Institute, Yerevan, Armenia

A. Tumasyan¹ 













Institut für Hochenergiephysik, Vienna, Austria

W. Adam , J.W. Andrejkovic, T. Bergauer , S. Chatterjee , K. Damanakis , M. Dragicevic , A. Escalante Del Valle , P.S. Hussain , M. Jeitler² , N. Krammer , L. Lechner , D. Liko , I. Mikulec , P. Paulitsch, F.M. Pitters, J. Schieck² , R. Schöfbeck , D. Schwarz , S. Templ , W. Waltenberger , C.-E. Wulz² 

Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish³ , T. Janssen , T. Kello⁴, H. Rejeb Sfar, P. Van Mechelen 










Vrije Universiteit Brussel, Brussel, Belgium

E.S. Bols , J. D'Hondt , A. De Moor , M. Delcourt , H. El Faham , S. Lowette , S. Moortgat , A. Morton , D. Müller , A.R. Sahasransu , S. Tavernier , W. Van Doninck, D. Vannerom 
















Université Libre de Bruxelles, Bruxelles, Belgium

B. Clerbaux , G. De Lentdecker , L. Favart , D. Hohov , J. Jaramillo , K. Lee , M. Mahdavihorrani , I. Makarenko , A. Malara , S. Paredes , L. Pétré , N. Postiau, E. Starling , L. Thomas , M. Vanden Bemden, C. Vander Velde , P. Vanlaer 






Ghent University, Ghent, Belgium

D. Dobur , J. Knolle , L. Lambrecht , G. Mestdach, M. Niedziela , C. Rendón, C. Roskas , A. Samalan, K. Skovpen , M. Tytgat , N. Van Den Bossche , B. Vermassen, L. Wezenbeek 






















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

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








Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

G.A. Alves , E. Coelho , C. Hensel , A. Moraes , P. Rebello Teles 

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

W.L. Aldá Júnior , M. Alves Gallo Pereira , M. Barroso Ferreira Filho , H. Brandao Malbouisson , W. Carvalho , J. Chinellato⁵, E.M. Da Costa , G.G. Da Silveira⁶ , D. De Jesus Damiao , V. Dos Santos Sousa , S. Fonseca De Souza , J. Martins⁷ , C. Mora Herrera , K. Mota Amarilo , L. Mundim , H. Nogima , A. Santoro , S.M. Silva Do Amaral , A. Sznajder , M. Thiel , F. Torres Da Silva De Araujo⁸ , A. Vilela Pereira 

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

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

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

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





University of Sofia, Sofia, Bulgaria

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

Beihang University, Beijing, China

T. Cheng , T. Javaid⁹ , M. Mittal , L. Yuan 











Department of Physics, Tsinghua University, Beijing, China

M. Ahmad , G. Bauer¹⁰, Z. Hu , S. Lezki , K. Yi^{10,11} 

Institute of High Energy Physics, Beijing, China

G.M. Chen⁹ , H.S. Chen⁹ , M. Chen⁹ , F. Iemmi , C.H. Jiang, A. Kapoor , H. Liao , Z.-A. Liu¹² , V. Milosevic , F. Monti , R. Sharma , J. Tao , J. Thomas-Wilsker , J. Wang , H. Zhang , J. Zhao 

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

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

Sun Yat-Sen University, Guangzhou, China

J. Li, M. Lu , Z. You 





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

X. Gao⁴ , D. Leggat, H. Okawa , Y. Zhang 





Zhejiang University, Hangzhou, Zhejiang, China

Z. Lin , C. Lu , M. Xiao 

Universidad de Los Andes, Bogota, Colombia

C. Avila , D.A. Barbosa Trujillo, A. Cabrera , C. Florez , J. Fraga 

Universidad de Antioquia, Medellin, Colombia

J. Mejia Guisao , F. Ramirez , M. Rodriguez , J.D. Ruiz Alvarez 

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

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










University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac , T. Sculac 




Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic , B.K. Chitroda , D. Ferencek , D. Majumder , M. Roguljic , A. Starodumov¹³ , T. Susa 

University of Cyprus, Nicosia, Cyprus

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


Charles University, Prague, Czech Republic

M. Finger¹³ , M. Finger Jr.¹³ , A. Kveton 


































































































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






E. Ayala 

Universidad San Francisco de Quito, Quito, Ecuador


E. Carrera Jarrin 

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian

Network of High Energy Physics, Cairo, EgyptA.A. Abdelalim^{14,15} , E. Salama^{16,17} **Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt**M. Abdullah Al-Mashad , M.A. Mahmoud **National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**S. Bhowmik , R.K. Dewanjee , K. Ehataht , M. Kadastik, T. Lange , S. Nandan ,
C. Nielsen , J. Pata , M. Raidal , L. Tani , C. Veelken **Department of Physics, University of Helsinki, Helsinki, Finland**P. Eerola , H. Kirschenmann , K. Osterberg , M. Voutilainen **Helsinki Institute of Physics, Helsinki, Finland**S. Bharthuar , E. Brücken , F. Garcia , J. Havukainen , M.S. Kim , R. Kinnunen,
T. Lampén , K. Lassila-Perini , S. Lehti , T. Lindén , M. Lotti, L. Martikainen ,
M. Myllymäki , J. Ott , M.m. Rantanen , H. Siikonen , E. Tuominen , J. Tuominiemi **Lappeenranta-Lahti University of Technology, Lappeenranta, Finland**P. Luukka , H. Petrow , T. Tuuva**IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France**C. Amendola , M. Besancon , F. Couderc , M. Dejardin , D. Denegri, J.L. Faure,
F. Ferri , S. Ganjour , P. Gras , G. Hamel de Monchenault , P. Jarry , V. Lohezic ,
J. Malcles , J. Rander, A. Rosowsky , M.Ö. Sahin , A. Savoy-Navarro¹⁸ , P. Simkina ,
M. Titov **Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France**C. Baldenegro Barrera , F. Beaudette , A. Buchot Perraguin , P. Busson , A. Cappati ,
C. Charlot , F. Damas , O. Davignon , B. Diab , G. Falmagne , B.A. Fontana Santos
Alves , S. Ghosh , R. Granier de Cassagnac , A. Hakimi , B. Harikrishnan ,
G. Liu , J. Motta , M. Nguyen , C. Ochando , L. Portales , J. Rembser , R. Salerno ,
U. Sarkar , J.B. Sauvan , Y. Sirois , A. Tarabini , E. Vernazza , A. Zabi , A. Zghiche **Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France**J.-L. Agram¹⁹ , J. Andrea , D. Apparú , D. Bloch , G. Bourgatte , J.-M. Brom ,
E.C. Chabert , C. Collard , D. Darej, U. Goerlach , C. Grimault, A.-C. Le Bihan ,
P. Van Hove **Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France**S. Beauceron , C. Bernet , B. Blancon , G. Boudoul , A. Carle, N. Chanon , J. Choi ,
D. Contardo , P. Depasse , C. Dozen²⁰ , H. El Mamouni, J. Fay , S. Gascon ,
M. Gouzevitch , G. Grenier , B. Ille , I.B. Laktineh, M. Lethuillier , L. Mirabito, S. Perries,
V. Sordini , L. Torterotot , M. Vander Donckt , P. Verdier , S. Viret**Georgian Technical University, Tbilisi, Georgia**A. Khvedelidze¹³ , I. Lomidze , Z. Tsamalaidze¹³ **RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany**V. Botta , L. Feld , K. Klein , M. Lipinski , D. Meuser , A. Pauls , N. Röwert ,
M. Teroerde **RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany**S. Diekmann , A. Dodonova , N. Eich , D. Eliseev , M. Erdmann , P. Fackeldey 

D. Fasanella , B. Fischer , T. Hebbeker , K. Hoepfner , F. Ivone , M.y. Lee , L. Mastrolorenzo, M. Merschmeyer , A. Meyer , S. Mondal , S. Mukherjee , D. Noll , A. Novak , F. Nowotny, A. Pozdnyakov , Y. Rath, W. Redjeb , H. Reithler , A. Schmidt , S.C. Schuler, A. Sharma , L. Vigilante, S. Wiedenbeck , S. Zaleski



































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

C. Dziwok , G. Flügge , W. Haj Ahmad²¹ , O. Hlushchenko, T. Kress , A. Nowack , O. Pooth , A. Stahl²² , T. Ziemons , A. Zotz 
































Deutsches Elektronen-Synchrotron, Hamburg, Germany

H. Aarup Petersen , M. Aldaya Martin , P. Asmuss, S. Baxter , M. Bayatmakou , O. Behnke , A. Bermúdez Martínez , S. Bhattacharya , A.A. Bin Anuar , F. Blekman²³ , K. Borras²⁴ , D. Brunner , A. Campbell , A. Cardini , C. Cheng, F. Colombina, S. Consuegra Rodríguez , G. Correia Silva , M. De Silva , L. Didukh , G. Eckerlin, D. Eckstein , L.I. Estevez Banos , O. Filatov , E. Gallo²³ , A. Geiser , A. Giraldi , G. Greau, A. Grohsjean , V. Guglielmi , M. Guthoff , A. Jafari²⁵ , N.Z. Jomhari , B. Kaech , A. Kasem²⁴ , M. Kasemann , H. Kaveh , C. Kleinwort , R. Kogler , M. Komm , D. Krücker , W. Lange, D. Leyva Pernia , K. Lipka , W. Lohmann²⁶ , R. Mankel , I.-A. Melzer-Pellmann , M. Mendizabal Morentin , J. Metwally, A.B. Meyer , G. Milella , M. Mormile , A. Mussgiller , A. Nürnberg , Y. Otariid, D. Pérez Adán , A. Raspereza , B. Ribeiro Lopes , J. Rübenach, A. Saggio , A. Saibel , M. Savitskyi , M. Scham^{27,24} , V. Scheurer, S. Schnake²⁴ , P. Schütze , C. Schwanenberger²³ , M. Shchedrolosiev , R.E. Sosa Ricardo , D. Stafford, N. Tonon[†] , M. Van De Klundert , F. Vazzoler , A. Ventura Barroso , R. Walsh , D. Walter , Q. Wang , Y. Wen , K. Wichmann, L. Wiens²⁴ , C. Wissing , S. Wuchterl , Y. Yang , A. Zimmermann Castro Santos 

University of Hamburg, Hamburg, Germany

R. Aggleton, A. Albrecht , S. Albrecht , M. Antonello , S. Bein , L. Benato , M. Bonanomi , P. Connor , K. De Leo , M. Eich, K. El Morabit , F. Feindt, A. Fröhlich, C. Garbers , E. Garutti , M. Hajheidari, J. Haller , A. Hinzmann , H.R. Jabusch , G. Kasieczka , R. Klanner , W. Korcari , T. Kramer , V. Kutzner , J. Lange , A. Lobanov , C. Matthies , A. Mehta , L. Moureaux , M. Mrowietz, A. Nigamova , Y. Nissan, A. Paasch , K.J. Pena Rodriguez , M. Rieger , O. Rieger, P. Schleper , M. Schröder , J. Schwandt , H. Stadie , G. Steinbrück , A. Tews, M. Wolf 










Karlsruher Institut fuer Technologie, Karlsruhe, Germany

J. Bechtel , S. Brommer , M. Burkart, E. Butz , R. Caspart , T. Chwalek , A. Dierlamm , A. Droll, N. Faltermann , M. Giffels , J.O. Gosewisch, A. Gottmann , F. Hartmann²² , M. Horzela , U. Husemann , P. Keicher, M. Klute , R. Koppenhöfer , S. Maier , S. Mitra , Th. Müller , M. Neukum, G. Quast , K. Rabbertz , J. Rauser, D. Savoie , M. Schnepf, D. Seith, I. Shvetsov , H.J. Simonis , N. Trevisani , R. Ulrich , J. van der Linden , R.F. Von Cube , M. Wassmer , M. Weber , S. Wieland , R. Wolf , S. Wozniowski , S. Wunsch




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

G. Anagnostou, P. Assiouras , G. Daskalakis , A. Kyriakis, A. Stakia 





National and Kapodistrian University of Athens, Athens, Greece

M. Diamantopoulou, D. Karasavvas, P. Kontaxakis , A. Manousakis-Katsikakis , A. Panagiotou, I. Papavergou , N. Saoulidou , K. Theofilatos , E. Tziaferi , K. Vellidis , E. Vourliotis , I. Zisopoulos 

National Technical University of Athens, Athens, Greece

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






University of Ioánnina, Ioánnina, Greece

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

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

M. Csanád , K. Farkas , M.M.A. Gadallah²⁸ , S. Lökös²⁹ , P. Major , K. Mandal , G. Pásztor , A.J. Rádl³⁰ , O. Surányi , G.I. Veres 

Wigner Research Centre for Physics, Budapest, Hungary

M. Bartók³¹ , G. Bencze, C. Hajdu , D. Horvath^{32,33} , F. Sikler , V. Veszpremi 




Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni , S. Czellar, J. Karancsi³¹ , J. Molnar, Z. Szillasi, D. Teyssier 


















Institute of Physics, University of Debrecen, Debrecen, Hungary

P. Raics, B. Ujvari³⁴ 





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

T. Csorgo³⁰ , F. Nemes³⁰ , T. Novak 







Panjab University, Chandigarh, India

J. Babbar , S. Bansal , S.B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan , N. Dhingra³⁵ , R. Gupta, A. Kaur , A. Kaur , H. Kaur , M. Kaur , S. Kumar , P. Kumari , M. Meena , K. Sandeep , T. Sheokand, J.B. Singh³⁶ , A. Singla , A. K. Viridi 














University of Delhi, Delhi, India

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


Saha Institute of Nuclear Physics, HBNI, Kolkata, India

S. Baradia , S. Barman³⁷ , S. Bhattacharya , D. Bhowmik, S. Dutta , S. Dutta, B. Gomber³⁸ , M. Maity³⁷, P. Palit , P.K. Rout , G. Saha , B. Sahu , S. Sarkar

Indian Institute of Technology Madras, Madras, India

P.K. Behera , S.C. Behera , P. Kalbhor , J.R. Komaragiri³⁹ , D. Kumar³⁹ , A. Muham-
mad , L. Panwar³⁹ , R. Pradhan , P.R. Pujahari , A. Sharma , A.K. Sikdar ,
P.C. Tiwari³⁹ , S. Verma 

Bhabha Atomic Research Centre, Mumbai, India

K. Naskar⁴⁰ 

Tata Institute of Fundamental Research-A, Mumbai, India

T. Aziz, I. Das , S. Dugad, M. Kumar , G.B. Mohanty , P. Suryadevara

Tata Institute of Fundamental Research-B, Mumbai, India








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

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

Institute, Bhubaneswar, Odisha, India

S. Bahinipati⁴¹ , A.K. Das, C. Kar , P. Mal , T. Mishra , V.K. Muraleedharan Nair Bindhu⁴² , A. Nayak⁴² , P. Saha , N. Sur , S.K. Swain, D. Vats⁴² 

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

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

Isfahan University of Technology, Isfahan, Iran

H. Bakhshiansohi⁴³ , E. Khazaie , M. Zeinali⁴⁴ 

































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

S. Chenarani⁴⁵ , S.M. Etesami , M. Khakzad , M. Mohammadi Najafabadi 




























University College Dublin, Dublin, Ireland

M. Grunewald 

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

M. Abbrescia^{a,b} , R. Aly^{a,c,14} , C. Aruta^{a,b} , A. Colaleo^a , D. Creanza^{a,c} , N. De Filippis^{a,c} , M. De Palma^{a,b} , A. Di Florio^{a,b} , W. Elmetenawee^{a,b} , F. Errico^{a,b} , L. Fiore^a , G. Iaselli^{a,c} , M. Ince^{a,b} , G. Maggi^{a,c} , M. Maggi^a , I. Margjeka^{a,b} , V. Mastrapasqua^{a,b} , S. My^{a,b} , S. Nuzzo^{a,b} , A. Pellecchia^{a,b} , A. Pompili^{a,b} , G. Pugliese^{a,c} , R. Radogna^a , D. Ramos^a , A. Ranieri^a , G. Selvaggi^{a,b} , L. Silvestris^a , F.M. Simone^{a,b} , Ü. Sözbilir^a , A. Stamerra^a , R. Venditti^a , P. Verwilligen^a 

















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

G. Abbiendi^a , C. Battilana^{a,b} , D. Bonacorsi^{a,b} , L. Borghonovi^a , L. Brigliadori^a, R. Campanini^{a,b} , P. Capiluppi^{a,b} , A. Castro^{a,b} , F.R. Cavallo^a , M. Cuffiani^{a,b} , G.M. Dallavalle^a , T. Diotallevi^{a,b} , F. Fabbri^a , A. Fanfani^{a,b} , P. Giacomelli^a , L. Giommi^{a,b} , C. Grandi^a , L. Guiducci^{a,b} , S. Lo Meo^{a,46} , L. Lunerti^{a,b} , S. Marcellini^a , G. Masetti^a , F.L. Navarria^{a,b} , A. Perrotta^a , F. Primavera^{a,b} , A.M. Rossi^{a,b} , T. Rovelli^{a,b} , G.P. Siroli^{a,b} 

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

S. Costa^{a,b,47} , A. Di Mattia^a , R. Potenza^{a,b}, A. Tricomi^{a,b,47} , C. Tuve^{a,b} 

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

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
























INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi , S. Bianco , S. Meola²² , D. Piccolo 

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










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

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


















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

INFN Sezione di Napoli^a, Università di Napoli 'Federico II'^b, Napoli, Italy; Università della












Basilicata^c, Potenza, Italy; Università G. Marconi^d, Roma, Italy

S. Buontempo^a , F. Carnevali^{a,b} , N. Cavallo^{a,c} , A. De Iorio^{a,b} , F. Fabozzi^{a,c} , A.O.M. Iorio^{a,b} , L. Lista^{a,b,48} , P. Paolucci^{a,22} , B. Rossi^a , C. Sciacca^{a,b} 
















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

P. Azzi^a , N. Bacchetta^{a,49} , D. Bisello^{a,b} , P. Bortignon^a , A. Bragagnolo^{a,b} , R. Carlin^{a,b} , P. Checchia^a , T. Dorigo^a , F. Gasparini^{a,b} , U. Gasparini^{a,b} , G. Grosso^a , L. Layer^{a,50} , E. Lusiani^a , M. Margoni^{a,b} , A.T. Meneguzzo^{a,b} , J. Pazzini^{a,b} , P. Ronchese^{a,b} , R. Rossin^{a,b} , F. Simonetto^{a,b} , G. Strong^a , M. Tosi^{a,b} , H. Yarar^{a,b} , M. Zanetti^{a,b} , P. Zotto^{a,b} , A. Zucchetta^{a,b} , G. Zumerle^{a,b}


















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

S. Abu Zeid^{a,17} , C. Aimè^{a,b} , A. Braghieri^a , S. Calzaferri^{a,b} , D. Fiorina^{a,b} , P. Montagna^{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

P. Asenov^{a,51} , G.M. Bilei^a , D. Ciangottini^{a,b} , L. Fanò^{a,b} , M. Magherini^{a,b} , G. Mantovani^{a,b} , V. Mariani^{a,b} , M. Menichelli^a , F. Moscatelli^{a,51} , A. Piccinelli^{a,b} , M. Presilla^{a,b} , A. Rossi^{a,b} , A. Santocchia^{a,b} , D. Spiga^a , T. Tedeschi^{a,b} 


















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

P. Azzurri^a , G. Bagliesi^a , V. Bertacchi^{a,c} , R. Bhattacharya^a , L. Bianchini^{a,b} , T. Boccali^a , E. Bossini^{a,b} , D. Bruschini^{a,c} , R. Castaldi^a , M.A. Ciocci^{a,b} , V. D'Amante^{a,d} , R. Dell'Orso^a , M.R. Di Domenico^{a,d} , S. Donato^a , A. Giassi^a , F. Ligabue^{a,c} , E. Manca^{a,c} , G. Mandorli^{a,c} , D. Matos Figueiredo^a , A. Messineo^{a,b} , M. Musich^{a,b} , F. Palla^a , S. Parolia^{a,b} , G. Ramirez-Sanchez^{a,c} , A. Rizzi^{a,b} , G. Rolandi^{a,c} , S. Roy Chowdhury^{a,c} , T. Sarkar^{a,37} , A. Scribano^a , N. Shafiei^{a,b} , P. Spagnolo^a , R. Tenchini^a , G. Tonelli^{a,b} , N. Turini^{a,d} , A. Venturi^a , P.G. Verdini^a








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

P. Barria^a , M. Campana^{a,b} , F. Cavallari^a , D. Del Re^{a,b} , E. Di Marco^a , M. Diemoz^a , E. Longo^{a,b} , P. Meridiani^a , G. Organtini^{a,b} , F. Pandolfi^a , R. Paramatti^{a,b} , C. Quaranta^{a,b} , S. Rahatlou^{a,b} , C. Rovelli^a , F. Santanastasio^{a,b} , L. Soffi^a , R. Tramontano^{a,b} 














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

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

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

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

Kyungpook National University, Daegu, Korea

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





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

H. Kim , D.H. Moon 

Hanyang University, Seoul, Korea

E. Asilar , T.J. Kim , J. Park 

Korea University, Seoul, Korea

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















Kyung Hee University, Department of Physics, Seoul, Korea

J. Goh 

Sejong University, Seoul, Korea

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

Seoul National University, Seoul, Korea

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






University of Seoul, Seoul, Korea

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


Yonsei University, Department of Physics, Seoul, Korea

S. Ha , H.D. Yoo 






Sungkyunkwan University, Suwon, Korea

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

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

T. Beyrouthy, Y. Maghrbi 




Riga Technical University, Riga, Latvia

K. Dreimanis , A. Gaile , A. Potrebko , T. Torims , V. Veckalns 







Vilnius University, Vilnius, Lithuania

M. Ambrozas , A. Carvalho Antunes De Oliveira , A. Juodagalvis , A. Rinkevicius , G. Tamulaitis 






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

N. Bin Norjoharuddeen , S.Y. Hoh⁵² , I. Yusuff⁵² , Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico

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

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

G. Ayala , H. Castilla-Valdez , I. Heredia-De La Cruz⁵³ , R. Lopez-Fernandez , C.A. Mondragon Herrera, D.A. Perez Navarro , A. Sánchez Hernández 

Universidad Iberoamericana, Mexico City, Mexico

C. Oropeza Barrera , F. Vazquez Valencia 

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

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

University of Montenegro, Podgorica, Montenegro

I. Bubanja, J. Mijuskovic⁵⁴, N. Raicevic 








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

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






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

V. Avati, L. Grzanka , M. Malawski 

National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska , M. Bluj , B. Boimska , M. Górski , M. Kazana , M. Szeleper ,
P. Zalewski 

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

K. Bunkowski , K. Doroba , A. Kalinowski , M. Konecki , J. Krolikowski 





























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

M. Araujo , P. Bargassa , D. Bastos , A. Boletti , P. Faccioli , M. Gallinaro , J. Hollar ,
N. Leonardo , T. Niknejad , M. Pisano , J. Seixas , O. Toldaiev , J. Varela 

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

P. Adzic⁵⁵ , M. Dordevic , P. Milenovic , J. Milosevic 













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

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
















Universidad Autónoma de Madrid, Madrid, Spain

J.F. de Trocóniz 

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

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

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

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

University of Colombo, Colombo, Sri Lanka

M.K. Jayananda , B. Kailasapathy⁵⁶ , D.U.J. Sonnadara , D.D.C. Wickramarathna 


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

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


































CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo , J. Alimena , E. Auffray , G. Auzinger , J. Baechler, P. Baillon[†], D. Barney , J. Bendavid , M. Bianco , B. Bilin , A. Bocci , E. Brondolin , C. Caillol , T. Camporesi , G. Cerminara , N. Chernyavskaya , S.S. Chhibra , S. Choudhury, M. Cipriani , L. Cristella , D. d'Enterria , A. Dabrowski , A. David , A. De Roeck , M.M. Defranchis , M. Deile , M. Dobson , M. Dünser , N. Dupont, A. Elliott-Peisert, F. Fallavollita⁵⁷, A. Florent , L. Forthomme , G. Franzoni , W. Funk , S. Ghosh , S. Giani, D. Gigi, K. Gill , F. Glege , L. Gouskos , E. Govorkova , M. Haranko , J. Hegeman , V. Innocente , T. James , P. Janot , J. Kaspar , J. Kieseler , N. Kratochwil , S. Laurila , P. Lecoq , E. Leutgeb , A. Lintuluoto , C. Lourenço , B. Maier , L. Malgeri , M. Mannelli , A.C. Marini , F. Meijers , S. Mersi , E. Meschi , F. Moortgat , M. Mulders , S. Orfanelli, L. Orsini, F. Pantaleo , E. Perez, M. Peruzzi , A. Petrilli , G. Petrucciani , A. Pfeiffer , M. Pierini , D. Piparo , M. Pitt , H. Qu , T. Quast, D. Rabadý , A. Racz, G. Reales Gutiérrez, M. Rovere , H. Sakulin , J. Salfeld-Nebgen , S. Scarfi , M. Selvaggi , A. Sharma , P. Silva , P. Sphicas⁵⁸ , A.G. Stahl Leiton , S. Summers , K. Tatar , V.R. Tavolaro , D. Treille , P. Tropea , A. Tsiros, J. Wanczyk⁵⁹ , K.A. Wozniak , W.D. Zeuner





















Paul Scherrer Institut, Villigen, Switzerland

L. Caminada⁶⁰ , A. Ebrahimi , W. Erdmann , R. Horisberger , Q. Ingram , H.C. Kaestli , D. Kotlinski , C. Lange , M. Missiroli⁶⁰ , L. Noehte⁶⁰ , T. Rohe 

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

T.K. Aarrestad , K. Androsov⁵⁹ , M. Backhaus , P. Berger, A. Calandri , K. Datta , A. De Cosa , G. Dissertori , M. Dittmar, M. Donegà , F. Eble , M. Galli , K. Gedia , F. Glessgen , T.A. Gómez Espinosa , C. Grab , D. Hits , W. Lustermann , A.-M. Lyon , R.A. Manzoni , L. Marchese , C. Martin Perez , A. Mascellani⁵⁹ , M.T. Meinhard , F. Nessi-Tedaldi , J. Niedziela , F. Pauss , V. Perovic , S. Pigazzini , M.G. Ratti , M. Reichmann , C. Reissel , T. Reitenspiess , B. Ristic , F. Riti , D. Ruini, D.A. Sanz Becerra , J. Steggemann⁵⁹ , D. Valsecchi²² , R. Wallny 










Universität Zürich, Zurich, Switzerland

C. Amsler⁶¹ , P. Bäertschi , C. Botta , D. Brzhechko, M.F. Canelli , K. Cormier , A. De Wit , R. Del Burgo, J.K. Heikkilä , M. Huwiler , W. Jin , A. Jofrehei , B. Kilminster , S. Leontsinis , S.P. Liechi , A. Macchiolo , P. Meiring , V.M. Mikuni , U. Molinatti , I. Neutelings , A. Reimers , P. Robmann, S. Sanchez Cruz , K. Schweiger , M. Senger , Y. Takahashi

National Central University, Chung-Li, Taiwan

C. Adloff⁶², C.M. Kuo, W. Lin, S.S. Yu 





















National Taiwan University (NTU), Taipei, Taiwan

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



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

C. Asawatangtrakuldee , N. Srimanobhas 

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

D. Agyel , F. Boran , Z.S. Demiroglu , F. Dolek , I. Dumanoglu⁶³ , E. Eskut , Y. Guler⁶⁴ , E. Gurpinar Guler⁶⁴ , C. Isik , O. Kara, A. Kayis Topaksu , U. Kiminsu , G. Onengut , K. Ozdemir⁶⁵ , A. Polatoz , A.E. Simsek , B. Tali⁶⁶ , U.G. Tok , S. Turkcapar , E. Uslan , I.S. Zorbakir 

Middle East Technical University, Physics Department, Ankara, Turkey

G. Karapinar⁶⁷, K. Ocalan⁶⁸ , M. Yalvac⁶⁹ 

Bogazici University, Istanbul, Turkey

B. Akgun , I.O. Atakisi , E. Gülmez , M. Kaya⁷⁰ , O. Kaya⁷¹ , Ö. Özçelik , S. Tekten⁷² 


Istanbul Technical University, Istanbul, Turkey

A. Cakir , K. Cankocak⁶³ , Y. Komurcu , S. Sen⁷³ 


Istanbul University, Istanbul, Turkey

O. Aydilek , S. Cerci⁶⁶ , B. Hacisahinoglu , I. Hos⁷⁴ , B. Isildak⁷⁵ , B. Kaynak , S. Ozkorucuklu , C. Simsek , D. Sunar Cerci⁶⁶ 
















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

B. Grynyov 

















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

L. Levchuk 


































University of Bristol, Bristol, United Kingdom

D. Anthony , E. Bhal , J.J. Brooke , A. Bundock , E. Clement , D. Cussans , H. Flacher , M. Glowacki, J. Goldstein , G.P. Heath, H.F. Heath , L. Kreczko , B. Krikler , S. Paramesvaran , S. Seif El Nasr-Storey, V.J. Smith , N. Stylianou⁷⁶ , K. Walkingshaw Pass, R. White 




Rutherford Appleton Laboratory, Didcot, United Kingdom

A.H. Ball, K.W. Bell , A. Belyaev⁷⁷ , C. Brew , R.M. Brown , D.J.A. Cockerill , C. Cooke , K.V. Ellis, K. Harder , S. Harper , M.-L. Holmberg⁷⁸ , J. Linacre , K. Manolopoulos, D.M. Newbold , E. Olaiya, D. Petyt , T. Reis , G. Salvi , T. Schuh, C.H. Shepherd-Themistocleous , I.R. Tomalin, T. Williams 

Imperial College, London, United Kingdom

R. Bainbridge , P. Bloch , S. Bonomally, J. Borg , S. Breeze, C.E. Brown , O. Buchmuller, V. Cacchio, V. Cepaitis , G.S. Chahal⁷⁹ , D. Colling , J.S. Dancu, P. Dauncey , G. Davies , J. Davies, M. Della Negra , S. Fayer, G. Fedi , G. Hall , M.H. Hassanshahi , A. Howard, G. Iles , J. Langford , L. Lyons , A.-M. Magnan , S. Malik, A. Martelli , M. Mieskolainen , D.G. Monk , J. Nash⁸⁰ , M. Pesaresi, B.C. Radburn-Smith , D.M. Raymond, A. Richards, A. Rose , E. Scott , C. Seez , A. Shtipliyski, R. Shukla , A. Tapper , K. Uchida , G.P. Uttley , L.H. Vage, T. Virdee²² , M. Vojinovic , N. Wardle , S.N. Webb , D. Winterbottom

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, Texas, USA

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

















Catholic University of America, Washington, DC, USA

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






















The University of Alabama, Tuscaloosa, Alabama, USA

A. Buccilli , S.I. Cooper , D. Di Croce , S.V. Gleyzer , C. Henderson , C.U. Perez , P. Rumerio⁸¹ , C. West 



















Boston University, Boston, Massachusetts, USA

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














Brown University, Providence, Rhode Island, USA

G. Benelli , B. Burkle , X. Coubez²⁴ , D. Cutts , M. Hadley , U. Heintz , J.M. Hogan⁸² , T. Kwon , G. Landsberg , K.T. Lau , D. Li , J. Luo , M. Narain , N. Pervan , S. Sagir⁸³ , F. Simpson , E. Usai , W.Y. Wong , X. Yan , D. Yu , W. Zhang 











University of California, Davis, Davis, California, USA

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























University of California, Los Angeles, California, USA

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
























University of California, Riverside, Riverside, California, USA

Y. Chen , R. Clare , J.W. Gary , M. Gordon , G. Hanson , G. Karapostoli , O.R. Long , N. Manganelli , W. Si , S. Wimpenny 














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

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













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

N. Amin , C. Campagnari , M. Citron , G. Collura , A. Dorsett , V. Dutta , J. Incandela , M. Kilpatrick , J. Kim , A.J. Li , B. Marsh , P. Masterson , H. Mei , M. Oshiro , M. Quinnan , J. Richman , U. Sarica , R. Schmitz , F. Setti , J. Sheplock , P. Siddireddy , D. Stuart , S. Wang 

California Institute of Technology, Pasadena, California, USA

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


















Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

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






































































University of Colorado Boulder, Boulder, Colorado, USA

J.P. Cumalat , W.T. Ford , A. Hassani , G. Karathanasis , E. MacDonald , F. Marini , R. Patel , A. Perloff , C. Savard , N. Schonbeck , K. Stenson , K.A. Ulmer , S.R. Wagner , N. Zipper 






















Cornell University, Ithaca, New York, USA

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













Fermi National Accelerator Laboratory, Batavia, Illinois, USA

M. Albrow , M. Alyari , G. Apollinari , A. Apresyan , L.A.T. Bauerdick , D. Berry , J. Berryhill , P.C. Bhat , K. Burkett , J.N. Butler , A. Canepa , G.B. Cerati , H.W.K. Cheung , F. Chlebana , K.F. Di Petrillo , J. Dickinson , V.D. Elvira , Y. Feng , J. Freeman , A. Gandrakota , Z. Gece , L. Gray , D. Green , S. Grünendahl , O. Gutsche , R.M. Harris , R. Heller , T.C. Herwig , J. Hirschauer , L. Horyn , B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , T. Klijnsma , B. Klima , K.H.M. Kwok , S. Lammel , D. Lincoln , R. Lipton , T. Liu , C. Madrid , K. Maeshima , C. Mantilla , D. Mason , P. McBride , P. Merkel , S. Mrenna , S. Nahn , J. Ngadiuba , D. Noonan , V. Papadimitriou , N. Pastika , K. Pedro , C. Pena⁸⁴ , F. Ravera , A. Reinsvold Hall⁸⁵ , L. Ristori , E. Sexton-Kennedy , N. Smith , A. Soha , L. Spiegel , J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger , E.W. Vaandering , H.A. Weber , I. Zoi 








University of Florida, Gainesville, Florida, USA

P. Avery , D. Bourilkov , L. Cadamuro , V. Cherepanov , R.D. Field , D. Guerrero , M. Kim , E. Koenig , J. Konigsberg , A. Korytov , K.H. Lo , K. Matchev , N. Menendez , G. Mitselmakher , A. Muthirakalayil Madhu , N. Rawal , D. Rosenzweig , S. Rosenzweig , K. Shi , J. Wang , Z. Wu 



















Florida State University, Tallahassee, Florida, USA

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














Florida Institute of Technology, Melbourne, Florida, USA

M.M. Baarmand , S. Butalla , T. Elkafrawy¹⁷ , M. Hohlmann , R. Kumar Verma , M. Rahmani , F. Yumiceva 

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

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



























The University of Iowa, Iowa City, Iowa, USA

M. Alhusseini , K. Dilsiz⁸⁶ , L. Emediato , R.P. Gandrajula , G. Karaman , O.K. Köseyan , J.-P. Merlo , A. Mestvirishvili⁸⁷ , J. Nachtman , O. Neogi , H. Ogul⁸⁸ , Y. Onel , A. Penzo , C. Snyder , E. Tiras⁸⁹ 








Johns Hopkins University, Baltimore, Maryland, USA

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

The University of Kansas, Lawrence, Kansas, USA

A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , P. Baringer , A. Bean , Z. Flowers , T. Isidori , S. Khalil , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu , C. Lindsey , J. Marquez , N. Minafra , M. Murray , M. Nickel , C. Rogan , C. Royon , R. Salvatico , S. Sanders , E. Schmitz , C. Smith , Q. Wang , J. Williams , G. Wilson 



















Kansas State University, Manhattan, Kansas, USA

B. Allmond , S. Duric, R. Gujju Gurunadha , A. Ivanov , K. Kaadze , D. Kim, Y. Maravin , T. Mitchell, A. Modak, K. Nam, J. Natoli , D. Roy 






















Lawrence Livermore National Laboratory, Livermore, California, USA

F. Rebassoo , D. Wright 
















University of Maryland, College Park, Maryland, USA

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

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

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














University of Minnesota, Minneapolis, Minnesota, USA

R.M. Chatterjee, B. Crossman , A. Evans , J. Hiltbrand , Sh. Jain , B.M. Joshi , C. Kapsiak , M. Krohn , Y. Kubota , J. Mans , M. Revering , R. Rusack , R. Saradhy , N. Schroeder , N. Strobbe , M.A. Wadud 

University of Mississippi, Oxford, Mississippi, USA

L.M. Cremaldi 




















University of Nebraska-Lincoln, Lincoln, Nebraska, USA

K. Bloom , M. Bryson, D.R. Claes , C. Fangmeier , L. Finco , F. Golf , C. Joo , I. Kravchenko , I. Reed , J.E. Siado , G.R. Snow[†], W. Tabb , A. Wightman , F. Yan , A.G. Zecchinelli 









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

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























Northeastern University, Boston, Massachusetts, USA

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

Northwestern University, Evanston, Illinois, USA

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




















University of Notre Dame, Notre Dame, Indiana, USA

R. Band , R. Bucci, S. Castells , M. Cremonesi, A. Das , R. Goldouzian , M. Hildreth , K. Hurtado Anampa , C. Jessop , K. Lannon , J. Lawrence , N. Loukas , L. Lutton , J. Mariano, N. Marinelli, I. Mcalister, T. McCauley , C. Mcgrady , K. Mohrman , C. Moore , Y. Musienko¹³ , H. Nelson , R. Ruchti , A. Townsend , M. Wayne , H. Yockey, M. Zarucki , L. Zygala 

The Ohio State University, Columbus, Ohio, USA

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




















Princeton University, Princeton, New Jersey, USA

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



University of Puerto Rico, Mayaguez, Puerto Rico, USA

S. Malik , S. Norberg














Purdue University, West Lafayette, Indiana, USA

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












Purdue University Northwest, Hammond, Indiana, USA

J. Dolen , N. Parashar 

Rice University, Houston, Texas, USA

D. Acosta , A. Baty , T. Carnahan , M. Decaro, S. Dildick , K.M. Ecklund , P.J. Fernández Manteca , S. Freed, P. Gardner, F.J.M. Geurts , A. Kumar , W. Li , B.P. Padley , R. Redjimi, J. Rotter , W. Shi , S. Yang , E. Yigitbasi , L. Zhang⁹⁰, Y. Zhang , X. Zuo











University of Rochester, Rochester, New York, USA

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

The Rockefeller University, New York, New York, USA

K. Goulianos 








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

B. Chiarito, J.P. Chou , Y. Gershtein , E. Halkiadakis , A. Hart , M. Heindl , D. Jaroslowski , O. Karacheban²⁶ , I. Laflotte , A. Lath , R. Montalvo, K. Nash, M. Osherson , S. Salur , S. Schnetzer, S. Somalwar , R. Stone , S.A. Thayil , S. Thomas, H. Wang

University of Tennessee, Knoxville, Tennessee, USA

H. Acharya, A.G. Delannoy , S. Fiorendi , T. Holmes , E. Nibigira , S. Spanier 




Texas A&M University, College Station, Texas, USA

O. Bouhali⁹¹ , M. Dalchenko , A. Delgado , R. Eusebi , J. Gilmore , T. Huang , T. Kamon⁹² , H. Kim , S. Luo , S. Malhotra, R. Mueller , D. Overton , D. Rathjens , A. Safonov

Texas Tech University, Lubbock, Texas, USA

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

Vanderbilt University, Nashville, Tennessee, USA

E. Appelt , S. Greene, A. Gurrola , W. Johns , A. Melo , F. Romeo , P. Sheldon , S. Tuo , J. Velkovska , J. Viinikainen






















University of Virginia, Charlottesville, Virginia, USA

B. Cardwell , B. Cox , G. Cummings , J. Hakala , R. Hirosky , M. Joyce ,
A. Ledovskoy , A. Li , C. Neu , C.E. Perez Lara , B. Tannenwald 

Wayne State University, Detroit, Michigan, USA

P.E. Karchin , N. Poudyal 

University of Wisconsin - Madison, Madison, Wisconsin, USA

S. Banerjee , K. Black , T. Bose , S. Dasu , I. De Bruyn , P. Everaerts , C. Galloni,
H. He , M. Herndon , A. Herve , C.K. Koraka , A. Lanaro, A. Loeliger , R. Loveless ,
J. Madhusudanan Sreekala , A. Mallampalli , A. Mohammadi , S. Mondal, G. Parida ,
D. Pinna, A. Savin, V. Shang , V. Sharma , W.H. Smith , D. Teague, H.F. Tsoi ,
W. Vetens 

Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN

S. Afanasiev , V. Andreev , Yu. Andreev , T. Aushev , M. Azarkin , A. Babaev ,
A. Belyaev , V. Blinov⁹³, E. Boos , V. Borshch , D. Budkouski , V. Bunichev ,
V. Chekhovsky, R. Chistov⁹³ , M. Danilov⁹³ , A. Dermenev , T. Dimova⁹³ , I. Dremin ,
M. Dubinin⁸⁴ , L. Dudko , V. Epshteyn , A. Ershov , G. Gavrilo , V. Gavrilo ,
S. Gninenko , V. Golovtsov , N. Golubev , I. Golutvin , I. Gorbunov , V. Ivanchenko ,
Y. Ivanov , V. Kachanov , L. Kardapoltsev⁹³ , V. Karjavine , A. Karneyeu , V. Kim⁹³ ,
M. Kirakosyan, D. Kirpichnikov , M. Kirsanov , V. Klyukhin , O. Kodolova⁹⁴ , D. Kon-
stantinov , V. Korenkov , A. Kozyrev⁹³ , N. Krasnikov , E. Kuznetsova⁹⁵ , A. Lanev ,
P. Levchenko , A. Litomin, N. Lychkovskaya , V. Makarenko , A. Malakhov ,
V. Matveev⁹³ , V. Murzin , A. Nikitenko⁹⁶ , S. Obraztsov , V. Okhotnikov , A. Oskin,
I. Ovtin⁹³ , V. Palichik , P. Parygin , V. Perelygin , S. Petrushanko , G. Pivovarov ,
S. Polikarpov⁹³ , V. Popov, O. Radchenko⁹³ , M. Savina , V. Savrin , D. Selivanova ,
V. Shalaev , S. Shmatov , S. Shulha , Y. Skovpen⁹³ , S. Slabospitskii , V. Smirnov ,
A. Snigirev , D. Sosnov , A. Stepenov , V. Sulimov , E. Tcherniaev , A. Terkulov ,
O. Teryaev , I. Tlisova , M. Toms , A. Toropin , L. Uvarov , A. Uzunian , E. Vlasov ,
A. Vorobyev, N. Voytishin , B.S. Yuldashev⁹⁷, A. Zarubin , I. Zhizhin , A. Zhokin 

†: Deceased

¹Also at Yerevan State University, Yerevan, Armenia

²Also at TU Wien, Vienna, Austria

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

⁴Also at Université Libre de Bruxelles, Bruxelles, Belgium

⁵Also at Universidade Estadual de Campinas, Campinas, Brazil

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

⁷Also at UFMS, Nova Andradina, Brazil

⁸Also at The University of the State of Amazonas, Manaus, Brazil

⁹Also at University of Chinese Academy of Sciences, Beijing, China

¹⁰Also at Nanjing Normal University Department of Physics, Nanjing, China

¹¹Now at The University of Iowa, Iowa City, Iowa, USA

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

¹³Also at an institute or an international laboratory covered by a cooperation agreement with CERN

¹⁴Also at Helwan University, Cairo, Egypt

¹⁵Now at Zewail City of Science and Technology, Zewail, Egypt

¹⁶Also at British University in Egypt, Cairo, Egypt

-
- ¹⁷Now at Ain Shams University, Cairo, Egypt
- ¹⁸Also at Purdue University, West Lafayette, Indiana, USA
- ¹⁹Also at Université de Haute Alsace, Mulhouse, France
- ²⁰Also at Department of Physics, Tsinghua University, Beijing, China
- ²¹Also at Erzincan Binali Yildirim University, Erzincan, Turkey
- ²²Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- ²³Also at University of Hamburg, Hamburg, Germany
- ²⁴Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- ²⁵Also at Isfahan University of Technology, Isfahan, Iran
- ²⁶Also at Brandenburg University of Technology, Cottbus, Germany
- ²⁷Also at Forschungszentrum Jülich, Juelich, Germany
- ²⁸Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- ²⁹Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
- ³⁰Also at Wigner Research Centre for Physics, Budapest, Hungary
- ³¹Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
- ³²Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- ³³Now at Universitatea Babeş-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
- ³⁴Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary
- ³⁵Also at Punjab Agricultural University, Ludhiana, India
- ³⁶Also at UPES - University of Petroleum and Energy Studies, Dehradun, India
- ³⁷Also at University of Visva-Bharati, Santiniketan, India
- ³⁸Also at University of Hyderabad, Hyderabad, India
- ³⁹Also at Indian Institute of Science (IISc), Bangalore, India
- ⁴⁰Also at Indian Institute of Technology (IIT), Mumbai, India
- ⁴¹Also at IIT Bhubaneswar, Bhubaneswar, India
- ⁴²Also at Institute of Physics, Bhubaneswar, India
- ⁴³Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- ⁴⁴Also at Sharif University of Technology, Tehran, Iran
- ⁴⁵Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- ⁴⁶Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- ⁴⁷Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- ⁴⁸Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
- ⁴⁹Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
- ⁵⁰Also at Università di Napoli 'Federico II', Napoli, Italy
- ⁵¹Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- ⁵²Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
- ⁵³Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- ⁵⁴Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- ⁵⁵Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- ⁵⁶Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- ⁵⁷Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
- ⁵⁸Also at National and Kapodistrian University of Athens, Athens, Greece
- ⁵⁹Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- ⁶⁰Also at Universität Zürich, Zurich, Switzerland
- ⁶¹Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- ⁶²Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-

Vieux, France

⁶³Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey

⁶⁴Also at Konya Technical University, Konya, Turkey

⁶⁵Also at Izmir Bakircay University, Izmir, Turkey

⁶⁶Also at Adiyaman University, Adiyaman, Turkey

⁶⁷Also at Istanbul Gedik University, Istanbul, Turkey

⁶⁸Also at Necmettin Erbakan University, Konya, Turkey

⁶⁹Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey

⁷⁰Also at Marmara University, Istanbul, Turkey

⁷¹Also at Milli Savunma University, Istanbul, Turkey

⁷²Also at Kafkas University, Kars, Turkey

⁷³Also at Hacettepe University, Ankara, Turkey

⁷⁴Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey

⁷⁵Also at Yildiz Technical University, Istanbul, Turkey

⁷⁶Also at Vrije Universiteit Brussel, Brussel, Belgium

⁷⁷Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom

⁷⁸Also at University of Bristol, Bristol, United Kingdom

⁷⁹Also at IPPP Durham University, Durham, United Kingdom

⁸⁰Also at Monash University, Faculty of Science, Clayton, Australia

⁸¹Also at Università di Torino, Torino, Italy

⁸²Also at Bethel University, St. Paul, Minnesota, USA

⁸³Also at Karamanoğlu Mehmetbey University, Karaman, Turkey

⁸⁴Also at California Institute of Technology, Pasadena, California, USA

⁸⁵Also at United States Naval Academy, Annapolis, Maryland, USA

⁸⁶Also at Bingol University, Bingol, Turkey

⁸⁷Also at Georgian Technical University, Tbilisi, Georgia

⁸⁸Also at Sinop University, Sinop, Turkey

⁸⁹Also at Erciyes University, Kayseri, Turkey

⁹⁰Also at Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China

⁹¹Also at Texas A&M University at Qatar, Doha, Qatar

⁹²Also at Kyungpook National University, Daegu, Korea

⁹³Also at another institute or international laboratory covered by a cooperation agreement with CERN

⁹⁴Also at Yerevan Physics Institute, Yerevan, Armenia

⁹⁵Now at University of Florida, Gainesville, Florida, USA

⁹⁶Also at Imperial College, London, United Kingdom

⁹⁷Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan