EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2017-159
2017/11/15

CMS-HIG-15-009

Search for a light pseudoscalar Higgs boson produced in association with bottom quarks in pp collisions at $\sqrt{s} = 8\,\mathrm{TeV}$

The CMS Collaboration*

Abstract

A search for a light pseudoscalar Higgs boson (A) produced in association with bottom quarks and decaying into a muon pair is reported. The search uses $19.7\,\mathrm{fb}^{-1}$ of proton-proton collisions at a center-of-mass energy of 8 TeV, collected by the CMS experiment. No signal is observed in the dimuon mass range from 25 to 60 GeV. Upper limits on the cross section times branching fraction, $\sigma(\mathrm{pp} \to \mathrm{b\bar{b}A})\,\mathcal{B}(\mathrm{A} \to \mu\mu)$, are set.

Published in the Journal of High Energy Physics as doi:10.1007/JHEP11(2017)010.

*See Appendix A for the list of collaboration members

1 Introduction

The CMS and ATLAS experiments at the CERN LHC have made clear observations of a particle compatible with the standard model (SM) Higgs boson [1–4]. While the observation serves as a powerful affirmation of the SM mechanism for generating particle masses, the discovery does not rule out the existence of a more complex theory with an extended Higgs sector. The discovery of additional scalar or pseudoscalar bosons may be evidence of such a scenario.

A number of well-motivated models extending the SM predict the existence of new Higgs bosons. One well studied scenario is the Two Higgs Doublet Model (2HDM) [5, 6] predicting the existence of additional elementary Higgs particles. The 2HDM includes a CP-odd Higgs boson, A, that could be light and produced in association with bottom quarks at the LHC. In some schemes, with a negatively-signed Yukawa coupling to the down-type fermions, the associated $b\bar{b}A$ production cross section times branching fraction into muons can be very large for an A boson with a mass below about 60 GeV, i.e. less than half of the mass of the observed SM-like Higgs boson [7]. It can vary from 1000 to 35 fb for A boson masses in the range from 25 to 60 GeV at a center-of-mass energy of 8 TeV in proton-proton collisions.

We present a search for muon pairs, in the mass range from 25 to 60 GeV, produced in association with bottom quarks in the context of the 2HDM. The search uses 19.7 fb^{-1} of data collected by the CMS experiment in proton-proton collisions at a center-of-mass energy of 8 TeV. The analysis of the $\mu\mu$ final state complements the CMS searches for a low-mass A boson decaying into τ lepton pairs by the CMS Collaboration [8, 9]. Despite the significantly lower branching fraction, the $\mu\mu$ final state profits from much better dilepton mass resolution as well as higher trigger and lepton identification efficiencies. This is the first time associated production with b quarks in the dimuon decay channel has been searched for in the low dimuon mass range.

In the following, Sections 2 and 3 describe the CMS detector, the data, and simulated samples. The event reconstruction and selections are presented in Section 4. In Section 5, the result of the search for the $b\bar{b}A$ process is presented. The paper is summarized in Section 6.

2 The CMS detector

The central feature of the CMS apparatus [10] is a superconducting solenoid, 13 m in length and 6 m in diameter, which provides an axial magnetic field of 3.8 T. Within the field volume there are several particle detection systems. Charged-particle trajectories are measured by silicon pixel and strip trackers, covering $0 \leq \phi \leq 2\pi$ in azimuth and $|\eta| < 2.5$ in pseudorapidity. A lead tungstate crystal electromagnetic calorimeter (ECAL) surrounds the tracking volume. It is comprised of a barrel region $|\eta| < 1.48$ and two endcaps that extend up to $|\eta| = 3$. A lead and silicon-strip preshower detector is located in front of the ECAL endcaps. A brass and scintillator hadron calorimeter surrounds the ECAL and also covers the region $|\eta| < 3$. Steel forward calorimeters with quartz fibers, read out by photomultipliers, extend the calorimetric coverage up to $|\eta| = 5$. Muons are identified and measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. The detector is nearly hermetic, allowing energy balance measurements in the plane transverse to the beam direction.

3 Data and simulated samples

A two-tier trigger system selects collision events of interest. For this analysis, events are first selected by requiring a single muon (μ) or two muons within the detector acceptance and passing loose identification and kinematic requirements. For the single-muon trigger, the muon must have $|\eta| < 2.1$. The muon is required to be isolated and must have transverse momentum (p_{T}) greater than 24 GeV. The dimuon trigger requires two muons with p_{T} greater than 17 GeV for the leading muon and 8 GeV for the sub-leading muon. The dielectron trigger requires two electrons with p_{T} greater than 17 GeV for the leading electron and 8 GeV for the sub-leading electron and the electrons are required to be isolated.

The analysis uses opposite-sign dimuon events with additional jets, with at least one of them being identified as originating from b quark fragmentation ("b jet"). The invariant mass of the opposite-sign lepton pair ($m_{\mu\mu}$) is required to be greater than 12 GeV to reject low-mass resonances and remove poorly-modeled backgrounds.

The Monte Carlo (MC) simulation is used to optimize the event selection to give the best sensitivity for signal discovery. Predictions for the yields of background processes, which are also based on simulation, are validated using data in appropriate control regions. The $\mathrm{pp} \to \mathrm{b\bar{b}A}$ signal events are simulated with PYTHIA (v6.4.26) [11]. The signal samples have been generated for A masses in intervals of 10 GeV. The natural width of the A boson has been set to a value of less than 50 MeV, which is much smaller than the dimuon mass resolution in the mass range from 25 to 60 GeV ($\sigma_{\mu\mu} = 0.45$ GeV for $m_{\mathrm{A}} = 30$ GeV).

The following background processes have been considered: Drell–Yan (DY), W+jets, $\mathrm{t\bar{t}}$, single top quark, and diboson production.

The DY events are simulated at leading order (LO) using the MADGRAPH (v5.1.3.30) generator [12, 13] interfaced to PYTHIA (v6.4.26) for parton showering and hadronization. The CTEQ6L1 [14] parton distribution functions (PDFs) are used to generate the events. The MADGRAPH generation includes up to four partons in the matrix element calculations and a procedure to properly merge jets from the matrix element calculations and parton shower [15, 16]. The DY sample is normalized to the next-to-next-to-leading order (NNLO) cross section computed with FEWZ (v3.1) [17]. The W+jets sample is simulated and normalized in a similar way to the DY+jets sample. The $\ell\ell$ ($\ell\nu$) production in association with b and c quarks is included in the DY+jets (W+jets) samples.

Top quark pair events are generated with MADGRAPH, including up to three extra partons, and the simulated sample is normalized to the NNLO+NNLL (next-to-next-to-leading-logarithmic) inclusive cross section [18]. Single top quark processes (t, s, and Wt channels) are modeled at next-to-leading order (NLO) with POWHEG [19–21] and normalized to the approximate NNLO cross sections [22, 23]. Diboson production processes (VV) WW, WZ/γ^* and $\mathrm{Z}/\gamma^*\mathrm{Z}/\gamma^*$ are generated with MADGRAPH and normalized, respectively, to their NLO cross sections [24, 25]. The WZ/γ^* and $\mathrm{Z}/\gamma^*\mathrm{Z}/\gamma^*$ processes are generated with $m_{\gamma^*} > 10$ GeV.

The PYTHIA parameters for the underlying event are set according to the Z2* tune [26, 27], an update of the Z1 tune described in Refs. [28, 29].

A detector simulation based on GEANT4 (v.9.4p03) [30, 31] is applied to all the generated signal and background samples. The presence of multiple pp interactions (pileup) in the same or adjacent bunch crossings is incorporated by simulating additional interactions (both in-time and out-of-time with the collision) with a multiplicity distribution that matches the one observed in data. The average number of pileup events is estimated as 21 interactions per bunch crossing. The observed jet energy resolution and jet energy scale measurements [32], b tagging efficiency and b tagging discriminator distributions [33] in data are used to correct the simulated events.

4 Event reconstruction and selection

Events are required to have at least one vertex, with the reconstructed longitudinal position (z) within 24 cm of the geometric center of the detector and the transverse position within 2 cm of the beam interaction region. In the case of multiple reconstructed vertices associated with additional pp interactions, the one with the highest scalar sum of the p_{T}^2 of its associated tracks is chosen as the primary vertex. Muons are required to originate from the same primary vertex by requiring the longitudinal and transverse impact parameters with respect to the primary vertex to be less than 0.5 cm and 0.2 cm, respectively.

Muon candidates are reconstructed with a global trajectory fit using hits in the tracker and the muon system [34]. The efficiency for muons to pass both the identification and isolation requirements is measured to be more than 95% for the kinematic region studied in this analysis [3].

The electron selection criteria are optimized using a multivariate approach, and have a combined identification and isolation efficiency of approximately 60% at low p_{T} ($\approx$10 GeV) and 90% at high p_{T} ($>$50 GeV) for electrons from W or Z boson decays [35]. The training of the multivariate electron reconstruction is performed using simulated events, while the performance is validated using data.

In the interest of distinguishing between prompt and nonprompt lepton candidates (predominantly arising from decays of b hadrons), a relative isolation is defined for each lepton candidate. The muon isolation variable is computed as the sum of the transverse momenta of the charged particles inside a cone of radius $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ around the lepton direction divided by the muon p_{T}. The isolation is required to be smaller than 0.1. If the signal muons are within a distance of $\Delta R < 0.3$ of each other the p_{T} of one lepton is subtracted from the isolation value of the other lepton.

The anti-k_{T} clustering algorithm [36, 37] with a distance parameter of 0.5 is used for jet reconstruction.

Two types of jets are used in the analysis, "jet-plus-track" (JPT) [38] and particle-flow (PF) [39] jets. The two algorithms combine the information from all subdetectors. However, the PF algorithm separates deposits in the calorimeter into clusters and matches clusters with reconstructed tracks (PF candidates), while the JPT algorithm does not require cluster separation as it starts from the reconstructed calorimeter jets (calojet) and track matching is done with respect to the calojet area at the surface of the calorimeter. Also the algorithms have a different approach to the calibration of the constituents: cluster calibration from simulation in the case of the PF algorithm; and corrections due to calorimeter thresholds and tracking inefficiency in the case of the JPT algorithm. These jet reconstruction algorithms are affected differently by detector effects, like tracker misalignment or the calibration of the calorimeter, and thus serve as an important cross-check of each other. The two types of jet, JPT and PF, provide similar jet energy resolution. The final results are presented with PF jets.

Jets with a significant fraction of energy coming from pileup interactions or not associated with the primary vertex are rejected [38, 40]. The remaining pileup energy in jets is subtracted using a technique that relies on information about the jet area [37, 41, 42]. Jets are required to satisfy identification criteria that remove jets originating from noisy channels in the calorimeters [43, 44]. Calibrated jets [32, 45] are required to have $p_{\mathrm{T}} > 20$ GeV, $|\eta| < 4.7$ and to be separated by at least 0.5 in ΔR from muons passing the selection requirements described above.

The missing transverse momentum ($p_{\mathrm{T}}^{\mathrm{miss}}$) is defined as the modulus of the vector sum of the transverse momenta of all reconstructed PF candidates in the event. The calibrations applied to jets are propagated to the $p_{\mathrm{T}}^{\mathrm{miss}}$.

Jets originating from the hadronization of b (or c) quarks are identified by a multivariate analysis [46] based on a secondary vertex b tagging algorithm described in Refs. [33, 47]. The algorithm combines information on track impact parameter significance, secondary vertices, and jet kinematics. Several working points are available; these are designed to yield successively higher purity at the cost of reduced efficiency for identifying b jets. The working point used in this analysis corresponds to a b tagging identification efficiency of 45% and a misidentification rate of 0.05% for light-flavor (u, d, s, g) jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$. The misidentification rate for c jets is $\simeq$6%.

Selections are optimized using simulated events for the signal model $\mathrm{pp} \rightarrow \mathrm{b\bar{b}A}$, $\mathrm{A} \rightarrow \mu\mu$ with $m_{\mathrm{A}} = 30\,\mathrm{GeV}$ and simulated backgrounds. The threshold on the leading muon $p_{\mathrm{T}}^{\mu_1}$ is fixed to 25 GeV. This choice is determined by the single-muon trigger p_{T} threshold of 24 GeV. The rapidity requirements on the muons and b jets are driven by the trigger and particle identification conditions. The optimization procedure selects the thresholds on the subleading p_{T} muon ($p_{\mathrm{T}}^{\mu_2}$), the leading b jet p_{T} ($p_{\mathrm{T}}^{\text{b jet}}$), and $p_{\mathrm{T}}^{\mathrm{miss}}$, where an approximate estimate of signal significance, defined as $Z = 2(\sqrt{S+B} - \sqrt{B})$ [48] reaches its maximal value. The $p_{\mathrm{T}}^{\mathrm{miss}}$ requirement is used to suppress the $\mathrm{t\bar{t}}$ background. The presence of a second jet (b tagged or not) is not required since in the $\mathrm{b\bar{b}A}$ production process the second b jet is often at high η or has too low p_{T}.

Optimization in this way gives rise to:

- $p_{\mathrm{T}}^{\mu_1} > 25\,\mathrm{GeV}$, $|\eta_{\mu_1}| < 2.1$;
- $p_{\mathrm{T}}^{\mu_2} > 5\,\mathrm{GeV}$, $|\eta_{\mu_2}| < 2.4$;
- $p_{\mathrm{T}}^{\text{b jet}} > 20\,\mathrm{GeV}$ and $|\eta| < 2.4$;
- $p_{\mathrm{T}}^{\mathrm{miss}} < 40\,\mathrm{GeV}$.

The optimization of the selections was repeated for an A boson mass of 60 GeV and similar values were obtained. The signal selection efficiency is 0.013 for $m_{\mathrm{A}} = 30\,\mathrm{GeV}$.

5 Results and systematic uncertainties

Figure 1 shows the transverse momentum of the leading (left) and subleading (right) muons, and Fig. 2 shows the p_{T} of the leading b jet (left) and the $p_{\mathrm{T}}^{\mathrm{miss}}$ (right) for the events passing the selection requirements for the other variables. The histogram labeled as MC(Top) shows the sum of the single top and top quark pair production processes.

The upper limits on the signal contribution in the mass range of $25 < m_{\mu\mu} < 60\,\mathrm{GeV}$ have been extracted using a fit of the binned background and signal templates to the dimuon mass distribution in the region $12 < m_{\mu\mu} < 70\,\mathrm{GeV}$. The mass intervals of [12–25] and [60–70] GeV have been used for a verification of the background expectation obtained from the simulation.

The signal and background templates are obtained from simulation rescaled and corrected using information from data. To obtain signal mass shapes in 1 GeV steps we perform a linear interpolation between histograms as a function of the mass using the algorithm described in Ref. [49] and implemented in the ROOT package [50]. The W+jets and VV background event yields are found to be negligible. The predicted yields for the background processes take into account the following sources of systematic uncertainty, where the range of variations of each

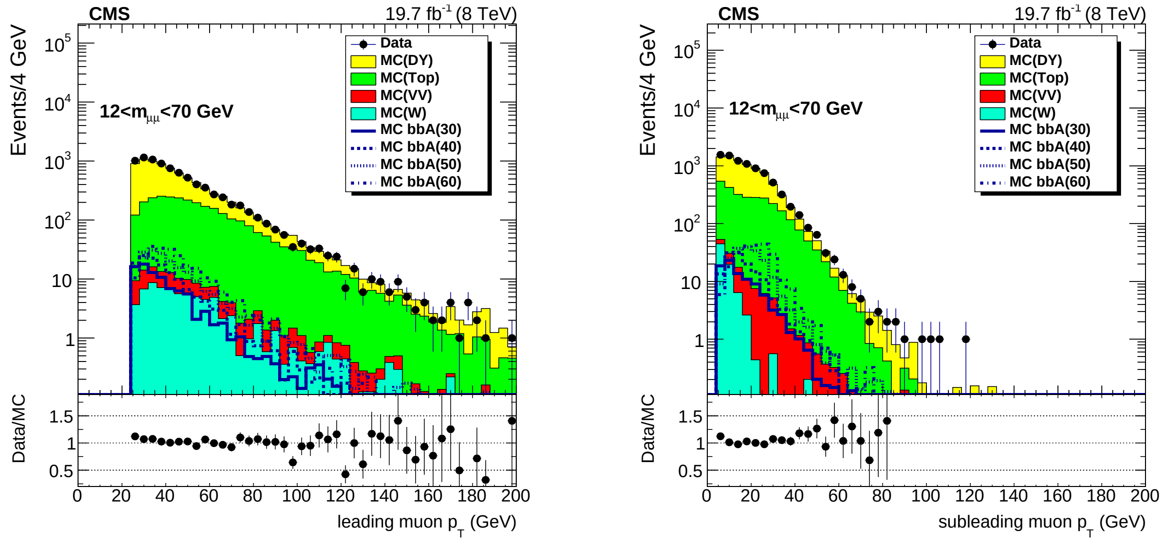

Figure 1: The transverse momentum of the leading (left) and the subleading (right) muon for data (dots) and simulation (histograms). The histograms for simulated backgrounds are stacked. The histogram labeled as MC(Top) shows the sum of the single top and top quark pair production processes. The expected signal is shown assuming a signal cross section times branching fraction of 350 fb. The background is normalized to the number of events expected from simulation. In the lower panel, the ratio of the number of events in data and background simulation is shown.

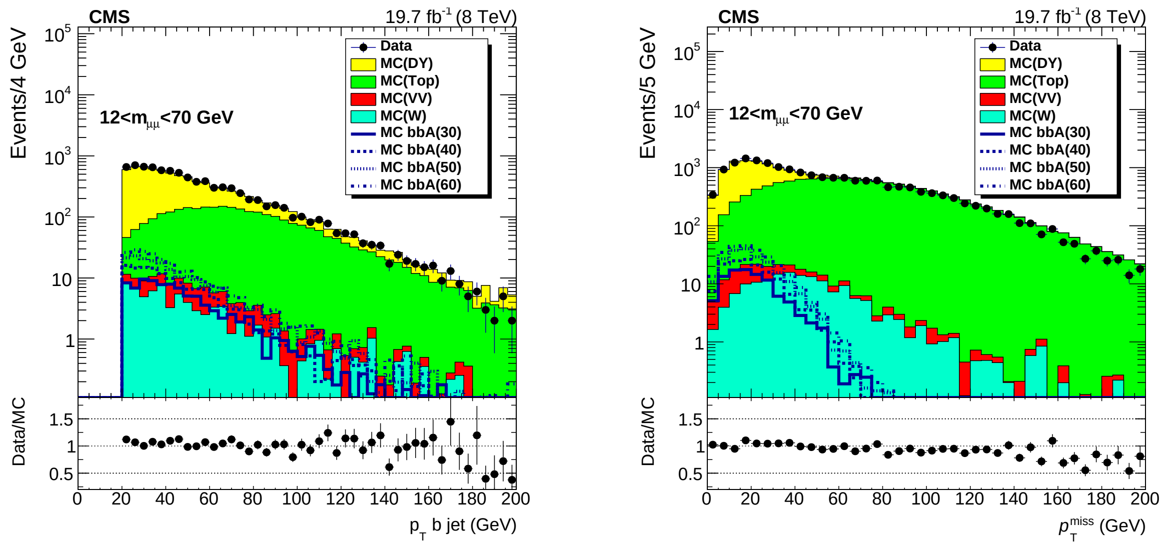

Figure 2: The transverse momentum of the leading p_{T} b jet (left) and the missing transverse momentum (right) for data (dots) and simulation (histograms). The histograms for simulated backgrounds are stacked. The histogram labeled as MC(Top) shows the sum of the single top and top quark pair production processes. The expected signal is shown assuming a signal cross section times branching fraction of 350 fb. The background is normalized to the number of events expected from simulation. In the lower panel, the ratio of the number of events in data and background simulation is shown.

source was determined in dedicated studies with appropriate data control samples or, if relevant, from the theory uncertainty affecting the prediction:

- luminosity uncertainty, 2.6% [51];
- muon identification and isolation efficiency uncertainty, 3%;
- top quark background normalization uncertainty, 7%;
- jet energy scale uncertainty, 3% for the DY+jets and 0.2% for top quark backgrounds;
- jet energy resolution uncertainty, 0.3% for DY+jet and 0.1% for top quark backgrounds;
- pileup modeling uncertainty, 2% for DY+jets and 1% for top quark backgrounds;
- $E_{\mathrm{T}}^{\text{miss}}$ measurement uncertainty, 2% for DY+jets and 4% for top quark backgrounds.

While the above uncertainties only affect the expected total event yield, others can have an impact both on the total event yield and on the shape of the predicted $m_{\mu\mu}$ distribution. The following set of systematic uncertainties in the $m_{\mu\mu}$ background shape and the normalization have been taken into account:

- b tagging scaling factor uncertainty [47];
- renormalization and factorization scale, and PDF uncertainties;

The renormalization and factorization scale uncertainties are particularly important for the modeling of the shape of the DY+jets background, which after the final selections is dominated by the $\mu\mu\mathrm{b\overline{b}}$ process. The scale uncertainty in the $\mu\mu\mathrm{b\overline{b}}$ prediction, taken from simulation, has been evaluated as a function of the dimuon mass using the $\mathrm{pp} \rightarrow \mu\mu\mathrm{b\overline{b}}$ process implemented in MADGRAPH5_aMC@NLO v2.3.0 in a four-flavor production scheme with massive b quarks [52]. The renormalization and factorization scales (μ_{R} and μ_{F}) have been varied simultaneously by factors of 0.5 and 2.0. The uncertainty on the differential cross-section as a function of the dimuon mass varies from 20 to 15% in the dimuon mass region of $12 < m_{\mu\mu} < 70\,\mathrm{GeV}$. It is applied to the total DY+jets background, motivated by the fact the DY plus light-flavor jets background after the b tagging requirement is much smaller than the $\mu\mu\mathrm{b\overline{b}}$ background, and the scale uncertainty for the $\mu\mu\mathrm{c\overline{c}}$ process is expected to be similar to that for the $\mu\mu\mathrm{b\overline{b}}$ process.

Uncertainties related to the imprecision in our knowledge of the PDFs are also evaluated. The uncertainty in the gluon-gluon luminosity is considered, since in the four-flavor scheme the dominant LO production process is $\mathrm{gg} \rightarrow \mu\mu\mathrm{b\overline{b}}$. The $\mathrm{q\overline{q}} \rightarrow \mu\mu\mathrm{b\overline{b}}$ process represents only $\simeq$15% of the total cross-section. The gluon-gluon luminosity uncertainty is compared for three PDF sets, CT10NLO [53], MSTW2008NLO [54], and NNPDF2.3NLO [55]. In the mass region of $\simeq$30–70 GeV the CT10NLO uncertainty envelope covers the uncertainties of the other two PDF sets, therefore the CT10NLO gluon-gluon luminosity uncertainty is used in the analysis. This PDF uncertainty is applied as a function of the dimuon mass to the total DY+jets background after b tagging has been applied. It is motivated by the fact that the $\mu\mu\mathrm{c\overline{c}}$ and $\mu\mu\mathrm{b\overline{b}}$ processes are both initiated by gluon-gluon interactions in the four-flavor scheme at LO.

The dimuon mass spectrum, the expected background, and its uncertainty are presented in Fig. 3 (left) together with the expected signal for $m_{\mathrm{A}} = 30\,\mathrm{GeV}$ assuming a signal cross section times branching fraction of 350 fb. The PF jet reconstruction algorithm is used. There is a fair agreement between data and background.

To cross-check the background estimation technique that relies on the accuracy of the simulation for the background, we consider data where instead of requiring the presence of two muons, we require two opposite-sign electrons. Since the dielectron final state would be suppressed by $(m_e/m_\mu)^2$ in the pseudoscalar Higgs decay, we do not consider it for our search. Kinematic thresholds and all other requirements are kept exactly the same as in the main analysis, except the threshold on the second leading p_T electron, which is taken higher than in the dimuon analysis ($p_T^{e_2} > 10\,\text{GeV}$) to reduce the QCD multijet background. The data are found to be in good agreement with the background model prediction, as illustrated in Fig. 3 (right).

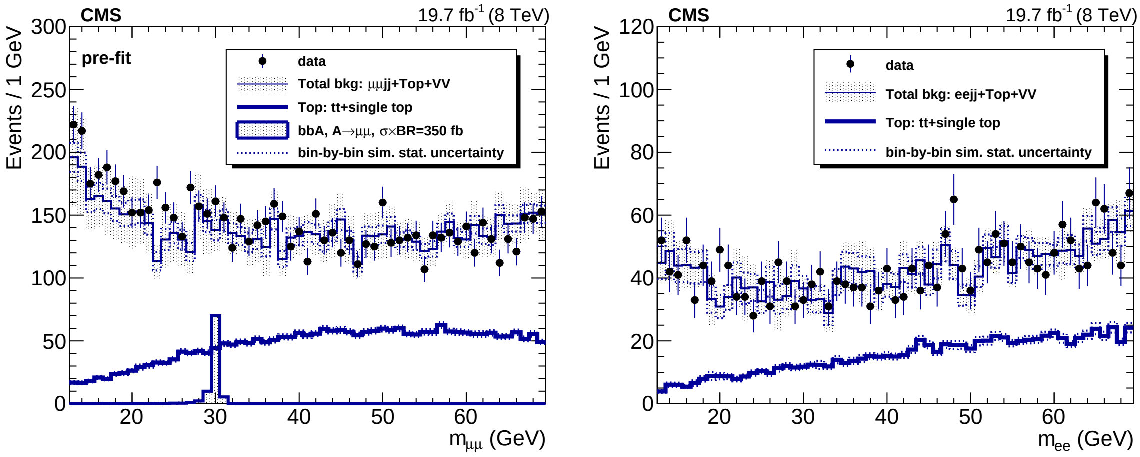

Figure 3: Left: the dimuon mass distribution with the pre-fit expected background event yield and its uncertainty, and the expected signal for $m_A = 30\,\text{GeV}$ assuming a signal cross section times branching fraction of 350 fb. Right: cross-check with the e^+e^- final state showing the dielectron mass spectrum with the expected background event yield and its uncertainty.

To cross-check the effect of event migration on the exclusion limits due to the choice of jet reconstruction algorithm we use the JPT algorithm as an alternative and repeat the full analysis chain. Figure 4 shows the dimuon mass spectrum for events selected by both the main (PF) and alternative (JPT) jet reconstruction methods as well as for events selected by only the JPT algorithm. The two reconstruction methods select slightly different events. The fraction of migrated events due to the choice of jet algorithm is of the order of 20% and almost independent of the dimuon mass. The expected and observed upper limits obtained using PF or JPT jets are very similar. The final results presented use PF jets.

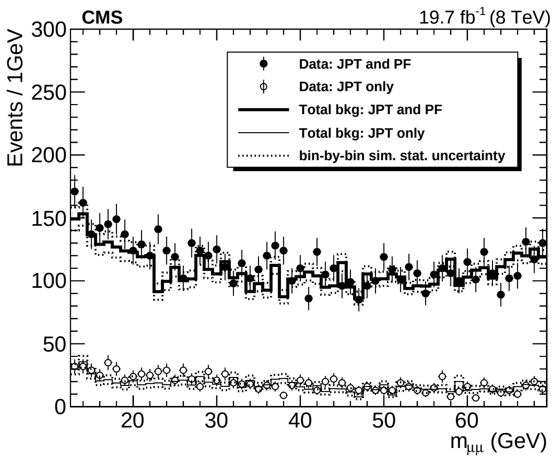

Figure 4: The dimuon mass distribution with the pre-fit expected background event yield for events selected by both the main (PF) and alternative (JPT) jet reconstruction methods as well as events selected by only the JPT algorithm.

The experimental uncertainties considered above for the background are also taken into account for the signal. In addition, the uncertainty in the signal acceptance due to the signal modeling is evaluated using a MADGRAPH5_aMC@NLO+PYTHIA 8 particle level simulation of the pp $\rightarrow$ b$\overline{\text{b}}$A, A $\rightarrow \mu\mu$ process in the four-flavor production scheme [56–58]. It includes the uncertainty in the shower scale parameter, α (an upper scale allowed for the shower in PYTHIA) [13] , the renormalization and factorization scales, and the PDFs. In the evaluation of the uncertainties we follow the recommendations of LHC Higgs Cross Section Working Group [59]. The renormalization and factorization scales are varied with two constraints such that $0.5\mu_0 \leq \mu_\mathrm{R}, \mu_\mathrm{F} \leq 2\mu_0$ varies while requiring $0.5 \leq \mu_\mathrm{R}/\mu_\mathrm{F} \leq 2$ (μ_0 is the recommended central scale value [59]); the shower scale parameter is varied as $\alpha \in [1/(4\sqrt{2}), \sqrt{2}/4]$. The PDF uncertainty is obtained with the PDF4LHC15_nlo_nf4_30 set [60–63]. The total theoretical uncertainty on the signal acceptance, taken as the linear sum of the shower scale, the renormalization and factorization scale, and the PDF uncertainties, varies from -16% to $+18\%$. The difference in the signal acceptance between the PYTHIA 6 and MADGRAPH5_aMC@NLO+PYTHIA 8 particle level simulation is less than the total theoretical uncertainty discussed above.

The dimuon mass distribution in Fig. 3 (left) is used in the evaluation of the limits on the cross section times branching fraction, $\sigma(\text{pp} \rightarrow \text{b}\overline{\text{b}}\text{A})\,\mathcal{B}(\text{A} \rightarrow \mu\mu)$. The limits have been extracted using a test statistic based on the profile likelihood ratio and asymptotic formulae, along with the constraint of a positive signal, as proposed in Refs. [64, 65]. Systematic uncertainties are included in the form of nuisance parameters. The dimuon mass spectrum and the post-fit background event yield and its uncertainty given by the fit is presented in Fig. 5 (left), along with the expected signal for $m_\mathrm{A} = 30\,\text{GeV}$ assuming a signal cross section times branching fraction of 350 fb.

We scan over A masses from 25 to 60 GeV. The expected and observed upper limits at 95% confidence level (CL) on $\sigma(\text{pp} \rightarrow \text{b}\overline{\text{b}}\text{A})\,\mathcal{B}(\text{A} \rightarrow \mu\mu)$ are shown in Fig. 5 (right). Due to the good agreement between the data and the expected background before and after the fit the limits for all mass points in the mass interval of $25 < m_{\mu\mu} < 60\,\text{GeV}$ are within two standard deviations of the expected limit.

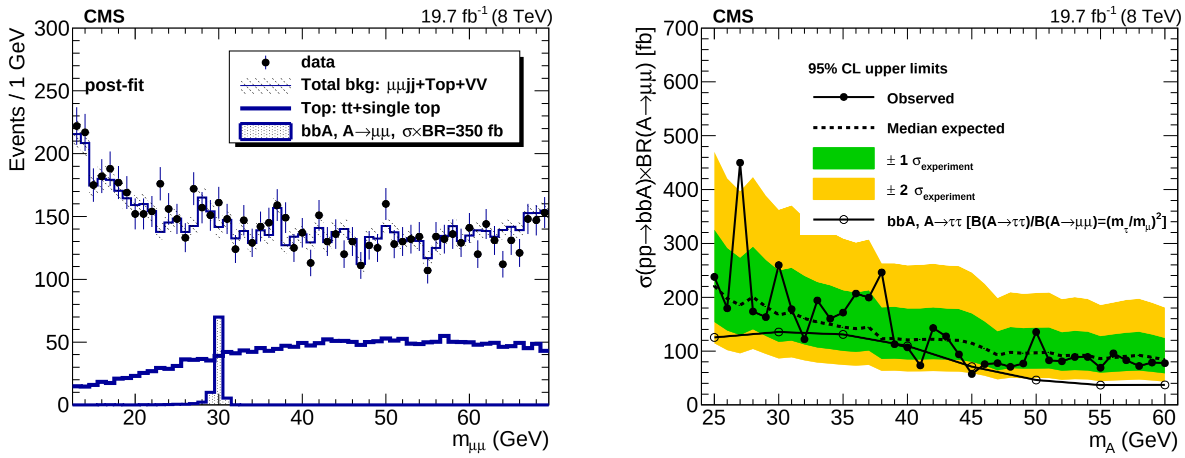

Figure 5: Left: the dimuon mass distribution with the post-fit background event yield and its uncertainty given by the fit, and the expected signal for $m_\mathrm{A} = 30\,\text{GeV}$ assuming a signal cross section times branching fraction of 350 fb. Right: expected and observed upper limit at 95% CL on $\sigma(\text{pp} \rightarrow \text{b}\overline{\text{b}}\text{A})\,\mathcal{B}\text{A} \rightarrow \mu\mu)$ as a function of m_A. The open circles show the limits obtained in the CMS analysis of the A $\rightarrow \tau\tau$ final state [8] when translated into limits for the A $\rightarrow \mu\mu$ final state using Eq.(1).

In the 2HDM, the $\mathcal{B}(\text{A} \rightarrow \mu\mu)$ and $\mathcal{B}(\text{A} \rightarrow \tau\tau)$ are related through the ratio of the Yukawa couplings, and thus are proportional to the square of the lepton masses, i.e.

$$\frac{\mathcal{B}(\mathrm{A} \to \tau\tau)}{\mathcal{B}(\mathrm{A} \to \mu\mu)} = \left(\frac{m_\tau}{m_\mu}\right)^2. \tag{1}$$

The open circles in Fig. 5 show the upper limits on $\sigma(\mathrm{pp} \to \mathrm{b\overline{b}A})\,\mathcal{B}(\mathrm{A} \to \mu\mu)$ obtained from the limits on $\sigma(\mathrm{pp} \to \mathrm{b\overline{b}A})\,\mathcal{B}(\mathrm{A} \to \tau\tau)$ evaluated in the CMS analysis of the $\mathrm{A} \to \tau\tau$ final state [8]. One can see that upper limits evaluated from the direct search for the $\mathrm{A} \to \mu\mu$ decay in $\mathrm{b\overline{b}A}$ associated production are comparable with those from the $\mathrm{A} \to \tau\tau$ search using the same production process.

6 Summary

A light pseudoscalar Higgs boson, produced in association with a pair of b jets and decaying into two muons, has been searched for in pp collisions at $\sqrt{s} = 8\,\mathrm{TeV}$ with an integrated luminosity of $19.7\,\mathrm{fb}^{-1}$. This is the first time associated production with b quarks in the dimuon decay channel has been looked for in the low dimuon mass range. No signal has been observed in the dimuon mass range from 25 to 60 GeV. Upper limits on the cross section times branching fraction, $\sigma(\mathrm{pp} \to \mathrm{b\overline{b}A})\,\mathcal{B}(\mathrm{A} \to \mu\mu)$, have been set. Despite the significantly lower branching fraction, the limits evaluated from the direct search for the $\mathrm{A} \to \mu\mu$ decay in $\mathrm{b\overline{b}A}$ associated production are comparable with those from the $\mathrm{A} \to \tau\tau$ search using the same production process.

Acknowledgments

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

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract No. 675440 (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Clarín-COFUND del Principado de Asturias; the Thalis and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); and the Welch Foundation, contract C-1845.

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria
W. Adam, F. Ambrogi, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth[1], V.M. Ghete, J. Grossmann, J. Hrubec, M. Jeitler[1], A. König, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, E. Pree, D. Rabady, N. Rad, H. Rohringer, J. Schieck[1], R. Schöfbeck, M. Spanring, D. Spitzbart, W. Waltenberger, J. Wittmann, C.-E. Wulz[1], M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus
V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium
E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium
S. Abu Zeid, F. Blekman, J. D'Hondt, I. De Bruyn, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskyi, S. Lowette, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Université Libre de Bruxelles, Bruxelles, Belgium
H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, J. Luetic, T. Maerschalk, A. Marinov, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, D. Vannerom, R. Yonamine, F. Zenoni, F. Zhang[2]

Ghent University, Ghent, Belgium
A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov, D. Poyraz, C. Roskas, S. Salva, M. Tytgat, W. Verbeke, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, A. Caudron, S. De Visscher, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, A. Jafari, M. Komm, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, K. Piotrzkowski, L. Quertenmont, M. Vidal Marono, S. Wertz

Université de Mons, Mons, Belgium
N. Beliy

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
W.L. Aldá Júnior, F.L. Alves, G.A. Alves, L. Brito, M. Correa Martins Junior, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato[3], A. Custódio, E.M. Da Costa, G.G. Da Silveira[4], D. De Jesus Damiao, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, A. Santoro, A. Sznajder, E.J. Tonelli Manganote[3], F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista [a], Universidade Federal do ABC [b], São Paulo, Brazil
S. Ahuja[a], C.A. Bernardes[a], T.R. Fernandez Perez Tomei[a], E.M. Gregores[b], P.G. Mercadante[b], S.F. Novaes[a], Sandra S. Padula[a], D. Romero Abad[b], J.C. Ruiz Vargas[a]

Institute for Nuclear Research and Nuclear Energy of Bulgaria Academy of Sciences
A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, S. Stoykova, G. Sultanov

University of Sofia, Sofia, Bulgaria
A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China
W. Fang[5], X. Gao[5]

Institute of High Energy Physics, Beijing, China
M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, E. Yazgan, H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
Y. Ban, G. Chen, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, J.D. Ruiz Alvarez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
B. Courbon, N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano, T. Sculac

University of Split, Faculty of Science, Split, Croatia
Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov[6], T. Susa

University of Cyprus, Nicosia, Cyprus
M.W. Ather, A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

Charles University, Prague, Czech Republic
M. Finger[7], M. Finger Jr.[7]

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran[8,9], S. Elgammal[9], A. Mahrous[10]

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
R.K. Dewanjee, M. Kadastik, L. Perrini, M. Raidal, A. Tiko, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
J. Härkönen, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, E. Tuominen, J. Tuominiemi, E. Tuovinen

Lappeenranta University of Technology, Lappeenranta, Finland
J. Talvitie, T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, S. Ghosh, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, I. Kucher, E. Locci, M. Machet, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M.Ö. Sahin, M. Titov

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France
A. Abdulsalam, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, C. Charlot, R. Granier de Cassagnac, M. Jo, S. Lisniak, A. Lobanov, J. Martin Blanco, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, T. Strebler, Y. Yilmaz, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
J.-L. Agram[11], J. Andrea, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte[11], X. Coubez, J.-C. Fontaine[11], D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

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

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
S. Beauceron, C. Bernet, G. Boudoul, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov[12], V. Sordini, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia
T. Toriashvili[13]

Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze[7]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, S. Beranek, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, C. Schomakers, J. Schulz, T. Verlage

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
A. Albert, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, M. Hamer, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, M. Olschewski, K. Padeken, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, D. Teyssier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
G. Flügge, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, A. Stahl[14]

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras[15], V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Eckerlin, D. Eckstein, T. Eichhorn,

E. Eren, E. Gallo[16], J. Garay Garcia, A. Geiser, A. Gizhko, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, M. Guthoff, A. Harb, J. Hauk, M. Hempel[17], H. Jung, A. Kalogeropoulos, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, T. Lenz, J. Leonard, K. Lipka, W. Lohmann[17], R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, A. Raspereza, B. Roland, M. Savitskyi, P. Saxena, R. Shevchenko, S. Spannagel, N. Stefaniuk, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

University of Hamburg, Hamburg, Germany
S. Bein, V. Blobel, M. Centis Vignali, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, A. Hinzmann, M. Hoffmann, A. Karavdina, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, T. Lapsien, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo[14], T. Peiffer, A. Perieanu, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

Institut für Experimentelle Kernphysik, Karlsruhe, Germany
M. Akbiyik, C. Barth, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, B. Freund, R. Friese, M. Giffels, A. Gilbert, D. Haitz, F. Hartmann[14], S.M. Heindl, U. Husemann, F. Kassel[14], S. Kudella, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, T. Geralis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, I. Topsis-Giotis

National and Kapodistrian University of Athens, Athens, Greece
G. Karathanasis, S. Kesisoglou, A. Panagiotou, N. Saoulidou

University of Ioánnina, Ioánnina, Greece
I. Evangelou, C. Foudas, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F.A. Triantis

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanad, N. Filipovic, G. Pasztor, G.I. Veres[18]

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, D. Horvath[19], Á. Hunyadi, F. Sikler, V. Veszpremi, G. Vesztergombi[18], A.J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi[20], A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary
M. Bartók[18], P. Raics, Z.L. Trocsanyi, B. Ujvari

Indian Institute of Science (IISc), Bangalore, India
S. Choudhury, J.R. Komaragiri

National Institute of Science Education and Research, Bhubaneswar, India
S. Bahinipati[21], S. Bhowmik, P. Mal, K. Mandal, A. Nayak[22], D.K. Sahoo[21], N. Sahoo, S.K. Swain

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, N. Dhingra, A.K. Kalsi, A. Kaur, M. Kaur, R. Kumar, P. Kumari, A. Mehta, J.B. Singh, G. Walia

University of Delhi, Delhi, India
Ashok Kumar, Aashaq Shah, A. Bhardwaj, S. Chauhan, B.C. Choudhary, R.B. Garg, S. Keshri, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, R. Sharma, V. Sharma

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
R. Bhardwaj, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

Indian Institute of Technology Madras, Madras, India
P.K. Behera

Bhabha Atomic Research Centre, Mumbai, India
R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty[14], P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, S. Dugad, B. Mahakud, S. Mitra, G.B. Mohanty, N. Sur, B. Sutar

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Kumar, M. Maity[23], G. Majumder, K. Mazumdar, T. Sarkar[23], N. Wickramage[24]

Indian Institute of Science Education and Research (IISER), Pune, India
S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani[25], E. Eskandari Tadavani, S.M. Etesami[25], M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi[26], F. Rezaei Hosseinabadi, B. Safarzadeh[27], M. Zeinali

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy
M. Abbrescia[a,b], C. Calabria[a,b], C. Caputo[a,b], A. Colaleo[a], D. Creanza[a,c], L. Cristella[a,b], N. De Filippis[a,c], M. De Palma[a,b], F. Errico[a,b], L. Fiore[a], G. Iaselli[a,c], S. Lezki[a,b], G. Maggi[a,c], M. Maggi[a], G. Miniello[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a,b], A. Ranieri[a], G. Selvaggi[a,b], A. Sharma[a], L. Silvestris[a,14], 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], S. Braibant-Giacomelli[a,b], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], S.S. Chhibra[a], G. Codispoti[a,b], M. Cuffiani[a,b], G.M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a,b], P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], S. Marcellini[a], G. Masetti[a], A. Montanari[a], F.L. Navarria[a,b], A. Perrotta[a], A.M. Rossi[a,b], T. Rovelli[a,b], G.P. Siroli[a,b], N. Tosi[a]

INFN Sezione di Catania [a], Università di Catania [b], Catania, Italy
S. Albergo[a,b], S. Costa[a,b], A. Di Mattia[a], F. Giordano[a,b], R. Potenza[a,b], A. Tricomi[a,b], C. Tuve[a,b]

INFN Sezione di Firenze [a], Università di Firenze [b], Firenze, Italy
G. Barbagli[a], K. Chatterjee[a,b], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], P. Lenzi[a,b], M. Meschini[a], S. Paoletti[a], L. Russo[a,28], G. Sguazzoni[a], D. Strom[a], L. Viliani[a,b,14]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera[14]

INFN Sezione di Genova [a], Università di Genova [b], Genova, Italy
V. Calvelli[a,b], F. Ferro[a], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy
L. Brianza[a,b], F. Brivio[a,b], V. Ciriolo[a,b], M.E. Dinardo[a,b], S. Fiorendi[a,b], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], S. Gundacker, M. Malberti[a,b], S. Malvezzi[a], R.A. Manzoni[a,b], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], K. Pauwels[a,b], D. Pedrini[a], S. Pigazzini[a,b,29], S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b]

INFN Sezione di Napoli [a], Università di Napoli 'Federico II' [b], Napoli, Italy, Università della Basilicata [c], Potenza, Italy, Università G. Marconi [d], Roma, Italy
S. Buontempo[a], N. Cavallo[a,c], S. Di Guida[a,d,14], F. Fabozzi[a,c], F. Fienga[a,b], A.O.M. Iorio[a,b], W.A. Khan[a], L. Lista[a], S. Meola[a,d,14], P. Paolucci[a,14], C. Sciacca[a,b], F. Thyssen[a]

INFN Sezione di Padova [a], Università di Padova [b], Padova, Italy, Università di Trento [c], Trento, Italy
P. Azzi[a,14], N. Bacchetta[a], L. Benato[a,b], A. Boletti[a,b], R. Carlin[a,b], A. Carvalho Antunes De Oliveira[a,b], P. Checchia[a], M. Dall'Osso[a,b], P. De Castro Manzano[a], T. Dorigo[a], U. Dosselli[a], F. Gasparini[a,b], U. Gasparini[a,b], A. Gozzelino[a], S. Lacaprara[a], P. Lujan, M. Margoni[a,b], A.T. Meneguzzo[a,b], N. Pozzobon[a,b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], E. Torassa[a], S. Ventura[a], P. Zotto[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
A. Braghieri[a], A. Magnani[a,b], P. Montagna[a,b], S.P. Ratti[a,b], V. Re[a], M. Ressegotti, C. Riccardi[a,b], P. Salvini[a], I. Vai[a,b], P. Vitulo[a,b]

INFN Sezione di Perugia [a], Università di Perugia [b], Perugia, Italy
L. Alunni Solestizi[a,b], M. Biasini[a,b], G.M. Bilei[a], C. Cecchi[a,b], D. Ciangottini[a,b], L. Fanò[a,b], P. Lariccia[a,b], R. Leonardi[a,b], E. Manoni[a], G. Mantovani[a,b], V. Mariani[a,b], M. Menichelli[a], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a]

INFN Sezione di Pisa [a], Università di Pisa [b], Scuola Normale Superiore di Pisa [c], Pisa, Italy
K. Androsov[a], P. Azzurri[a,14], G. Bagliesi[a], J. Bernardini[a], T. Boccali[a], L. Borrello, R. Castaldi[a], M.A. Ciocci[a,b], R. Dell'Orso[a], G. Fedi[a], L. Giannini[a,c], A. Giassi[a], M.T. Grippo[a,28], F. Ligabue[a,c], T. Lomtadze[a], E. Manca[a,c], G. Mandorli[a,c], L. Martini[a,b], A. Messineo[a,b], F. Palla[a], A. Rizzi[a,b], A. Savoy-Navarro[a,30], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma [a], Sapienza Università di Roma [b], Rome, Italy
L. Barone[a,b], F. Cavallari[a], M. Cipriani[a,b], D. Del Re[a,b,14], E. Di Marco[a,b], M. Diemoz[a], S. Gelli[a,b], E. Longo[a,b], F. Margaroli[a,b], B. Marzocchi[a,b], P. Meridiani[a], G. Organtini[a,b], R. Paramatti[a,b], F. Preiato[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[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], C. Biino[a], N. Cartiglia[a], F. Cenna[a,b], M. Costa[a,b], R. Covarelli[a,b], A. Degano[a,b], N. Demaria[a], B. Kiani[a,b], C. Mariotti[a], S. Maselli[a], E. Migliore[a,b], V. Monaco[a,b], E. Monteil[a,b], M. Monteno[a],

M.M. Obertino[a,b], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], G.L. Pinna Angioni[a,b], F. Ravera[a,b], A. Romero[a,b], M. Ruspa[a,c], R. Sacchi[a,b], K. Shchelina[a,b], V. Sola[a], A. Solano[a,b], A. Staiano[a], P. Traczyk[a,b]

INFN Sezione di Trieste [a], Università di Trieste [b], Trieste, Italy
S. Belforte[a], M. Casarsa[a], F. Cossutti[a], G. Della Ricca[a,b], A. Zanetti[a]

Kyungpook National University, Daegu, Korea
D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S. Sekmen, D.C. Son, Y.C. Yang

Chonbuk National University, Jeonju, Korea
A. Lee

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
H. Kim, D.H. Moon, G. Oh

Hanyang University, Seoul, Korea
J.A. Brochero Cifuentes, J. Goh, T.J. Kim

Korea University, Seoul, Korea
S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, Y. Kim, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park, Y. Roh

Seoul National University, Seoul, Korea
J. Almond, J. Kim, J.S. Kim, H. Lee, K. Lee, K. Nam, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

University of Seoul, Seoul, Korea
M. Choi, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park

Sungkyunkwan University, Suwon, Korea
Y. Choi, C. Hwang, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania
V. Dudenas, A. Juodagalvis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali[31], F. Mohamad Idris[32], W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
Reyes-Almanza, R, Ramirez-Sanchez, G., Duran-Osuna, M. C., H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz[33], Rabadan-Trejo, R. I., R. Lopez-Fernandez, J. Mejia Guisao, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
A. Morelos Pineda

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, A. Byszuk[34], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Seixas, O. Toldaiev, D. Vadruccio, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev[35,36], V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
Y. Ivanov, V. Kim[37], E. Kuznetsova[38], P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

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

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepennov, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia
T. Aushev, A. Bylinkin[36]

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
M. Chadeeva[39], P. Parygin, D. Philippov, S. Polikarpov, E. Popova, V. Rusinov

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin[36], I. Dremin[36], M. Kirakosyan[36], A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin[40], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin

Novosibirsk State University (NSU), Novosibirsk, Russia
V. Blinov[41], Y.Skovpen[41], D. Shtol[41]

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic[42], P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
J. Alcaraz Maestre, M. Barrio Luna, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares, A. Álvarez Fernández

Universidad Autónoma de Madrid, Madrid, Spain
J.F. de Trocóniz, M. Missiroli, D. Moran

Universidad de Oviedo, Oviedo, Spain
J. Cuevas, C. Erice, J. Fernandez Menendez, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, S. Sanchez Cruz, I. Suárez Andrés, P. Vischia, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
I.J. Cabrillo, A. Calderon, B. Chazin Quero, E. Curras, J. Duarte Campderros, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, E. Auffray, P. Baillon, A.H. Ball, D. Barney, M. Bianco, P. Bloch, A. Bocci, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, A. De Roeck, M. Dobson, B. Dorney, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, F. Glege, D. Gulhan, P. Harris, J. Hegeman, V. Innocente, P. Janot, O. Karacheban[17], J. Kieseler, H. Kirschenmann, V. Knünz, A. Kornmayer[14], M.J. Kortelainen, M. Krammer[1], C. Lange, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic[43], F. Moortgat, M. Mulders, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, A. Racz, T. Reis, G. Rolandi[44], M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas[45], A. Stakia, J. Steggemann, M. Stoye, M. Tosi, D. Treille, A. Triossi, A. Tsirou, V. Veckalns[46], M. Verweij, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
W. Bertl[†], L. Caminada[47], K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
F. Bachmair, L. Bäni, P. Berger, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, T. Klijnsma, W. Lustermann, B. Mangano, M. Marionneau, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi,

J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Reichmann, M. Schönenberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland
T.K. Aarrestad, C. Amsler[48], M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, C. Seitz, Y. Takahashi, A. Zucchetta

National Central University, Chung-Li, Taiwan
V. Candelise, T.H. Doan, Sh. Jain, R. Khurana, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
Arun Kumar, P. Chang, Y. Chao, K.F. Chen, P.H. Chen, F. Fiori, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, J.f. Tsai

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
B. Asavapibhop, K. Kovitanggoon, G. Singh, N. Srimanobhas

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
A. Adiguzel[49], F. Boran, S. Cerci[50], S. Damarseckin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, I. Hos[51], E.E. Kangal[52], O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut[53], K. Ozdemir[54], D. Sunar Cerci[50], B. Tali[50], S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey
B. Bilin, G. Karapinar[55], K. Ocalan[56], M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey
E. Gülmez, M. Kaya[57], O. Kaya[58], S. Tekten, E.A. Yetkin[59]

Istanbul Technical University, Istanbul, Turkey
M.N. Agaras, S. Atay, A. Cakir, K. Cankocak

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk, P. Sorokin

University of Bristol, Bristol, United Kingdom
R. Aggleton, F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, D.M. Newbold[60], S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev[61], C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom
G. Auzinger, R. Bainbridge, S. Breeze, O. Buchmuller, A. Bundock, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, R. Di Maria, A. Elwood, Y. Haddad, G. Hall, G. Iles, T. James, R. Lane, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, T. Matsushita, J. Nash, A. Nikitenko[6], V. Palladino, M. Pesaresi,

D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta[62], T. Virdee[14], N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

Brunel University, Uxbridge, United Kingdom
J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, USA
A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika, C. Smith

Catholic University of America, Washington DC, USA
R. Bartek, A. Dominguez

The University of Alabama, Tuscaloosa, USA
A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

Boston University, Boston, USA
D. Arcaro, A. Avetisyan, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Brown University, Providence, USA
G. Benelli, D. Cutts, A. Garabedian, J. Hakala, U. Heintz, J.M. Hogan, K.H.M. Kwok, E. Laird, G. Landsberg, Z. Mao, M. Narain, J. Pazzini, S. Piperov, S. Sagir, R. Syarif, D. Yu

University of California, Davis, Davis, USA
R. Band, C. Brainerd, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, M. Gardner, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, J. Smith, M. Squires, D. Stolp, K. Tos, M. Tripathi, Z. Wang

University of California, Los Angeles, USA
M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, D. Saltzberg, C. Schnaible, V. Valuev

University of California, Riverside, Riverside, USA
E. Bouvier, K. Burt, R. Clare, J. Ellison, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, J. Heilman, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, A. Shrinivas, W. Si, L. Wang, H. Wei, S. Wimpenny, B. R. Yates

University of California, San Diego, La Jolla, USA
J.G. Branson, S. Cittolin, M. Derdzinski, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, I. Macneill, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech[63], J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara - Department of Physics, Santa Barbara, USA
N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, M. Franco Sevilla, C. George, F. Golf, L. Gouskos, J. Gran, R. Heller, J. Incandela, S.D. Mullin, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, J. Yoo

California Institute of Technology, Pasadena, USA
D. Anderson, J. Bendavid, A. Bornheim, J.M. Lawhorn, H.B. Newman, T. Nguyen, C. Pena, M. Spiropulu, J.R. Vlimant, S. Xie, Z. Zhang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev, M. Weinberg

University of Colorado Boulder, Boulder, USA
J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, S. Leontsinis, T. Mulholland, K. Stenson, S.R. Wagner

Cornell University, Ithaca, USA
J. Alexander, J. Chaves, J. Chu, S. Dittmer, K. Mcdermott, N. Mirman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla[†], K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, B. Schneider, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck

University of Florida, Gainesville, USA
D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, R.D. Field, I.K. Furic, J. Konigsberg, A. Korytov, K. Kotov, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, D. Rank, D. Sperka, N. Terentyev, L. Thomas, J. Wang, S. Wang, J. Yelton

Florida International University, Miami, USA
Y.R. Joshi, S. Linn, P. Markowitz, J.L. Rodriguez

Florida State University, Tallahassee, USA
A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, A. Santra, R. Yohay

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, I.D. Sandoval Gonzalez, M.B. Tonjes, H. Trauger, N. Varelas, H. Wang, Z. Wu, J. Zhang

The University of Iowa, Iowa City, USA
B. Bilki[64], W. Clarida, K. Dilsiz[65], S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya[66], A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul[67], Y. Onel, F. Ozok[68], A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, USA
B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

The University of Kansas, Lawrence, USA
A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, J. Castle, S. Khalil, A. Kropivnitskaya,

D. Majumder, W. Mcbrayer, M. Murray, C. Royon, S. Sanders, E. Schmitz, R. Stringer, J.D. Tapia Takaki, Q. Wang

Kansas State University, Manhattan, USA
A. Ivanov, K. Kaadze, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

Lawrence Livermore National Laboratory, Livermore, USA
F. Rebassoo, D. Wright

University of Maryland, College Park, USA
C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar

Massachusetts Institute of Technology, Cambridge, USA
D. Abercrombie, B. Allen, V. Azzolini, R. Barbieri, A. Baty, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, D. Hsu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, B. Maier, A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephans, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

University of Minnesota, Minneapolis, USA
A.C. Benvenuti, R.M. Chatterjee, A. Evans, P. Hansen, S. Kalafut, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, J. Turkewitz

University of Mississippi, Oxford, USA
J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA
E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

State University of New York at Buffalo, Buffalo, USA
M. Alyari, J. Dolen, A. Godshalk, C. Harrington, I. Iashvili, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA
G. Alverson, E. Barberis, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, D. Wood

Northwestern University, Evanston, USA
S. Bhattacharya, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, B. Pollack, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA
N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko[35], M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, M. Wayne, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA
J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, B. Liu, W. Luo, D. Puigh, B.L. Winer, H.W. Wulsin

Princeton University, Princeton, USA
A. Benaglia, S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S. Higginbotham,

D. Lange, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, USA
S. Malik, S. Norberg

Purdue University, West Lafayette, USA
A. Barker, V.E. Barnes, S. Das, S. Folgueras, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, A. Khatiwada, D.H. Miller, N. Neumeister, C.C. Peng, J.F. Schulte, J. Sun, F. Wang, W. Xie

Purdue University Northwest, Hammond, USA
T. Cheng, N. Parashar, J. Stupak

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

University of Rochester, Rochester, USA
A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, M. Verzetti

The Rockefeller University, New York, USA
R. Ciesielski, K. Goulianos, C. Mesropian

Rutgers, The State University of New Jersey, Piscataway, USA
A. Agapitos, J.P. Chou, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, USA
A.G. Delannoy, M. Foerster, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

Texas A&M University, College Station, USA
O. Bouhali[69], A. Castaneda Hernandez[69], A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[70], R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov, K.A. Ulmer

Texas Tech University, Lubbock, USA
N. Akchurin, J. Damgov, F. De Guio, P.R. Dudero, J. Faulkner, E. Gurpinar, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Vanderbilt University, Nashville, USA
S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

University of Virginia, Charlottesville, USA
M.W. Arenton, P. Barria, B. Cox, R. Hirosky, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, X. Sun, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, USA
R. Harr, P.E. Karchin, J. Sturdy, S. Zaleski

University of Wisconsin - Madison, Madison, WI, USA
M. Brodski, J. Buchanan, C. Caillol, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe,

M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, G.A. Pierro, G. Polese, T. Ruggles, A. Savin, N. Smith, W.H. Smith, D. Taylor, N. Woods

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
3: Also at Universidade Estadual de Campinas, Campinas, Brazil
4: Also at Universidade Federal de Pelotas, Pelotas, Brazil
5: Also at Université Libre de Bruxelles, Bruxelles, Belgium
6: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
7: Also at Joint Institute for Nuclear Research, Dubna, Russia
8: Also at Suez University, Suez, Egypt
9: Now at British University in Egypt, Cairo, Egypt
10: Now at Helwan University, Cairo, Egypt
11: Also at Université de Haute Alsace, Mulhouse, France
12: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
13: Also at Tbilisi State University, Tbilisi, Georgia
14: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
15: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
16: Also at University of Hamburg, Hamburg, Germany
17: Also at Brandenburg University of Technology, Cottbus, Germany
18: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
19: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
20: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
21: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
22: Also at Institute of Physics, Bhubaneswar, India
23: Also at University of Visva-Bharati, Santiniketan, India
24: Also at University of Ruhuna, Matara, Sri Lanka
25: Also at Isfahan University of Technology, Isfahan, Iran
26: Also at Yazd University, Yazd, Iran
27: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
28: Also at Università degli Studi di Siena, Siena, Italy
29: Also at INFN Sezione di Milano-Bicocca; Università di Milano-Bicocca, Milano, Italy
30: Also at Purdue University, West Lafayette, USA
31: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
32: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
33: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
34: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
35: Also at Institute for Nuclear Research, Moscow, Russia
36: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
37: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
38: Also at University of Florida, Gainesville, USA
39: Also at P.N. Lebedev Physical Institute, Moscow, Russia
40: Also at California Institute of Technology, Pasadena, USA
41: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia

42: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
43: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
44: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
45: Also at National and Kapodistrian University of Athens, Athens, Greece
46: Also at Riga Technical University, Riga, Latvia
47: Also at Universität Zürich, Zurich, Switzerland
48: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
49: Also at Istanbul University, Faculty of Science, Istanbul, Turkey
50: Also at Adiyaman University, Adiyaman, Turkey
51: Also at Istanbul Aydin University, Istanbul, Turkey
52: Also at Mersin University, Mersin, Turkey
53: Also at Cag University, Mersin, Turkey
54: Also at Piri Reis University, Istanbul, Turkey
55: Also at Izmir Institute of Technology, Izmir, Turkey
56: Also at Necmettin Erbakan University, Konya, Turkey
57: Also at Marmara University, Istanbul, Turkey
58: Also at Kafkas University, Kars, Turkey
59: Also at Istanbul Bilgi University, Istanbul, Turkey
60: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
61: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
62: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
63: Also at Utah Valley University, Orem, USA
64: Also at Beykent University, Istanbul, Turkey
65: Also at Bingol University, Bingol, Turkey
66: Also at Erzincan University, Erzincan, Turkey
67: Also at Sinop University, Sinop, Turkey
68: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
69: Also at Texas A&M University at Qatar, Doha, Qatar
70: Also at Kyungpook National University, Daegu, Korea