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Search for a boosted Higgs boson decaying to bottom quark pairs in association with a W or Z boson in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$

The CMS Collaboration*

Abstract

A search is conducted for standard model Higgs bosons with large transverse momentum (p_{T}) decaying to bottom quark pairs and produced in association with a hadronically decaying W or Z boson at the LHC. The result is based on a dataset of proton-proton collisions at a center-of-mass energy of 13 TeV collected with the CMS detector in 2016–2018, corresponding to an integrated luminosity of $138\,\mathrm{fb}^{-1}$. Boosted Higgs, W, and Z boson decays are reconstructed using large-radius jets with $p_{\mathrm{T}} > 450\,\mathrm{GeV}$ and identified with heavy-flavor classifiers based on a graph convolutional neural network. The observed signal strength relative to the standard model expectation is $\mu = 0.72^{+0.75}_{-0.71}$ including statistical and systematic uncertainties.

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*See Appendix A for the list of collaboration members

1 Introduction

The observation of a Higgs boson (H) consistent with the standard model (SM) expectation in 2012 [1–3] and subsequent measurements of its properties [4, 5] have advanced our understanding of electroweak (EW) symmetry breaking and the origin of particle masses [6–13]. The Higgs boson has been observed at the CERN LHC in its main production processes and several decay channels.

At high transverse momentum (p_T), H production can probe beyond-the-SM (BSM) effects [14–19]. The decay of a Higgs boson into a bottom quark-antiquark pair ($H \to b\overline{b}$) is particularly well suited for studying boosted Higgs boson production because of its large branching fraction of 58% [20]. Furthermore, at high p_T the decay products become collimated and can be reconstructed within a single large-radius jet, allowing for background suppression through the study of the jet substructure.

The dominant Higgs boson production mechanism at the LHC is gluon fusion (ggH), contributing about 87% of the inclusive Higgs boson cross section at $\sqrt{s} = 13\,\mathrm{TeV}$. However, at high p_T, the relative ggH contribution decreases to $\sim$50% for $p_T > 450\,\mathrm{GeV}$ and $\sim$30% for $p_T > 1200\,\mathrm{GeV}$ [21]. The relative fraction of vector boson fusion (VBF) shows minimal p_T dependence, while the relative fraction of associated production with vector bosons (VH, $V = W$ or Z) increases with p_T. Therefore, precise measurements of the VH process could uncover BSM phenomena in the Higgs boson sector, which may appear more prominently at high p_T [22–24].

Searches for VH production with $H \to b\overline{b}$ have been performed at the LHC in both leptonic [25, 26] and hadronic [27] V decay channels. Furthermore, this channel has been used to constrain BSM phenomena within an effective field theory framework [28]. Other boosted $H \to b\overline{b}$ measurements have targeted the ggH [29, 30] and VBF [31] processes. The excess of 2.7 standard deviations (σ) with respect to SM predictions observed in the previous VBF analysis [31] motivates further exploration of the VH process, as it could be explained by enhanced couplings of the H to vector bosons.

This work extends CMS high-p_T Higgs boson measurements in the $H \to b\overline{b}$ channel to VH production in final states with a hadronic W or Z decay, $V(qq)$. The search uses a dataset of proton-proton (pp) collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ collected by the CMS experiment at the LHC in 2016–2018, corresponding to an integrated luminosity of $138\,\mathrm{fb}^{-1}$ [32–34]. The same strategy is also used to measure $V(qq)Z(b\overline{b})$ production simultaneously as a validation of the method.

2 The CMS detector

The CMS apparatus [35, 36] is a multipurpose, nearly hermetic detector, designed to trigger on [37–39] and identify electrons, muons, photons, and hadrons [40–42]. Its central feature 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, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are reconstructed using gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. More detailed descriptions of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Refs. [35, 36].

A two-tiered trigger system selects events of interest. The first level, implemented in hardware, reduces the rate to about 100 kHz within 4 μs [37]. The high-level trigger, implemented in software, further reduces the rate to about 1 kHz before data storage [38, 39].

The dataset used here is divided into four periods: early 2016, late 2016, 2017, and 2018. These divisions reflect the 2017 tracking detector upgrade, variations in accelerator and detector conditions, and updates to reconstruction and calibration procedures. The 2016 data-taking period is split into early and late periods because of the configuration changes made mid-year.

3 Simulated samples

Signal and background events are simulated using various Monte Carlo (MC) event generators, with the CMS detector response modeled by GEANT4 [43]. Independent samples are produced for each data-taking period using identical generator settings and incorporating changes in running conditions.

The background from quantum chromodynamics (QCD) multijet processes, i.e. events consisting of multiple hadronic jets produced via the strong interaction, is generated at leading order (LO) accuracy with MADGRAPH5_aMC@NLO 2.6 [44, 45] using up to four partons in the matrix element calculation. The W+jets and Z+jets processes are also simulated at LO with MADGRAPH5_aMC@NLO, including decays to all flavors of quarks and up to three and four additional partons at the matrix element level for W+jets and Z+jets, respectively. The samples are corrected as a function of the boson p_{T} to match higher-order predictions. The QCD next-to-LO (NLO) corrections are derived with MADGRAPH5_aMC@NLO, simulating W and Z boson production with up to two additional partons. The EW NLO corrections are taken from theoretical calculations described in Refs. [46–49].

Diboson processes (WW, WZ, and ZZ) are generated at LO accuracy with PYTHIA 8.240 [50] and corrected to next-to-NLO (NNLO) cross sections using MCFM 7.0 [51]. Top quark pair and single-top processes are modeled at NLO in QCD with POWHEG 2.0 [52–56].

The ggH process is simulated with HJMINLO [57, 58], including finite top quark mass effects [59] as recommended in Ref. [21]. The POWHEG v2 generator [60–62] is used for VBF H production, VH, and $\mathrm{t\bar{t}H}$ at NLO. The VBF sample is reweighted to NNLO in the p_{T} spectrum and next-to-NNLO accuracy in the inclusive cross section [63, 64]. These corrections have a negligible effect on the yield of this process for events with Higgs boson $p_{\mathrm{T}} > 450\,\mathrm{GeV}$. Electroweak corrections are applied to the VBF, VH, and $\mathrm{t\bar{t}H}$ samples [21].

Parton showering and hadronization are modeled with PYTHIA using the CP5 tune [65]. Jets from the parton shower are matched to those from the matrix element calculations using the MLM [66] and FXFX [67] schemes for LO and NLO samples, respectively. The NNPDF3.1 [68] set of parton distribution functions (PDF) at NNLO accuracy is used for all processes. To account for additional pp interactions occurring in the same or nearby LHC bunch crossings (pileup), the PYTHIA generator is employed. All MC samples include effects of pileup by overlaying simulated minimum bias events on the hard-scattering event, with the multiplicity distribution matching that observed in data.

4 Event reconstruction and selection

A particle-flow (PF) algorithm [69] aims to reconstruct and identify each individual particle in an event (PF candidate) using an optimized combination of information from the various elements of the CMS detector. The primary vertex is defined as the one most consistent with the hardest scattering in the event, as determined from tracking information [42, 70].

Jets are formed from PF candidates using the anti-k_{T} clustering algorithm [71], as implemented in FASTJET [72]. Small-radius (AK4) jets use a distance parameter of 0.4, and large-radius (AK8) jets use 0.8 [73]. The latter are used to reconstruct the collimated hadronization of the quark pairs originating from the boosted H and V boson candidates. Jet momentum is calculated as the vector sum of all particle momenta in the jet.

Pileup interactions can contribute additional tracks and calorimetric energy depositions, increasing the apparent jet momentum. For AK4 jets, tracks identified to be originating from pileup vertices are discarded and an offset correction is applied to account for remaining contributions [74]. For AK8 jets, the pileup-per-particle identification algorithm [74, 75] is used to mitigate the effect of pileup at the reconstructed-particle level, making use of local shape information, event pileup properties, and tracking information. Jet energy corrections are derived from simulation studies so that the average measured energy of jets becomes identical to that of particle level jets. In-situ measurements of the momentum balance in dijet, Z+jet, photon+jet, and multijet events are used to determine any residual differences between the jet energy scale in data and simulation, and appropriate corrections are made [76]. Additional selection criteria are applied to each jet to remove jets potentially dominated by instrumental effects or reconstruction failures [74].

Events are selected by triggers requiring either an AK8 jet with large p_{T} or a minimum event H_{T}, defined as the scalar p_{T} sum of all AK4 jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 3$. These triggers are about 90% efficient for jets with $450 < p_{\mathrm{T}} < 500\,\mathrm{GeV}$, $|\eta| < 2.5$, and fully efficient above 500 GeV.

Offline, exactly two AK8 jets, corresponding to the boosted H and W/Z bosons, are required with $p_{\mathrm{T}} > 450\,\mathrm{GeV}$ and $|\eta| < 2.5$. They must pass tight jet identification requirements [73] and be separated from any isolated leptons or photons by $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} > 0.8$, where $\Delta\eta$ and $\Delta\phi$ are the differences in pseudorapidity and azimuthal angle, respectively. Jets must satisfy $-6.0 < \rho = 2\ln(m_{\mathrm{SD}}/p_{\mathrm{T}}) < -2.1$, where p_{T} is the jet transverse momentum and m_{SD} is the jet mass after soft drop grooming with parameters $z_{\mathrm{cut}} = 0.1$ and $\beta = 0$ [77]. The lower ρ threshold removes regions where nonperturbative effects are poorly modeled, and the upper ρ threshold removes jets where the constituents are not fully contained by the jet cone. The soft drop algorithm reduces contamination from underlying events and pileup, improving the jet mass resolution and stability across a wide range of jet momenta.

To suppress the background contribution from semi- and di-leptonic $\mathrm{t\bar{t}}$ decays, events are required to contain no isolated leptons. The relative isolation variable for electrons (muons) is defined as the scalar sum p_{T} of charged hadrons and neutral particles within a cone of radius $\Delta R = 0.3$ (0.4) around the lepton, corrected for pileup and divided by the lepton p_{T}. For the purpose of this veto, electrons must have $p_{\mathrm{T}} > 10\,\mathrm{GeV}$, $|\eta| < 2.5$, pass loose identification criteria [40], and have relative isolation less than 0.15. Muons must have $p_{\mathrm{T}} > 10\,\mathrm{GeV}$, $|\eta| < 2.4$, pass loose identification criteria [41], and have relative isolation less than 0.25. Hadronically decaying tau leptons, τ_{h}, must have $p_{\mathrm{T}} > 20\,\mathrm{GeV}$, $|\eta| < 2.3$, and pass the DEEPTAU algorithm identification requirements [78]. Events are also required to have $p_{\mathrm{T}}^{\mathrm{miss}} < 140\,\mathrm{GeV}$. The missing transverse momentum vector $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is computed as the negative vector sum of the transverse momenta of all the PF candidates in an event, and its magnitude is denoted as $p_{\mathrm{T}}^{\mathrm{miss}}$ [79]. The $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is modified to account for corrections to the energy scale of the reconstructed jets in the event. In order to reduce the contribution from fully hadronic $\mathrm{t\bar{t}}$ decays, events are also vetoed if they have six or more AK4 jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 5$ in addition to the AK8 jets.

The two selected AK8 jets are designated as the H and V candidates. The flavor properties of each jet are determined using the mass-decorrelated (MD) version of the PARTICLENET algorithm [80]. This version of the tagger, denoted PARTICLENET-MD, is trained on simulated jets with uniform distributions in mass and p_T to minimize dependence of the jet selection on its mass. The PARTICLENET-MD classifier assigns four scores to each AK8 jet, $p(\mathrm{X} \to \mathrm{b\overline{b}})$, $p(\mathrm{X} \to \mathrm{c\overline{c}})$, $p(\mathrm{X} \to \mathrm{q\overline{q}})$, and $p(\mathrm{QCD})$, corresponding to four categories: three for a boson X decaying to bottom, charm, or light quarks, and one for QCD jets [81]. The scores sum to unity. Discriminants formed from these scores are used to classify the AK8 jets and to suppress the QCD background.

The H candidate (Jet 1) is chosen to be the jet with the higher discriminant $\mathcal{D}(\mathrm{b\overline{b}}\text{ vs. }\mathrm{c\overline{c}}, \mathrm{q\overline{q}})$, where

$$\mathcal{D}(\mathrm{b\overline{b}}\text{ vs. }\mathrm{c\overline{c}}, \mathrm{q\overline{q}}) = \frac{p(\mathrm{X} \to \mathrm{b\overline{b}})}{p(\mathrm{X} \to \mathrm{b\overline{b}}) + p(\mathrm{X} \to \mathrm{c\overline{c}}) + p(\mathrm{X} \to \mathrm{q\overline{q}})}.$$

The other selected AK8 jet (Jet 2) is designated as the V candidate. Events where the V candidate jet has a high $p(\mathrm{QCD})$ score are discarded, where the $p(\mathrm{QCD})$ threshold corresponds to a signal efficiency of 25% and a misidentification rate of 3% on QCD jets [80]. Events are divided into three categories based on the m_{SD} of the V candidate jet: 40–68 GeV, 68–110 GeV, and 110–201 GeV. The middle category contains the peak corresponding to the V boson, while the others serve as sideband control regions (CRs) that constrain backgrounds containing only one hadronic decay of a heavy particle.

A second flavor discriminant, $\mathcal{D}(\mathrm{b\overline{b}}\text{ vs. QCD})$, is used to determine whether the H candidate jet originates from a heavy particle decaying to two b quarks. This discriminant is defined as a ratio of PARTICLENET-MD classifier scores:

$$\mathcal{D}(\mathrm{b\overline{b}}\text{ vs. QCD}) = \frac{p(\mathrm{X} \to \mathrm{b\overline{b}})}{p(\mathrm{X} \to \mathrm{b\overline{b}}) + p(\mathrm{QCD})}.$$

Events that have high $\mathcal{D}(\mathrm{b\overline{b}}\text{ vs. QCD})$, above the threshold corresponding to 40% $\mathrm{X} \to \mathrm{b\overline{b}}$ signal efficiency [80], enter the signal region (SR). Events with lower $\mathcal{D}(\mathrm{b\overline{b}}\text{ vs. QCD})$ form a CR dominated by QCD multijet processes, which is used to estimate the background contribution from QCD.

5 Background estimation

The QCD multijet process is the dominant background in all analysis categories. Significant resonant backgrounds arise from W+jets and Z+jets processes, where the two-prong decay of a high-p_T vector boson is mistagged as a H candidate. The $\mathrm{t\bar{t}}$ process and single top quarks produced in association with a W boson form nonresonant backgrounds, where the decay of a high-p_T top quark is reconstructed as a large-radius jet and passes the H candidate selection. Additional minor backgrounds arise from other Higgs boson production processes (ggH, VBF, and $\mathrm{t\bar{t}H}$). The QCD multijet and top quark backgrounds are determined with data in CRs, while the other backgrounds are estimated using simulation.

5.1 Multijet background

The QCD multijet background in the SR is estimated from data using events failing the $\mathcal{D}(\mathrm{b\overline{b}}\text{ vs. QCD})$ requirement, referred to as the QCD CR. The shape of the m_{SD} distribution of QCD background in the SR is taken from the QCD CR and multiplied by a polynomial transfer factor to account for shape differences due to the $\mathcal{D}(\mathrm{b\bar{b}}$ vs. QCD) requirement and differences in the tagger performance between data and simulation.

The QCD multijet background yield in the SR is

$$N_{\mathrm{SR}}(m_{\mathrm{SD}}) = R^{\mathrm{MC}}_{\mathrm{SR/CR}}\, N^{\mathrm{data}}_{\mathrm{CR}}(m_{\mathrm{SD}})\, TF(m_{\mathrm{SD}}),$$

where $R^{\mathrm{MC}}_{\mathrm{SR/CR}}$ is the ratio of the QCD MC event yield in the SR and CR, $N^{\mathrm{data}}_{\mathrm{CR}}$ is the number of data events minus the number of predicted non-QCD background events in the QCD CR, and $TF(m_{\mathrm{SD}})$ is a transfer factor that accounts for shape differences between the CR and SR. The same transfer factor is applied to all three bins in the V candidate m_{SD}, allowing the sideband regions to help constrain the QCD background. Independent transfer factors are defined for each data-taking period. Each transfer factor is defined as a Bernstein polynomial [31] in $\log(m_{\mathrm{SD}}/\mathrm{GeV})$, and a first-order polynomial is determined to be optimal for all data-taking periods using a Fisher F-test [82]. The transfer factor is therefore defined as

$$TF(m_{\mathrm{SD}}) = a(1 - \log(m_{\mathrm{SD}}/\mathrm{GeV})) + b\log(m_{\mathrm{SD}}/\mathrm{GeV}),$$

where the values of the coefficients a and b are obtained in the simultaneous fit to data described in Section 7. Alternative functional forms for $TF(m_{\mathrm{SD}})$ were tested and found to have a negligible impact on the final result.

5.2 Vector boson backgrounds

Resonant backgrounds due to V+jets and diboson processes are estimated using simulation. A W-enriched CR is used to calibrate jet mass scale and resolution, and to determine the efficiency of the PARTICLENET-MD $p(\mathrm{QCD})$ selection requirement on the W candidate jet.

Events in this CR are collected with single-muon triggers. Offline, events are required to have one muon with $p_{\mathrm{T}} > 53\,\mathrm{GeV}$, $|\eta| < 2.1$, relative isolation less than 0.15, $p_{\mathrm{T}}^{\mathrm{miss}} > 40\,\mathrm{GeV}$, no additional leptons, and an AK8 jet with $p_{\mathrm{T}} > 450\,\mathrm{GeV}$ passing the same selection criteria as the SR. The event must also contain at least one AK4 jet with $p_{\mathrm{T}} > 50\,\mathrm{GeV}$ and $|\eta| < 2.5$ that is separated by $\Delta R > 0.8$ from the AK8 jet and b-tagged using the DEEPJET algorithm [83, 84]. This CR contains a high fraction of $\mathrm{t\bar{t}}$ events where one top quark decays semi-leptonically and the other to a boosted W boson.

Template m_{SD} distributions are derived from simulation in two regions based on whether the AK8 jet passes or fails the $p(\mathrm{QCD})$ requirement. The templates in each region correspond to events that contain a W boson and events that do not. For the former, variations of the m_{SD} scale and resolution are calculated using linear morphing [85].

A fit to data in the CR is performed to extract three corrections: the efficiency of the $p(\mathrm{QCD})$ selection, the shift in the jet mass scale, and the jet mass resolution scale factor. The corrections are derived independently for each data-taking period. The measured $p(\mathrm{QCD})$ efficiency ranges from 0.70 to 0.89 with relative uncertainties of 7 to 16%, depending on the data-taking period. The jet mass scale correction is consistent with unity, with uncertainties of 200–300 MeV. The jet mass resolution scale factor ranges from 1.14 to 1.25, with uncertainties of 0.13–0.38.

5.3 Top quark backgrounds

Top quark processes constitute a nonresonant component of the background. The shapes of the m_{SD} distributions in $\mathrm{t\bar{t}}$ and single top quark processes are estimated from simulation. The normalizations of the $\mathrm{t\bar{t}}$ and single top quark backgrounds, as well as the efficiency of the $\mathcal{D}(\mathrm{b\bar{b}}$ vs. QCD) requirement on top quark jets, are constrained using a CR targeting $\mathrm{t\bar{t}}$ events, where one top quark decays via $t \rightarrow W(\mu\nu)b$ and the other decays hadronically. Events in this CR are required to have exactly one muon with $p_T > 55$ GeV, $|\eta| < 2.1$, and relative isolation less than 0.25; no electrons or τ_h; at least one AK4 jet b-tagged with DEEPJET; and one AK8 jet with $p_T > 450$ GeV and $|\eta| < 2.5$. The b-tagged AK4 jet must be separated from the AK8 jet by $\Delta R > 0.8$. This region is about 80% pure in $t\bar{t}$, with small contributions from QCD, W+jets, Z+jets, and single top quark processes. The region is split into passing and failing $\mathcal{D}(b\bar{b}$ vs. QCD) categories, and both are fitted simultaneously with the SR during the signal extraction. The resulting scale factors for the normalizations and the efficiency of the $\mathcal{D}(b\bar{b}$ vs. QCD) requirement are consistent with unity.

6 Systematic uncertainties

Systematic uncertainties account for possible mismodeling of the background and signal processes. They are included as nuisance parameters in the signal extraction procedure and treated according to the frequentist paradigm [86].

The dominant systematic uncertainty arises from the modeling of the QCD multijet background, specifically from the coefficients of $TF(m_{SD})$ that are left unconstrained in the fit. Additional small experimental systematic uncertainties are included, amounting to less than a few percent. The uncertainties in the jet m_{SD} scale and resolution derived from the W boson-enriched CR are propagated to all resonant processes using linear morphing of the templates, and the uncertainty in the p(QCD) tagging efficiency is propagated to the normalizations of the VH and VV processes. The integrated luminosities for the 2016, 2017, and 2018 data-taking years have 1.2–2.5% individual uncertainties, while the overall uncertainty is 1.6% [32–34]. The jet energy scale and resolution uncertainties range from 0.5 to 4.0%, and are treated as independent from the m_{SD} uncertainties. Variations in the amount of pileup obtained by adjusting the total inelastic cross section, modeling of the trigger efficiency, and the isolation and identification of the vetoed leptons are also considered, and contribute only a few percent to the total uncertainty.

Theoretical uncertainties are included in the final fit to account for inaccuracy in the modeling of SM processes. The dominant theoretical uncertainty is due to the renormalization and factorization scales chosen for the simulated H and diboson samples. These uncertainties are applied to the H and diboson processes and are assessed by varying the scales up and down by factors of two, while keeping their ratio between 0.5 and 2. This uncertainty is propagated to the total expected yield of the VH and VZ processes according to the prescription recommended in Ref. [21]. Uncertainties in the signal processes due to initial- and final-state radiation are also calculated by varying the renormalization scale and nonsingular term using the PYTHIA showering algorithm [87]. The Hessian PDF uncertainty is also applied to signal yield, according to the prescription of Ref. [88].

Theoretical uncertainties in the W+jets and Z+jets processes account for missing higher-order QCD and mixed QCD-EW effects beyond the corrections described in Section 3, following the prescription of Ref. [49]. All theoretical uncertainties are considered to be correlated across data-taking periods, and experimental systematic uncertainties are considered to be uncorrelated, with the exception of correlated components of the uncertainties in the integrated luminosity.

The dominant uncertainties arise from the coefficients of the data-to-simulation transfer factor used to extrapolate the QCD background from the fail to the pass region, whose parameters are determined directly on data. Subleading contributions originate from jet-mass scale and resolution calibrations, as well as from the top-quark background normalization and pass/fail efficiency constrained in the muon CR. Tagger-efficiency scale factors have smaller effects and are only weakly constrained. Theoretical and luminosity uncertainties primarily affect the overall normalization and have a negligible impact on the fitted signal strength. The precision on the signal strength is ultimately limited by the amount of data available, in particular by the finite sideband sample constraining the QCD yield beneath the H mass peak through the transfer factor.

7 Results

A binned maximum likelihood fit to the observed m_{SD} distributions is performed using the sum of the signal and background contributions. The test statistic chosen to determine the signal yield is based on the profile likelihood ratio [86]. The fit is performed simultaneously using the $\mathcal{D}(\mathrm{b\bar{b}}$ vs. QCD) pass and fail regions for all three bins in the V boson candidate mass and the $\mathrm{t\bar{t}}$ CR, and for all four data-taking periods. The results have been obtained using the CMS statistical analysis tool COMBINE [89], which is based on the ROOFIT [90] and ROOSTATS [91] frameworks.

The observed data and fitted m_{SD} distributions in the $\mathcal{D}(\mathrm{b\bar{b}}$ vs. QCD) fail and pass regions are shown in Fig. 1 for the category where the V candidate has m_{SD} between 68 and 110 GeV. The V mass sidebands (V candidate m_{SD} in the ranges 40–68 and 110–201 GeV) are shown in Fig. 2. The near-perfect model agreement with data in the fail regions is by construction: these regions dominate the QCD background determination due to the large event count compared to the pass regions.

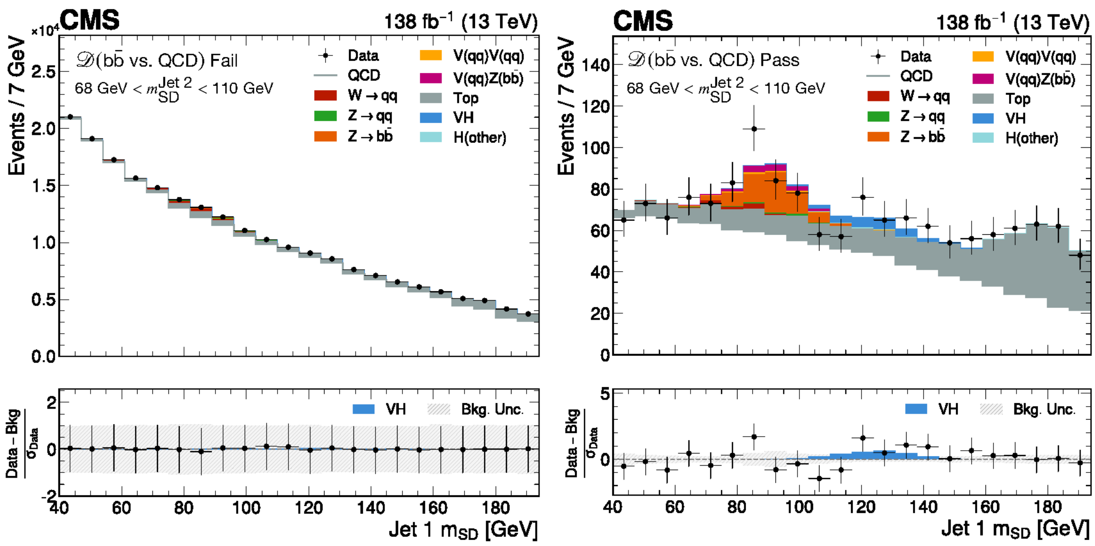

Figure 1: The Higgs boson candidate m_{SD} distribution in the $\mathcal{D}(\mathrm{b\bar{b}}$ vs. QCD) fail (left) and pass region (right), both in the category with V candidate mass between 68 and 110 GeV. The grey bands in the lower panels represent the systematic uncertainty in the background prediction. The $\mathrm{V(qq)Z(b\bar{b})}$ process is separated from other $\mathrm{V(qq)V(qq)}$ processes since it is used to validate the analysis strategy.

The background in both the $\mathcal{D}(\mathrm{b\bar{b}}$ vs. QCD) fail and pass regions is dominated by QCD. In the $\mathcal{D}(\mathrm{b\bar{b}}$ vs. QCD) pass region, the $\mathrm{t\bar{t}}$ background exhibits a peak in the m_{SD} of the H candidate near the top quark mass of 173 GeV. This peak corresponds to the decay of a highly boosted top quark, where the H candidate jet (Jet 1) captures most of the decay products. The large

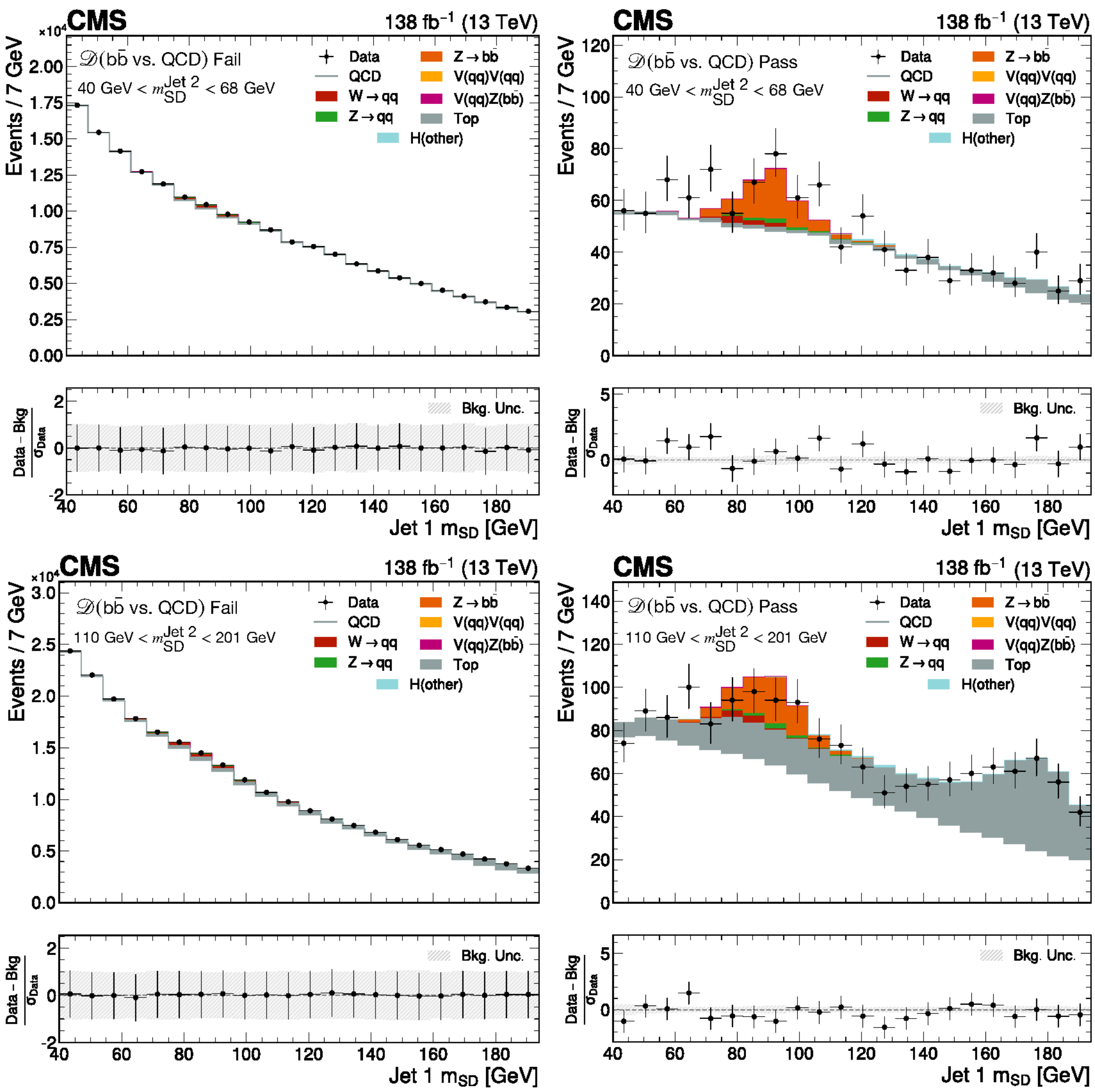

Figure 2: The Higgs boson candidate m_{SD} distribution in the $\mathcal{D}(\mathrm{b\overline{b}}$ vs. QCD) fail (left) and pass region (right) regions, in the category where the V candidate m_{SD} is in the range 40–68 GeV (upper) and 110–201 GeV (lower). Other details are as described in the caption of Fig. 1.

fraction of $\mathrm{t\bar{t}}$ events entering the highest V mass category (Fig. 2, lower right), where the top quark peak is especially prominent, corresponds to events where two boosted top quarks are captured in the two selected AK8 jets.

The contribution of $\mathrm{Z(b\bar{b})}$+jets production to the background in the $\mathcal{D}(\mathrm{b\bar{b}}$ vs. QCD) pass region is clearly visible at the Z mass peak for all three V mass categories. Mistagged W and Z decays to light quarks and diboson processes also comprise a small portion of the background. In particular, the $\mathrm{V(qq)Z(b\bar{b})}$ process generally satisfies the same selection criteria as the $\mathrm{V(qq)H(b\bar{b})}$ signal, and therefore it is used to validate the analysis strategy.

The best fit value of the VH signal strength (μ_{VH}), defined as the ratio of the measured to the SM expected cross section times $\mathrm{H} \to \mathrm{b\bar{b}}$ branching fraction, and an approximate 68% confidence level interval are extracted following Ref. [92]. The signal strength of the $\mathrm{V(qq)Z(b\bar{b})}$ process (μ_{VZ}) is extracted simultaneously with μ_{VH}.

The fitted signal strengths for VH and VZ production are extracted separately for the four data-taking periods, and a combined fit over the full dataset is performed for the final result. The ggH, VBF, and $\mathrm{t\bar{t}H}$ processes are fixed to their SM predictions. The results are summarized in Table 1. The observed (expected) signal strength for the VH process is $\mu_{\mathrm{VH}} = 0.72^{+0.75}_{-0.71}$ ($1.00^{+0.67}_{-0.62}$), and the observed (expected) signal strength for the VZ process is $\mu_{\mathrm{VZ}} = 0.09^{+0.63}_{-0.63}$ ($1.00^{+0.58}_{-0.58}$). This corresponds to an observed (expected) significance with respect to the background-only hypothesis of 1.00 (1.64) σ for the $\mathrm{V(qq)H(b\bar{b})}$ process and 0.15 (1.76) σ for the $\mathrm{V(qq)Z(b\bar{b})}$ process. Tabulated results are provided in the HEPData record for this analysis [93].

Table 1: Fitted signal strengths and their total uncertainties for the VH and VZ processes, shown individually for each data-taking period and for the combined dataset.

	$\mathcal{L}$ [fb^{-1}]	μ_{VH}	μ_{VZ}
Early 2016	19.5	$1.02^{+2.52}_{-2.23}$	$-0.15^{+1.77}_{-1.77}$
Late 2016	16.8	$1.34^{+2.20}_{-1.87}$	$-0.83^{+1.53}_{-1.53}$
2017	41.5	$0.00^{+1.26}_{-1.18}$	$1.20^{+1.28}_{-1.28}$
2018	59.8	$1.04^{+1.22}_{-1.10}$	$-0.40^{+0.92}_{-0.92}$
Combined	138.0	$0.72^{+0.75}_{-0.71}$	$0.09^{+0.63}_{-0.63}$

8 Summary

A search for standard model Higgs boson (H) candidates with high transverse momentum (p_{T}) decaying to bottom quark pairs ($\mathrm{b\bar{b}}$) in association with a hadronically decaying W or Z (V) boson at the LHC has been presented. The analysis identifies collision events containing boosted hadronic jets with $p_{\mathrm{T}} > 450\,\mathrm{GeV}$ and with substructure and flavor properties characteristic of $\mathrm{H} \to \mathrm{b\bar{b}}$ and hadronic V decays. The signal strength for the $\mathrm{V(qq)H(b\bar{b})}$ process extracted from a maximum likelihood fit to the data in the large-radius jet mass distribution is $\mu_{\mathrm{VH}} = 0.72^{+0.75}_{-0.71}$ including statistical and systematic uncertainties. This corresponds to a significance of 1.00 standard deviations (σ), compared to 1.64 σ expected. The sensitivity of this measurement is primarily limited by the amount of data available.

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A. Hayrapetyan, V. Makarenko, A. Tumasyan[1]

Institut für Hochenergiephysik, Vienna, Austria
W. Adam, J.W. Andrejkovic, L. Benato, T. Bergauer, M. Dragicevic, C. Giordano, P.S. Hussain, M. Jeitler[2], N. Krammer, A. Li, D. Liko, M. Matthewman, I. Mikulec, J. Schieck[2], R. Schöfbeck[2], D. Schwarz, M. Shooshtari, M. Sonawane, W. Waltenberger, C.-E. Wulz[2]

Universiteit Antwerpen, Antwerpen, Belgium
T. Janssen, H. Kwon, D. Ocampo Henao, T. Van Laer, P. Van Mechelen

Vrije Universiteit Brussel, Brussel, Belgium
J. Bierkens, N. Breugelmans, J. D'Hondt, S. Dansana, A. De Moor, M. Delcourt, F. Heyen, Y. Hong, P. Kashko, S. Lowette, I. Makarenko, D. Müller, J. Song, S. Tavernier, M. Tytgat[3], G.P. Van Onsem, S. Van Putte, D. Vannerom

Université Libre de Bruxelles, Bruxelles, Belgium
B. Bilin, B. Clerbaux, A.K. Das, I. De Bruyn, G. De Lentdecker, H. Evard, L. Favart, P. Gianneios, A. Khalilzadeh, F.A. Khan, A. Malara, M.A. Shahzad, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer, F. Zhang

Ghent University, Ghent, Belgium
M. De Coen, D. Dobur, G. Gokbulut, J. Knolle, D. Marckx, K. Skovpen, N. Van Den Bossche, J. van der Linden, J. Vandenbroeck, L. Wezenbeek

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Bein, A. Benecke, A. Bethani, G. Bruno, A. Cappati, J. De Favereau De Jeneret, C. Delaere, A. Giammanco, A.O. Guzel, V. Lemaitre, J. Lidrych, P. Malek, P. Mastrapasqua, S. Turkcapar

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, M. Barroso Ferreira Filho, E. Coelho, C. Hensel, T. Menezes De Oliveira, C. Mora Herrera[4], P. Rebello Teles, M. Soeiro, E.J. Tonelli Manganote[5], A. Vilela Pereira[4]

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[6], M. Costa Reis, E.M. Da Costa, G.G. Da Silveira[7], D. De Jesus Damiao, S. Fonseca De Souza, R. Gomes De Souza, S. S. Jesus, T. Laux Kuhn[7], M. Macedo, K. Mota Amarilo, L. Mundim, H. Nogima, J.P. Pinheiro, A. Santoro, A. Sznajder, M. Thiel, F. Torres Da Silva De Araujo[8]

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil
C.A. Bernardes[7], F. Damas, T.R. Fernandez Perez Tomei, E.M. Gregores, B. Lopes Da Costa, I. Maietto Silverio, P.G. Mercadante, S.F. Novaes, B. Orzari, Sandra S. Padula, V. Scheurer

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
A. Aleksandrov, G. Antchev, P. Danev, R. Hadjiiska, P. Iaydjiev, M. Shopova, G. Sultanov

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

Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile
S. Keshri, D. Laroze, S. Thakur

Universidad Tecnica Federico Santa Maria, Valparaiso, Chile
W. Brooks

Beihang University, Beijing, China
T. Cheng, T. Javaid, L. Wang, L. Yuan

Department of Physics, Tsinghua University, Beijing, China
Z. Hu, Z. Liang, J. Liu, X. Wang

Institute of High Energy Physics, Beijing, China
G.M. Chen[9], H.S. Chen[9], M. Chen[9], Y. Chen, Q. Hou, X. Hou, F. Iemmi, C.H. Jiang, A. Kapoor[10], H. Liao, G. Liu, Z.-A. Liu[11], J.N. Song[11], S. Song, J. Tao, C. Wang[9], J. Wang, H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. Ban, A. Carvalho Antunes De Oliveira, S. Deng, B. Guo, Q. Guo, C. Jiang, A. Levin, C. Li, Q. Li, Y. Mao, S. Qian, S.J. Qian, X. Qin, C. Quaranta, X. Sun, D. Wang, J. Wang, H. Yang, M. Zhang, Y. Zhao, C. Zhou

State Key Laboratory of Nuclear Physics and Technology, Institute of Quantum Matter, South China Normal University, Guangzhou, China
S. Yang

Sun Yat-Sen University, Guangzhou, China
Z. You

University of Science and Technology of China, Hefei, China
K. Jaffel, N. Lu

Nanjing Normal University, Nanjing, China
G. Bauer[12,13], Z. Cui[13], B. Li[14], H. Wang, K. Yi[15], J. Zhang

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

Zhejiang University, Hangzhou, Zhejiang, China
Z. Lin, C. Lu, M. Xiao[16]

Universidad de Los Andes, Bogota, Colombia
C. Avila, D.A. Barbosa Trujillo, A. Cabrera, C. Florez, J. Fraga, J.A. Reyes Vega

Universidad de Antioquia, Medellin, Colombia
C. Rendón, M. Rodriguez, A.A. Ruales Barbosa, J.D. Ruiz Alvarez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
N. Godinovic, D. Lelas, A. Sculac

University of Split, Faculty of Science, Split, Croatia
M. Kovac, A. Petkovic, T. Sculac

Institute Rudjer Boskovic, Zagreb, Croatia
P. Bargassa, V. Brigljevic, B.K. Chitroda, D. Ferencek, K. Jakovcic, A. Starodumov, T. Susa

University of Cyprus, Nicosia, Cyprus
A. Attikis, K. Christoforou, A. Hadjiagapiou, C. Leonidou, C. Nicolaou, L. Paizanos, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, A. Stepennov

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

Escuela Politecnica Nacional, Quito, Ecuador
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, Egypt
S. Khalil[17], E. Salama[18,19]

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
M. Abdullah Al-Mashad, A. Hussein, H. Mohammed

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
K. Ehataht, M. Kadastik, T. Lange, C. Nielsen, J. Pata, M. Raidal, N. Seeba, L. Tani

Department of Physics, University of Helsinki, Helsinki, Finland
A. Milieva, K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
N. Bin Norjoharuddeen, E. Brücken, F. Garcia, P. Inkaew, K.T.S. Kallonen, R. Kumar Verma, T. Lampén, K. Lassila-Perini, B. Lehtela, S. Lehti, T. Lindén, N.R. Mancilla Xinto, M. Myllymäki, M.m. Rantanen, S. Saariokari, N.T. Toikka, J. Tuominiemi

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland
H. Kirschenmann, P. Luukka, H. Petrow

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, P. Devouge, J.L. Faure, F. Ferri, P. Gaigne, S. Ganjour, P. Gras, G. Hamel de Monchenault, M. Kumar, V. Lohezic, J. Malcles, F. Orlandi, L. Portales, S. Ronchi, M.Ö. Sahin, A. Savoy-Navarro[20], P. Simkina, M. Titov, M. Tornago

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
F. Beaudette, G. Boldrini, P. Busson, C. Charlot, M. Chiusi, T.D. Cuisset, O. Davignon, A. De Wit, T. Debnath, I.T. Ehle, B.A. Fontana Santos Alves, S. Ghosh, A. Gilbert, R. Granier de Cassagnac, L. Kalipoliti, M. Manoni, M. Nguyen, S. Obraztsov, C. Ochando, R. Salerno, J.B. Sauvan, Y. Sirois, G. Sokmen, L. Urda Gómez, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[21], J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard,

G. Coulon, S. Falke, U. Goerlach, R. Haeberle, A.-C. Le Bihan, M. Meena, O. Poncet, G. Saha, P. Vaucelle

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

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
D. Amram, S. Beauceron, B. Blancon, G. Boudoul, N. Chanon, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, C. Greenberg, G. Grenier, B. Ille, E. Jourd'huy, I.B. Laktineh, M. Lethuillier, B. Massoteau, L. Mirabito, A. Purohit, M. Vander Donckt, J. Xiao

Georgian Technical University, Tbilisi, Georgia
I. Lomidze, T. Toriashvili[22], Z. Tsamalaidze[23]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
V. Botta, S. Consuegra Rodríguez, L. Feld, K. Klein, M. Lipinski, D. Meuser, P. Nattland, V. Oppenländer, A. Pauls, D. Pérez Adán, N. Röwert, M. Teroerde

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
C. Daumann, S. Diekmann, A. Dodonova, N. Eich, D. Eliseev, F. Engelke, J. Erdmann, M. Erdmann, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, A. Jung, N. Kumar, M.y. Lee, F. Mausolf, M. Merschmeyer, A. Meyer, F. Nowotny, A. Pozdnyakov, W. Redjeb, H. Reithler, U. Sarkar, V. Sarkisovi, A. Schmidt, C. Seth, A. Sharma, J.L. Spah, V. Vaulin, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
M.R. Beckers, C. Dziwok, G. Flügge, N. Hoeflich, T. Kress, A. Nowack, O. Pooth, A. Stahl, A. Zotz

Deutsches Elektronen-Synchrotron, Hamburg, Germany
H. Aarup Petersen, A. Abel, M. Aldaya Martin, J. Alimena, S. Amoroso, Y. An, I. Andreev, J. Bach, S. Baxter, M. Bayatmakou, H. Becerril Gonzalez, O. Behnke, A. Belvedere, F. Blekman[24], K. Borras[25], A. Campbell, S. Chatterjee, L.X. Coll Saravia, G. Eckerlin, D. Eckstein, E. Gallo[24], A. Geiser, V. Guglielmi, M. Guthoff, A. Hinzmann, L. Jeppe, M. Kasemann, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, W. Lange, D. Leyva Pernia, K.-Y. Lin, K. Lipka[26], W. Lohmann[27], J. Malvaso, R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, A.B. Meyer, G. Milella, K. Moral Figueroa, A. Mussgiller, L.P. Nair, J. Niedziela, A. Nürnberg, J. Park, E. Ranken, A. Raspereza, D. Rastorguev, L. Rygaard, M. Scham[28,25], S. Schnake[25], P. Schütze, C. Schwanenberger[24], D. Selivanova, K. Sharko, M. Shchedrolosiev, D. Stafford, M. Torkian, F. Vazzoler, A. Ventura Barroso, R. Walsh, D. Wang, Q. Wang, K. Wichmann, L. Wiens[25], C. Wissing, Y. Yang, S. Zakharov, A. Zimermmane Castro Santos

University of Hamburg, Hamburg, Germany
A.R. Alves Andrade, M. Antonello, S. Bollweg, M. Bonanomi, K. El Morabit, Y. Fischer, M. Frahm, E. Garutti, A. Grohsjean, A.A. Guvenli, J. Haller, D. Hundhausen, G. Kasieczka, P. Keicher, R. Klanner, W. Korcari, T. Kramer, C.c. Kuo, F. Labe, J. Lange, A. Lobanov, L. Moureaux, A. Nigamova, K. Nikolopoulos, A. Paasch, K.J. Pena Rodriguez, N. Prouvost, T. Quadfasel,

B. Raciti, M. Rieger, D. Savoiu, P. Schleper, M. Schröder, J. Schwandt, M. Sommerhalder, H. Stadie, G. Steinbrück, R. Ward, B. Wiederspan, M. Wolf

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
S. Brommer, E. Butz, Y.M. Chen, T. Chwalek, A. Dierlamm, G.G. Dincer, U. Elicabuk, N. Faltermann, M. Giffels, A. Gottmann, F. Hartmann[29], M. Horzela, F. Hummer, U. Husemann, J. Kieseler, M. Klute, R. Kunnilan Muhammed Rafeek, O. Lavoryk, J.M. Lawhorn, A. Lintuluoto, S. Maier, M. Mormile, Th. Müller, E. Pfeffer, M. Presilla, G. Quast, K. Rabbertz, B. Regnery, R. Schmieder, N. Shadskiy, I. Shvetsov, H.J. Simonis, L. Sowa, L. Stockmeier, K. Tauqeer, M. Toms, B. Topko, N. Trevisani, C. Verstege, T. Voigtländer, R.F. Von Cube, J. Von Den Driesch, M. Wassmer, R. Wolf, W.D. Zeuner, X. Zuo

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, A. Kyriakis

National and Kapodistrian University of Athens, Athens, Greece
G. Melachroinos, Z. Painesis, I. Paraskevas, N. Saoulidou, K. Theofilatos, E. Tziaferi, E. Tzovara, K. Vellidis, I. Zisopoulos

National Technical University of Athens, Athens, Greece
T. Chatzistavrou, G. Karapostoli, K. Kousouris, E. Siamarkou, G. Tsipolitis

University of Ioánnina, Ioánnina, Greece
I. Bestintzanos, I. Evangelou, C. Foudas, P. Katsoulis, P. Kokkas, P.G. Kosmoglou Kioseoglou, N. Manthos, I. Papadopoulos, J. Strologas

HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
D. Druzhkin, C. Hajdu, D. Horvath[30,31], K. Márton, A.J. Rádl[32], F. Sikler, V. Veszpremi

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanád, K. Farkas, A. Fehérkuti[33], M.M.A. Gadallah[34], Á. Kadlecsik, M. León Coello, G. Pásztor, G.I. Veres

Faculty of Informatics, University of Debrecen, Debrecen, Hungary
B. Ujvari, G. Zilizi

HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary
G. Bencze, S. Czellar, J. Molnar, Z. Szillasi

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
T. Csorgo[33], F. Nemes[33], T. Novak, I. Szanyi[35]

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra[36], A. Kaur, A. Kaur, H. Kaur, M. Kaur, S. Kumar, T. Sheokand, J.B. Singh, A. Singla

University of Delhi, Delhi, India
A. Bhardwaj, A. Chhetri, B.C. Choudhary, A. Kumar, A. Kumar, M. Naimuddin, S. Phor, K. Ranjan, M.K. Saini

University of Hyderabad, Hyderabad, India

S. Acharya[37], B. Gomber[37], B. Sahu[37]

Indian Institute of Technology Kanpur, Kanpur, India
S. Mukherjee

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
S. Baradia, S. Bhattacharya, S. Das Gupta, S. Dutta, S. Dutta, S. Sarkar

Indian Institute of Technology Madras, Madras, India
M.M. Ameen, P.K. Behera, S. Chatterjee, G. Dash, A. Dattamunsi, P. Jana, P. Kalbhor, S. Kamble, J.R. Komaragiri[38], T. Mishra, P.R. Pujahari, A.K. Sikdar, R.K. Singh, P. Verma, S. Verma, A. Vijay

IISER Mohali, India, Mohali, India
B.K. Sirasva

Tata Institute of Fundamental Research-A, Mumbai, India
L. Bhatt, S. Dugad, G.B. Mohanty, M. Shelake, P. Suryadevara

Tata Institute of Fundamental Research-B, Mumbai, India
A. Bala, S. Banerjee, S. Barman[39], R.M. Chatterjee, M. Guchait, Sh. Jain, A. Jaiswal, B.M. Joshi, S. Kumar, M. Maity[39], G. Majumder, K. Mazumdar, S. Parolia, R. Saxena, A. Thachayath

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India
S. Bahinipati[40], D. Maity[41], P. Mal, K. Naskar[41], A. Nayak[41], S. Nayak, K. Pal, R. Raturi, P. Sadangi, S.K. Swain, S. Varghese[41], D. Vats[41]

Indian Institute of Science Education and Research (IISER), Pune, India
A. Alpana, S. Dube, P. Hazarika, B. Kansal, A. Laha, R. Sharma, S. Sharma, K.Y. Vaish

Indian Institute of Technology Hyderabad, Telangana, India
S. Ghosh

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[42], A. Jafari[43], V. Sedighzadeh Dalavi, M. Zeinali[44]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Bashiri, S. Chenarani[45], S.M. Etesami, Y. Hosseini, M. Khakzad, E. Khazaie, M. Mohammadi Najafabadi, S. Tizchang[46]

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], M. Barbieri[a,b], M. Buonsante[a,b], A. Colaleo[a,b], D. Creanza[a,c], N. De Filippis[a,c], M. De Palma[a,b], W. Elmetenawee[a,b,47], N. Ferrara[a,c], L. Fiore[a], L. Longo[a], M. Louka[a,b], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a], V. Mastrapasqua[a,b], S. My[a,b], F. Nenna[a,b], S. Nuzzo[a,b], A. Pellecchia[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a,b], D. Ramos[a], A. Ranieri[a], L. Silvestris[a], F.M. Simone[a,c], Ü. Sözbilir[a], A. Stamerra[a,b], D. Troiano[a,b], R. Venditti[a,b], P. Verwilligen[a], A. Zaza[a,b]

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

G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], P. Capiluppi[a,b], F.R. Cavallo[a], M. Cuffiani[a,b], G.M. Dallavalle[a], T. Diotalevi[a,b], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a], P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], M. Lorusso[a,b], L. Lunerti[a], S. Marcellini[a], G. Masetti[a], F.L. Navarria[a,b], G. Paggi[a,b], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], S. Rossi Tisbeni[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,48], A. Di Mattia[a], A. Lapertosa[a], R. Potenza[a,b], A. Tricomi[a,b,48]

INFN Sezione di Firenze[a], Università di Firenze[b], Firenze, Italy
J. Altork[a,b], P. Assiouras[a], G. Barbagli[a], G. Bardelli[a], M. Bartolini[a,b], A. Calandri[a,b], B. Camaiani[a,b], A. Cassese[a], R. Ceccarelli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], L. Damenti[a,b], E. Focardi[a,b], T. Kello[a], G. Latino[a,b], P. Lenzi[a,b], M. Lizzo[a], M. Meschini[a], S. Paoletti[a], A. Papanastassiou[a,b], G. Sguazzoni[a], L. Viliani[a]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, S. Meola[49], D. Piccolo

INFN Sezione di Genova[a], Università di Genova[b], Genova, Italy
M. Alves Gallo Pereira[a], F. Ferro[a], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca[a], Università di Milano-Bicocca[b], Milano, Italy
A. Benaglia[a], F. Brivio[a], V. Camagni[a,b], F. Cetorelli[a,b], F. De Guio[a,b], M.E. Dinardo[a,b], P. Dini[a], S. Gennai[a], R. Gerosa[a,b], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a], M.R. Kim[a], G. Lavizzari[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], S. Palluotto[a,b], D. Pedrini[a], A. Perego[a,b], G. Pizzati[a,b], 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; Scuola Superiore Meridionale (SSM)[d], Napoli, Italy
S. Buontempo[a], C. Di Fraia[a,b], F. Fabozzi[a,c], L. Favilla[a,d], A.O.M. Iorio[a,b], L. Lista[a,b,50], P. Paolucci[a,29], B. Rossi[a]

INFN Sezione di Padova[a], Università di Padova[b], Padova, Italy; Universita degli Studi di Cagliari[c], Cagliari, Italy
P. Azzi[a], N. Bacchetta[a,51], M. Bellato[a], P. Bortignon[a,c], G. Bortolato[a,b], A.C.M. Bulla[a,c], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a,52], F. Gasparini[a,b], U. Gasparini[a,b], S. Giorgetti[a], E. Lusiani[a], M. Margoni[a,b], A.T. Meneguzzo[a,b], J. Pazzini[a,b], P. Ronchese[a,b], R. Rossin[a,b], M. Tosi[a,b], A. Triossi[a,b], S. Ventura[a], 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
A. Braghieri[a], S. Calzaferri[a], P. Montagna[a,b], M. Pelliccioni[a], V. Re[a], 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
S. Ajmal[a,b], M.E. Ascioti[a,b], G.M. Bilei[a], C. Carrivale[a,b], D. Ciangottini[a,b], L. Della Penna[a,b], L. Fanò[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,53], 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
C. Aimè[a,b], C.A. Alexe[a,c], P. Asenov[a,b], P. Azzurri[a], G. Bagliesi[a], R. Bhattacharya[a], L. Bianchini[a,b], T. Boccali[a], E. Bossini[a], D. Bruschini[a,c], L. Calligaris[a,b], R. Castaldi[a], F. Cattafesta[a,c], M.A. Ciocci[a,d], M. Cipriani[a,b], R. Dell'Orso[a], S. Donato[a,b], R. Forti[a,b], A. Giassi[a], F. Ligabue[a,c], A.C. Marini[a,b], D. Matos Figueiredo[a], A. Messineo[a,b], S. Mishra[a], V.K. Muraleedharan Nair Bindhu[a,b], S. Nandan[a], F. Palla[a], M. Riggirello[a,c], A. Rizzi[a,b], G. Rolandi[a,c], S. Roy Chowdhury[a,54], T. Sarkar[a], A. Scribano[a], P. Solanki[a,b], P. Spagnolo[a], F. Tenchini[a,b], R. Tenchini[a], G. Tonelli[a,b], N. Turini[a,d], F. Vaselli[a,c], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma[a], Sapienza Università di Roma[b], Roma, Italy
P. Akrap[a,b], C. Basile[a,b], S.C. Behera[a], F. Cavallari[a], L. Cunqueiro Mendez[a,b], F. De Riggi[a,b], D. Del Re[a,b], E. Di Marco[a], M. Diemoz[a], F. Errico[a], L. Frosina[a,b], R. Gargiulo[a,b], B. Harikrishnan[a,b], F. Lombardi[a,b], E. Longo[a,b], L. Martikainen[a,b], J. Mijuskovic[a,b], G. Organtini[a,b], N. Palmeri[a,b], R. Paramatti[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], L. Soffi[a], V. Vladimirov[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,c], R. Bellan[a,b], A. Bellora[a,b], C. Biino[a], C. Borca[a,b], N. Cartiglia[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], L. Finco[a], M. Grippo[a,b], B. Kiani[a,b], L. Lanteri[a,b], F. Legger[a], F. Luongo[a,b], C. Mariotti[a], S. Maselli[a], A. Mecca[a,b], L. Menzio[a,b], P. Meridiani[a], E. Migliore[a,b], M. Monteno[a], M.M. Obertino[a,b], G. Ortona[a], L. Pacher[a,b], N. Pastrone[a], M. Ruspa[a,c], F. Siviero[a,b], V. Sola[a,b], A. Solano[a,b], A. Staiano[a], C. Tarricone[a,b], D. Trocino[a], G. Umoret[a,b], E. Vlasov[a,b], R. White[a,b]

INFN Sezione di Trieste[a], Università di Trieste[b], Trieste, Italy
J. Babbar[a,b], S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], K. De Leo[a], G. Della Ricca[a,b], R. Delli Gatti[a,b]

Kyungpook National University, Daegu, Korea
S. Dogra, J. Hong, J. Kim, T. Kim, D. Lee, H. Lee, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S. Sekmen, B. Tae, Y.C. Yang

Department of Mathematics and Physics - GWNU, Gangneung, Korea
M.S. Kim

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
G. Bak, P. Gwak, H. Kim, D.H. Moon, J. Seo

Hanyang University, Seoul, Korea
E. Asilar, F. Carnevali, J. Choi[55], T.J. Kim, Y. Ryou

Korea University, Seoul, Korea
S. Ha, S. Han, B. Hong, J. Kim, K. Lee, K.S. Lee, S. Lee, J. Yoo

Kyung Hee University, Department of Physics, Seoul, Korea
J. Goh, J. Shin, S. Yang

Sejong University, Seoul, Korea
Y. Kang, H. S. Kim, Y. Kim, S. Lee

Seoul National University, Seoul, Korea
J. Almond, J.H. Bhyun, J. Choi, J. Choi, W. Jun, H. Kim, J. Kim, T. Kim, Y. Kim, Y.W. Kim, S. Ko, H. Lee, J. Lee, J. Lee, B.H. Oh, S.B. Oh, J. Shin, U.K. Yang, I. Yoon

University of Seoul, Seoul, Korea
W. Jang, D.Y. Kang, D. Kim, S. Kim, B. Ko, J.S.H. Lee, Y. Lee, I.C. Park, Y. Roh, I.J. Watson

Yonsei University, Department of Physics, Seoul, Korea
G. Cho, K. Hwang, B. Kim, S. Kim, K. Lee, H.D. Yoo

Sungkyunkwan University, Suwon, Korea
M. Choi, Y. Lee, I. Yu

College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait
T. Beyrouthy, Y. Gharbia

Kuwait University - College of Science - Department of Physics, Safat, Kuwait
F. Alazemi

Riga Technical University, Riga, Latvia
K. Dreimanis, O.M. Eberlins, A. Gaile, C. Munoz Diaz, D. Osite, G. Pikurs, R. Plese, A. Potrebko, M. Seidel, D. Sidiropoulos Kontos

University of Latvia (LU), Riga, Latvia
N.R. Strautnieks

Vilnius University, Vilnius, Lithuania
M. Ambrozas, A. Juodagalvis, S. Nargelas, A. Rinkevicius, G. Tamulaitis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Yusuff[56], Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, A. Cota Rodriguez, L.E. Cuevas Picos, H.A. Encinas Acosta, L.G. Gallegos Maríñez, J.A. Murillo Quijada, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
G. Ayala, H. Castilla-Valdez, H. Crotte Ledesma, R. Lopez-Fernandez, J. Mejia Guisao, R. Reyes-Almanza, A. Sánchez Hernández

Universidad Iberoamericana, Mexico City, Mexico
C. Oropeza Barrera, D.L. Ramirez Guadarrama, M. Ramírez García

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
I. Bautista, F.E. Neri Huerta, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

University of Montenegro, Podgorica, Montenegro
I. Bubanja, N. Raicevic

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

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, W.A. Khan

AGH University of Krakow, Krakow, Poland
V. Avati, L. Forthomme, L. Grzanka, M. Malawski, K. Piotrzkowski

National Centre for Nuclear Research, Swierk, Poland
M. Bluj, M. Górski, M. Kazana, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, A. Muhammad

Warsaw University of Technology, Warsaw, Poland
P. Fokow, K. Pozniak, W. Zabolotny

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, D. Bastos, C. Beirão Da Cruz E Silva, A. Boletti, M. Bozzo, T. Camporesi, G. Da Molin, M. Gallinaro, J. Hollar, N. Leonardo, G.B. Marozzo, A. Petrilli, M. Pisano, J. Seixas, J. Varela, J.W. Wulff

Faculty of Physics, University of Belgrade, Belgrade, Serbia
P. Adzic, L. Markovic, P. Milenovic, V. Milosevic

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
D. Devetak, M. Dordevic, J. Milosevic, L. Nadderd, V. Rekovic, M. Stojanovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Alcalde Martinez, J. Alcaraz Maestre, Cristina F. Bedoya, J.A. Brochero Cifuentes, Oliver M. Carretero, M. Cepeda, M. Cerrada, N. Colino, J. Cuchillo Ortega, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, D. Fernández Del Val, J.P. Fernández Ramos, J. Flix, M.C. Fouz, M. Gonzalez Hernandez, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. Llorente Merino, C. Martin Perez, E. Martin Viscasillas, D. Moran, C. M. Morcillo Perez, R. Paz Herrera, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, J. Vazquez Escobar

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. Ayllon Torresano, A. Cardini, J. Cuevas, J. Del Riego Badas, D. Estrada Acevedo, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, P. Leguina, M. Obeso Menendez, E. Palencia Cortezon, J. Prado Pico, A. Soto Rodríguez, C. Vico Villalba, P. Vischia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
S. Blanco Fernández, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, G. Gomez, C. Lasaosa García, R. Lopez Ruiz, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, E. Navarrete Ramos, J. Piedra Gomez, C. Quintana San Emeterio, L. Scodellaro, I. Vila, R. Vilar Cortabitarte, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
B. Kailasapathy[57], D.D.C. Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G.D. Dharmaratna[58], K. Liyanage, N. Perera

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, C. Amendola, R. Ardino, E. Auffray, J. Baechler, D. Barney, J. Bendavid, M. Bianco, A. Bocci, L. Borgonovi, C. Botta, A. Bragagnolo, C.E. Brown, C. Caillol, G. Cerminara, P. Connor, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, P.J. Fernández Manteca, W. Funk, A. Gaddi, S. Giani, D. Gigi, K. Gill, F. Glege, M. Glowacki, A. Gruber, J. Hegeman, J.K. Heikkilä, R. Hofsaess, B. Huber, V. Innocente, T. James, P. Janot, O. Kaluzinska, O. Karacheban[27], G. Karathanasis, S. Laurila, P. Lecoq, C. Lourenço, A.-M. Lyon, M. Magherini, L. Malgeri, M. Mannelli, A. Mehta, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, M. Migliorini, F. Monti, F. Moortgat, M. Mulders, M. Musich, I. Neutelings, S. Orfanelli, F. Pantaleo, M. Pari, G. Petrucciani, A. Pfeiffer, M. Pierini, M. Pitt, H. Qu, D. Rabady, A. Reimers, B. Ribeiro Lopes, F. Riti, P. Rosado, M. Rovere, H. Sakulin, R. Salvatico, S. Sanchez Cruz, S. Scarfi, M. Selvaggi, A. Sharma, K. Shchelina, P. Silva, P. Sphicas[59], A.G. Stahl Leiton, A. Steen, S. Summers, D. Treille, P. Tropea, E. Vernazza, J. Wanczyk[60], J. Wang, S. Wuchterl, M. Zarucki, P. Zehetner, P. Zejdl, G. Zevi Della Porta

PSI Center for Neutron and Muon Sciences, Villigen, Switzerland
T. Bevilacqua[61], L. Caminada[61], W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, U. Langenegger, L. Noehte[61], T. Rohe, A. Samalan

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
T.K. Aarrestad, M. Backhaus, G. Bonomelli, C. Cazzaniga, K. Datta, P. De Bryas Dexmiers D'archiacchiac[60], A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, K. Gedia, F. Glessgen, C. Grab, N. Härringer, T.G. Harte, W. Lustermann, M. Malucchi, R.A. Manzoni, M. Marchegiani, L. Marchese, A. Mascellani[60], F. Nessi-Tedaldi, F. Pauss, V. Perovic, B. Ristic, R. Seidita, J. Steggemann[60], A. Tarabini, D. Valsecchi, R. Wallny

Universität Zürich, Zurich, Switzerland
C. Amsler[62], P. Bärtschi, F. Bilandzija, M.F. Canelli, G. Celotto, K. Cormier, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, T.H. Kwok, S. Leontsinis, V. Lukashenko, A. Macchiolo, F. Meng, M. Missiroli, J. Motta, P. Robmann, M. Senger, E. Shokr, F. Stäger, R. Tramontano, P. Viscone

National Central University, Chung-Li, Taiwan
D. Bhowmik, C.M. Kuo, P.K. Rout, S. Taj, P.C. Tiwari[38]

National Taiwan University (NTU), Taipei, Taiwan
L. Ceard, K.F. Chen, Z.g. Chen, A. De Iorio, W.-S. Hou, T.h. Hsu, Y.w. Kao, S. Karmakar, G. Kole, Y.y. Li, R.-S. Lu, E. Paganis, X.f. Su, J. Thomas-Wilsker, L.s. Tsai, D. Tsionou, H.y. Wu, E. Yazgan

High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand
C. Asawatangtrakuldee, N. Srimanobhas

Tunis El Manar University, Tunis, Tunisia

Y. Maghrbi

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
D. Agyel, F. Dolek, I. Dumanoglu[63], Y. Guler[64], E. Gurpinar Guler[64], C. Isik, O. Kara, A. Kayis Topaksu, Y. Komurcu, G. Onengut, K. Ozdemir[65], B. Tali[66], U.G. Tok, E. Uslan, I.S. Zorbakir

Middle East Technical University, Physics Department, Ankara, Turkey
M. Yalvac[67]

Bogazici University, Istanbul, Turkey
B. Akgun, I.O. Atakisi[68], E. Gülmez, M. Kaya[69], O. Kaya[70], M.A. Sarkisla[71], S. Tekten[72]

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak[63,73], S. Sen[74]

Istanbul University, Istanbul, Turkey
O. Aydilek[75], B. Hacisahinoglu, I. Hos[76], B. Kaynak, S. Ozkorucuklu, O. Potok, H. Sert, C. Simsek, C. Zorbilmez

Yildiz Technical University, Istanbul, Turkey
S. Cerci, C. Dozen[77], B. Isildak[78], E. Simsek, D. Sunar Cerci, T. Yetkin[77]

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine
A. Boyaryntsev, O. Dadazhanova, B. Grynyov

National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom
J.J. Brooke, A. Bundock, F. Bury, E. Clement, D. Cussans, D. Dharmender, H. Flacher, J. Goldstein, H.F. Heath, M.-L. Holmberg, L. Kreczko, S. Paramesvaran, L. Robertshaw, M.S. Sanjrani[42], J. Segal, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom
A.H. Ball, K.W. Bell, A. Belyaev[79], C. Brew, R.M. Brown, D.J.A. Cockerill, A. Elliot, K.V. Ellis, J. Gajownik, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, M. Moallemi, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, A.R. Sahasransu, G. Salvi, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, K.C. Whalen, T. Williams

Imperial College, London, United Kingdom
I. Andreou, R. Bainbridge, P. Bloch, O. Buchmuller, C.A. Carrillo Montoya, D. Colling, J.S. Dancu, I. Das, P. Dauncey, G. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, H.R. Hoorani, A. Howard, G. Iles, C.R. Knight, P. Krueper, J. Langford, K.H. Law, J. León Holgado, E. Leutgeb, L. Lyons, A.-M. Magnan, B. Maier, S. Mallios, A. Mastronikolis, M. Mieskolainen, J. Nash[80], M. Pesaresi, P.B. Pradeep, B.C. Radburn-Smith, A. Richards, A. Rose, L. Russell, K. Savva, C. Seez, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, T. Virdee[29], M. Vojinovic, N. Wardle, D. Winterbottom

Brunel University, Uxbridge, United Kingdom
J.E. Cole, A. Khan, P. Kyberd, I.D. Reid

Baylor University, Waco, Texas, USA
S. Abdullin, A. Brinkerhoff, E. Collins, M.R. Darwish, J. Dittmann, K. Hatakeyama, V. Hegde, J. Hiltbrand, B. McMaster, J. Samudio, S. Sawant, C. Sutantawibul, J. Wilson

Bethel University, St. Paul, Minnesota, USA
J.M. Hogan[81]

Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez, S. Raj, A.E. Simsek, S.S. Yu

The University of Alabama, Tuscaloosa, Alabama, USA
B. Bam, A. Buchot Perraguin, S. Campbell, R. Chudasama, S.I. Cooper, C. Crovella, G. Fidalgo, S.V. Gleyzer, A. Khukhunaishvili, K. Matchev, E. Pearson, C.U. Perez, P. Rumerio[82], E. Usai, R. Yi

Boston University, Boston, Massachusetts, USA
S. Cholak, G. De Castro, Z. Demiragli, C. Erice, C. Fangmeier, C. Fernandez Madrazo, E. Fontanesi, J. Fulcher, F. Golf, S. Jeon, J. O'Cain, I. Reed, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, E. Wurtz, A.G. Zecchinelli

Brown University, Providence, Rhode Island, USA
G. Barone, G. Benelli, D. Cutts, S. Ellis, L. Gouskos, M. Hadley, U. Heintz, K.W. Ho, T. Kwon, L. Lambrecht, G. Landsberg, K.T. Lau, J. Luo, S. Mondal, J. Roloff, T. Russell, S. Sagir[83], X. Shen, M. Stamenkovic, N. Venkatasubramanian

University of California, Davis, Davis, California, USA
S. Abbott, B. Barton, R. Breedon, H. Cai, M. Calderon De La Barca Sanchez, E. Cannaert, M. Chertok, M. Citron, J. Conway, P.T. Cox, R. Erbacher, O. Kukral, G. Mocellin, S. Ostrom, I. Salazar Segovia, J.S. Tafoya Vargas, W. Wei, S. Yoo

University of California, Los Angeles, California, USA
K. Adamidis, M. Bachtis, D. Campos, R. Cousins, A. Datta, G. Flores Avila, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, Y.f. Lo, E. Manca, A. Nunez Del Prado, D. Saltzberg, V. Valuev

University of California, Riverside, Riverside, California, USA
R. Clare, J.W. Gary, G. Hanson

University of California, San Diego, La Jolla, California, USA
A. Aportela, A. Arora, J.G. Branson, S. Cittolin, S. Cooperstein, B. D'Anzi, D. Diaz, J. Duarte, L. Giannini, Y. Gu, J. Guiang, V. Krutelyov, R. Lee, J. Letts, H. Li, M. Masciovecchio, F. Mokhtar, S. Mukherjee, M. Pieri, D. Primosch, M. Quinnan, V. Sharma, M. Tadel, E. Vourliotis, F. Würthwein, A. Yagil, Z. Zhao

University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA
A. Barzdukas, L. Brennan, C. Campagnari, S. Carron Montero[84], K. Downham, C. Grieco, M.M. Hussain, J. Incandela, M.W.K. Lai, A.J. Li, P. Masterson, J. Richman, S.N. Santpur, U. Sarica, R. Schmitz, F. Setti, J. Sheplock, D. Stuart, T.Á. Vámi, X. Yan, D. Zhang

California Institute of Technology, Pasadena, California, USA

A. Albert, S. Bhattacharya, A. Bornheim, O. Cerri, R. Kansal, J. Mao, H.B. Newman, G. Reales Gutiérrez, T. Sievert, M. Spiropulu, J.R. Vlimant, R.A. Wynne, S. Xie

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
J. Alison, S. An, M. Cremonesi, V. Dutta, E.Y. Ertorer, T. Ferguson, T.A. Gómez Espinosa, A. Harilal, A. Kallil Tharayil, M. Kanemura, C. Liu, P. Meiring, T. Mudholkar, S. Murthy, P. Palit, K. Park, M. Paulini, A. Roberts, A. Sanchez, W. Terrill

University of Colorado Boulder, Boulder, Colorado, USA
J.P. Cumalat, W.T. Ford, A. Hart, A. Hassani, S. Kwan, J. Pearkes, C. Savard, N. Schonbeck, K. Stenson, K.A. Ulmer, S.R. Wagner, N. Zipper, D. Zuolo

Cornell University, Ithaca, New York, USA
J. Alexander, X. Chen, J. Dickinson, A. Duquette, J. Fan, X. Fan, J. Grassi, S. Hogan, P. Kotamnives, J. Monroy, G. Niendorf, M. Oshiro, J.R. Patterson, A. Ryd, J. Thom, P. Wittich, R. Zou, L. Zygala

Fermi National Accelerator Laboratory, Batavia, Illinois, USA
M. Albrow, M. Alyari, O. Amram, 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, C. Cosby, G. Cummings, I. Dutta, V.D. Elvira, J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, A. Grummer, S. Grünendahl, D. Guerrero, O. Gutsche, R.M. Harris, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, C. Lee, D. Lincoln, R. Lipton, T. Liu, K. Maeshima, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, D. Noonan, S. Norberg, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[85], C.E. Perez Lara, F. Ravera, A. Reinsvold Hall[86], L. Ristori, M. Safdari, E. Sexton-Kennedy, N. Smith, A. Soha, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Wang, I. Zoi

University of Florida, Gainesville, Florida, USA
C. Aruta, P. Avery, D. Bourilkov, P. Chang, V. Cherepanov, R.D. Field, C. Huh, E. Koenig, M. Kolosova, J. Konigsberg, A. Korytov, N. Menendez, G. Mitselmakher, K. Mohrman, A. Muthirakalayil Madhu, N. Rawal, S. Rosenzweig, V. Sulimov, Y. Takahashi, J. Wang

Florida State University, Tallahassee, Florida, USA
T. Adams, A. Al Kadhim, A. Askew, S. Bower, R. Goff, R. Hashmi, R.S. Kim, T. Kolberg, G. Martinez, M. Mazza, H. Prosper, P.R. Prova, R. Yohay

Florida Institute of Technology, Melbourne, Florida, USA
B. Alsufyani, S. Butalla, S. Das, M. Hohlmann, M. Lavinsky, E. Yanes

University of Illinois Chicago, Chicago, Illinois, USA
M.R. Adams, N. Barnett, A. Baty, C. Bennett, R. Cavanaugh, R. Escobar Franco, O. Evdokimov, C.E. Gerber, H. Gupta, M. Hawksworth, A. Hingrajiya, D.J. Hofman, J.h. Lee, C. Mills, S. Nanda, G. Nigmatkulov, B. Ozek, T. Phan, D. Pilipovic, R. Pradhan, E. Prifti, P. Roy, T. Roy, N. Singh, M.B. Tonjes, N. Varelas, M.A. Wadud, J. Yoo

The University of Iowa, Iowa City, Iowa, USA
M. Alhusseini, D. Blend, K. Dilsiz[87], O.K. Köseyan, A. Mestvirishvili[88], O. Neogi,

H. Ogul[89], Y. Onel, A. Penzo, C. Snyder, E. Tiras[90]

Johns Hopkins University, Baltimore, Maryland, USA
B. Blumenfeld, J. Davis, A.V. Gritsan, L. Kang, S. Kyriacou, P. Maksimovic, M. Roguljic, S. Sekhar, M.V. Srivastav, M. Swartz

The University of Kansas, Lawrence, Kansas, USA
A. Abreu, L.F. Alcerro Alcerro, J. Anguiano, S. Arteaga Escatel, P. Baringer, A. Bean, Z. Flowers, D. Grove, J. King, G. Krintiras, M. Lazarovits, C. Le Mahieu, J. Marquez, M. Murray, M. Nickel, S. Popescu[91], C. Rogan, C. Royon, S. Rudrabhatla, S. Sanders, C. Smith, G. Wilson

Kansas State University, Manhattan, Kansas, USA
B. Allmond, N. Islam, A. Ivanov, K. Kaadze, Y. Maravin, J. Natoli, G.G. Reddy, D. Roy, G. Sorrentino

University of Maryland, College Park, Maryland, USA
A. Baden, A. Belloni, J. Bistany-riebman, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, B. Kronheim, S. Lascio, P. Major, A.C. Mignerey, C. Palmer, C. Papageorgakis, M.M. Paranjpe, E. Popova[92], A. Shevelev, L. Zhang

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
C. Baldenegro Barrera, H. Bossi, S. Bright-Thonney, I.A. Cali, Y.c. Chen, P.c. Chou, M. D'Alfonso, J. Eysermans, C. Freer, G. Gomez-Ceballos, M. Goncharov, G. Grosso, P. Harris, D. Hoang, G.M. Innocenti, D. Kovalskyi, J. Krupa, L. Lavezzo, Y.-J. Lee, K. Long, C. Mcginn, A. Novak, M.I. Park, C. Paus, C. Reissel, C. Roland, G. Roland, S. Rothman, T.a. Sheng, G.S.F. Stephans, D. Walter, Z. Wang, B. Wyslouch, T. J. Yang

University of Minnesota, Minneapolis, Minnesota, USA
B. Crossman, W.J. Jackson, C. Kapsiak, M. Krohn, D. Mahon, J. Mans, B. Marzocchi, R. Rusack, O. Sancar, R. Saradhy, N. Strobbe

University of Nebraska-Lincoln, Lincoln, Nebraska, USA
K. Bloom, D.R. Claes, G. Haza, J. Hossain, C. Joo, I. Kravchenko, A. Rohilla, J.E. Siado, W. Tabb, A. Vagnerini, A. Wightman, F. Yan

State University of New York at Buffalo, Buffalo, New York, USA
H. Bandyopadhyay, L. Hay, H.w. Hsia, I. Iashvili, A. Kalogeropoulos, A. Kharchilava, A. Mandal, M. Morris, D. Nguyen, S. Rappoccio, H. Rejeb Sfar, A. Williams, P. Young, D. Yu

Northeastern University, Boston, Massachusetts, USA
G. Alverson, E. Barberis, J. Bonilla, B. Bylsma, M. Campana, J. Dervan, Y. Haddad, Y. Han, I. Israr, A. Krishna, M. Lu, N. Manganelli, R. Mccarthy, D.M. Morse, T. Orimoto, L. Skinnari, C.S. Thoreson, E. Tsai, D. Wood

Northwestern University, Evanston, Illinois, USA
S. Dittmer, K.A. Hahn, Y. Liu, M. Mcginnis, Y. Miao, D.G. Monk, M.H. Schmitt, A. Taliercio, M. Velasco, J. Wang

University of Notre Dame, Notre Dame, Indiana, USA
G. Agarwal, R. Band, R. Bucci, S. Castells, A. Das, A. Ehnis, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, T. Ivanov, C. Jessop, A. Karneyeu, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, J. Mariano, N. Marinelli, I. Mcalister,

T. McCauley, C. Mcgrady, C. Moore, Y. Musienko[23], H. Nelson, M. Osherson, A. Piccinelli, R. Ruchti, A. Townsend, Y. Wan, M. Wayne, H. Yockey

The Ohio State University, Columbus, Ohio, USA
A. Basnet, M. Carrigan, R. De Los Santos, L.S. Durkin, C. Hill, M. Joyce, M. Nunez Ornelas, D.A. Wenzl, B.L. Winer, B. R. Yates

Princeton University, Princeton, New Jersey, USA
H. Bouchamaoui, P. Das, G. Dezoort, P. Elmer, A. Frankenthal, M. Galli, B. Greenberg, N. Haubrich, K. Kennedy, G. Kopp, Y. Lai, D. Lange, A. Loeliger, D. Marlow, I. Ojalvo, J. Olsen, F. Simpson, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, Puerto Rico, USA
S. Malik, R. Sharma

Purdue University, West Lafayette, Indiana, USA
S. Chandra, R. Chawla, A. Gu, L. Gutay, M. Jones, A.W. Jung, D. Kondratyev, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, N.R. Saha, J.F. Schulte, F. Wang, A. Wildridge, W. Xie, Y. Yao, Y. Zhong

Purdue University Northwest, Hammond, Indiana, USA
N. Parashar, A. Pathak, E. Shumka

Rice University, Houston, Texas, USA
D. Acosta, A. Agrawal, C. Arbour, T. Carnahan, K.M. Ecklund, S. Freed, P. Gardner, F.J.M. Geurts, T. Huang, I. Krommydas, N. Lewis, W. Li, J. Lin, O. Miguel Colin, B.P. Padley, R. Redjimi, J. Rotter, M. Wulansatiti, E. Yigitbasi, Y. Zhang

University of Rochester, Rochester, New York, USA
O. Bessidskaia Bylund, A. Bodek, P. de Barbaro[†], R. Demina, A. Garcia-Bellido, H.S. Hare, O. Hindrichs, N. Parmar, P. Parygin[92], H. Seo, R. Taus

Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
B. Chiarito, J.P. Chou, S.V. Clark, S. Donnelly, D. Gadkari, Y. Gershtein, E. Halkiadakis, C. Houghton, D. Jaroslawski, A. Kobert, S. Konstantinou, I. Laflotte, A. Lath, J. Martins, M. Perez Prada, B. Rand, J. Reichert, P. Saha, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, J. Vora

University of Tennessee, Knoxville, Tennessee, USA
D. Ally, A.G. Delannoy, S. Fiorendi, J. Harris, T. Holmes, A.R. Kanuganti, N. Karunarathna, J. Lawless, L. Lee, E. Nibigira, B. Skipworth, S. Spanier

Texas A&M University, College Station, Texas, USA
D. Aebi, M. Ahmad, T. Akhter, K. Androsov, A. Bolshov, O. Bouhali[93], A. Cagnotta, V. D'Amante, R. Eusebi, P. Flanagan, J. Gilmore, Y. Guo, T. Kamon, S. Luo, R. Mueller, A. Safonov

Texas Tech University, Lubbock, Texas, USA
N. Akchurin, J. Damgov, Y. Feng, N. Gogate, Y. Kazhykarim, K. Lamichhane, S.W. Lee, C. Madrid, A. Mankel, T. Peltola, I. Volobouev

Vanderbilt University, Nashville, Tennessee, USA
E. Appelt, Y. Chen, S. Greene, A. Gurrola, W. Johns, R. Kunnawalkam Elayavalli, A. Melo, D. Rathjens, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, J. Viinikainen,

J. Zhang

University of Virginia, Charlottesville, Virginia, USA
B. Cardwell, H. Chung, B. Cox, J. Hakala, G. Hamilton Ilha Machado, R. Hirosky, M. Jose, A. Ledovskoy, C. Mantilla, C. Neu, C. Ramón Álvarez, Z. Wu

Wayne State University, Detroit, Michigan, USA
S. Bhattacharya, P.E. Karchin

University of Wisconsin - Madison, Madison, Wisconsin, USA
A. Aravind, S. Banerjee, K. Black, T. Bose, E. Chavez, S. Dasu, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Herve, C.K. Koraka, S. Lomte, R. Loveless, A. Mallampalli, A. Mohammadi, S. Mondal, T. Nelson, G. Parida, L. Pétré, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, H.F. Tsoi, W. Vetens, A. Warden

Authors affiliated with an international laboratory covered by a cooperation agreement with CERN
S. Afanasiev, V. Alexakhin, Yu. Andreev, T. Aushev, D. Budkouski, R. Chistov[94], M. Danilov[94], T. Dimova[94], A. Ershov[94], S. Gninenko, I. Gorbunov, A. Gribushin[94], A. Kamenev, V. Karjavine, M. Kirsanov, V. Klyukhin[94], O. Kodolova[95], V. Korenkov, I. Korsakov, A. Kozyrev[94], N. Krasnikov, A. Lanev, A. Malakhov, V. Matveev[94], A. Nikitenko[96,95], V. Palichik, V. Perelygin, S. Petrushanko[94], S. Polikarpov[94], O. Radchenko[94], M. Savina, V. Shalaev, S. Shmatov, S. Shulha, Y. Skovpen[94], K. Slizhevskiy, V. Smirnov, O. Teryaev, I. Tlisova[94], A. Toropin, N. Voytishin, A. Zarubin, I. Zhizhin

Authors affiliated with an institute formerly covered by a cooperation agreement with CERN
E. Boos, V. Bunichev, M. Dubinin[85], V. Savrin, A. Snigirev, L. Dudko, K. Ivanov, V. Kim[23], V. Murzin, V. Oreshkin, D. Sosnov

†: Deceased
[1]Also at Yerevan State University, Yerevan, Armenia
[2]Also at TU Wien, Vienna, Austria
[3]Also at Ghent University, Ghent, Belgium
[4]Also at Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
[5]Also at FACAMP - Faculdades de Campinas, Sao Paulo, Brazil
[6]Also at Universidade Estadual de Campinas, Campinas, Brazil
[7]Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
[8]Also at The University of the State of Amazonas, Manaus, Brazil
[9]Also at University of Chinese Academy of Sciences, Beijing, China
[10]Also at China Center of Advanced Science and Technology, Beijing, China
[11]Also at University of Chinese Academy of Sciences, Beijing, China
[12]Also at School of Physics, Zhengzhou University, Zhengzhou, China
[13]Now at Henan Normal University, Xinxiang, China
[14]Also at University of Shanghai for Science and Technology, Shanghai, China
[15]Now at The University of Iowa, Iowa City, Iowa, USA
[16]Also at Center for High Energy Physics, Peking University, Beijing, China
[17]Also at Zewail City of Science and Technology, Zewail, Egypt
[18]Also at British University in Egypt, Cairo, Egypt
[19]Now at Ain Shams University, Cairo, Egypt
[20]Also at Purdue University, West Lafayette, Indiana, USA

[21]Also at Université de Haute Alsace, Mulhouse, France
[22]Also at Tbilisi State University, Tbilisi, Georgia
[23]Also at an institute formerly covered by a cooperation agreement with CERN
[24]Also at University of Hamburg, Hamburg, Germany
[25]Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
[26]Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
[27]Also at Brandenburg University of Technology, Cottbus, Germany
[28]Also at Forschungszentrum Jülich, Juelich, Germany
[29]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
[30]Also at HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary
[31]Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
[32]Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
[33]Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
[34]Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
[35]Also at The University of Kansas, Lawrence, Kansas, USA
[36]Also at Punjab Agricultural University, Ludhiana, India
[37]Also at University of Hyderabad, Hyderabad, India
[38]Also at Indian Institute of Science (IISc), Bangalore, India
[39]Also at University of Visva-Bharati, Santiniketan, India
[40]Also at IIT Bhubaneswar, Bhubaneswar, India
[41]Also at Institute of Physics, Bhubaneswar, India
[42]Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
[43]Also at Isfahan University of Technology, Isfahan, Iran
[44]Also at Sharif University of Technology, Tehran, Iran
[45]Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
[46]Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran
[47]Also at Helwan University, Cairo, Egypt
[48]Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
[49]Also at Università degli Studi Guglielmo Marconi, Roma, Italy
[50]Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
[51]Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
[52]Also at Lulea University of Technology, Lulea, Sweden
[53]Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
[54]Also at UPES - University of Petroleum and Energy Studies, Dehradun, India
[55]Also at Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
[56]Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
[57]Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
[58]Also at Saegis Campus, Nugegoda, Sri Lanka
[59]Also at National and Kapodistrian University of Athens, Athens, Greece
[60]Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
[61]Also at Universität Zürich, Zurich, Switzerland
[62]Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
[63]Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
[64]Also at Konya Technical University, Konya, Turkey
[65]Also at Izmir Bakircay University, Izmir, Turkey

[66]Also at Adiyaman University, Adiyaman, Turkey
[67]Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
[68]Also at Istanbul Sabahattin Zaim University, Istanbul, Turkey
[69]Also at Marmara University, Istanbul, Turkey
[70]Also at Milli Savunma University, Istanbul, Turkey
[71]Also at Informatics and Information Security Research Center, Gebze/Kocaeli, Turkey
[72]Also at Kafkas University, Kars, Turkey
[73]Now at Istanbul Okan University, Istanbul, Turkey
[74]Also at Hacettepe University, Ankara, Turkey
[75]Also at Erzincan Binali Yildirim University, Erzincan, Turkey
[76]Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
[77]Also at Istinye University, Istanbul, Turkey
[78]Also at Yildiz Technical University, Istanbul, Turkey
[79]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
[80]Also at Monash University, Faculty of Science, Clayton, Australia
[81]Also at Bethel University, St. Paul, Minnesota, USA
[82]Also at Università di Torino, Torino, Italy
[83]Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
[84]Also at California Lutheran University;, Thousand Oaks, California, USA
[85]Also at California Institute of Technology, Pasadena, California, USA
[86]Also at United States Naval Academy, Annapolis, Maryland, USA
[87]Also at Bingol University, Bingol, Turkey
[88]Also at Georgian Technical University, Tbilisi, Georgia
[89]Also at Sinop University, Sinop, Turkey
[90]Also at Erciyes University, Kayseri, Turkey
[91]Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania
[92]Now at another institute formerly covered by a cooperation agreement with CERN
[93]Also at Hamad Bin Khalifa University (HBKU), Doha, Qatar
[94]Also at another institute formerly covered by a cooperation agreement with CERN
[95]Also at Yerevan Physics Institute, Yerevan, Armenia
[96]Also at Imperial College, London, United Kingdom