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Search for dark matter produced in association with a pair of bottom quarks in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

Abstract

A search for dark matter (DM) particles produced in association with bottom quarks is presented. The analysis uses proton-proton collision data at a center-of-mass energy of $\sqrt{s} = 13\,\text{TeV}$, corresponding to an integrated luminosity of $138\,\text{fb}^{-1}$. The search is performed in the final state with large missing transverse momentum and a pair of jets originating from bottom quarks. No significant excess of data is observed with respect to the standard model expectation. Results are interpreted in the context of a type-II two-Higgs-doublet model with an additional light pseudoscalar (2HDM+a). An upper limit is set on the mass of the lighter pseudoscalar, excluding masses up to 260 GeV at 95% confidence level. This is the first search at the LHC to probe DM produced in association with two nonresonant bottom quarks in the 2HDM+a model. Sensitivity to the parameter space with the ratio of the vacuum expectation values of the two Higgs doublets, $\tan\beta$, greater than 15 is achieved, capitalizing on the enhancement of couplings between pseudoscalars and bottom quarks with high $\tan\beta$.

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*See Appendix A for the list of collaboration members

1 Introduction

So far, the evidence for the existence of dark matter (DM) has come from astrophysics. According to the lambda cold dark matter (ΛCDM) model of cosmology [1], the high-precision Planck satellite map of the cosmic microwave background [2] indicates that DM constitutes about 26% of the total mass-energy of the known universe [3], however, the particle nature of DM has not been elucidated yet. If it is composed of subnuclear particles, then these could potentially be produced at the LHC. Such particles, whether elementary or composite, are weakly interacting with standard model (SM) particles, which means they might escape detection in collider experiments. Since these DM candidates are expected to be electrically neutral and long-lived, their presence could be inferred through an observed imbalance in transverse momentum vectors of particles in the detector, known as missing transverse momentum ($\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$) with magnitude represented by $p_{\mathrm{T}}^{\mathrm{miss}}$.

Many beyond-the-SM (BSM) theories hypothesize the particle nature of DM [4, 5]. Based on astrophysical and cosmological indications and the observed relic density of the universe, weakly interacting massive particles (WIMPs) [6], with masses in the range from a few GeV to a few TeV, are a popular type of DM candidates that can be searched for at colliders. Such searches can be performed by looking for the pair production of WIMPs through a mediator that recoils against one or more visible SM particles. WIMPs can give a detector signature of the type $\mathrm{X} + p_{\mathrm{T}}^{\mathrm{miss}}$ [7], where X is one or more SM particles, e.g. a heavy-quark pair, produced in association with DM.

In this paper, we perform a search for DM particles produced in association with a pair of bottom quarks ($\mathrm{b\overline{b}} + p_{\mathrm{T}}^{\mathrm{miss}}$) using the proton-proton (pp) collision data collected with the CMS detector in 2016–2018, corresponding to an integrated luminosity of 138 fb^{-1}. The search for DM produced in association with heavy-flavor quarks is complementary to other $\mathrm{X} + p_{\mathrm{T}}^{\mathrm{miss}}$ searches and to searches for DM production in cascades in the context of supersymmetry (SUSY) at the LHC. The ATLAS and CMS Collaborations have performed DM searches using heavy-flavor jets as tags, such as single top quarks ($\mathrm{t}/\bar{\mathrm{t}}$) [8], top quark pairs ($\mathrm{t\bar{t}}$) [9], and $\mathrm{b\overline{b}}$ [10–12].

2 Signal and background simulations

The model used for the interpretation of the results of this analysis is a type-II two-Higgs-doublet model with an additional pseudoscalar singlet interacting with DM particles, referred to as 2HDM+a [13, 14]. The model contains a scalar Higgs boson (h, assumed to be the observed Higgs boson with mass $m_{\mathrm{h}} = 125\,\mathrm{GeV}$), a pair of charged Higgs bosons ($\mathrm{H}^{\pm}$), a heavy scalar boson (H), a heavy pseudoscalar boson (A), a light pseudoscalar boson (a), and a Dirac fermion (χ), which is assumed to be the DM particle. Figure 1 shows the leading Feynman diagrams for the production of the $\mathrm{b\overline{b}} + \chi\overline{\chi}$ process within the 2HDM+a model.

The choice of the fixed and free parameters in this model follows the recommendations of Ref. [15]. The model contains the following parameters: the electroweak vacuum expectation value ($v \approx 246\,\mathrm{GeV}$), the mass of the DM candidate m_{χ}, the masses of the Higgs bosons ($m_{\mathrm{h}}, m_{\mathrm{H}}, m_{\mathrm{H}^{\pm}}$), the masses of the pseudoscalar bosons ($m_{\mathrm{a}}, m_{\mathrm{A}}$), the mixing angle between the two CP-even weak spin-0 eigenstates (α), the mixing angle between the two CP-odd weak spin-0 eigenstates (θ), the ratio of the vacuum expectation values of the two Higgs doublets ($\tan\beta$), and the quartic couplings ($\lambda_3, \lambda_{P1}, \lambda_{P2}$).

In the decoupling limit, where $\sin(\beta - \alpha) = 1$ and $\lambda_3 = \lambda_{P_1} = \lambda_{P_2} = 3$ ensure the boundedness of the Higgs potential, electroweak precision constraints give $m_{\mathrm{A}} = m_{\mathrm{H}} = m_{\mathrm{H}^{\pm}}$, and the DM coupling y_χ is set to 1. This results in five free parameters, namely, $\tan\beta$, $\sin\theta$, m_{A}, m_{a}, and m_χ. This choice is adopted in many 2HDM+a interpretations of heavy spin-0 resonances searches performed at the LHC [16–20]. Furthermore, the motivation for using the 2HDM+a model is that the couplings of both the heavier pseudoscalar ($g_{\mathrm{Ab\bar{b}}}$) and the lighter pseudoscalar ($g_{\mathrm{ab\bar{b}}}$) to bottom quarks are proportional to $\tan\beta$, resulting in increased interaction rates in the high-$\tan\beta$ region.

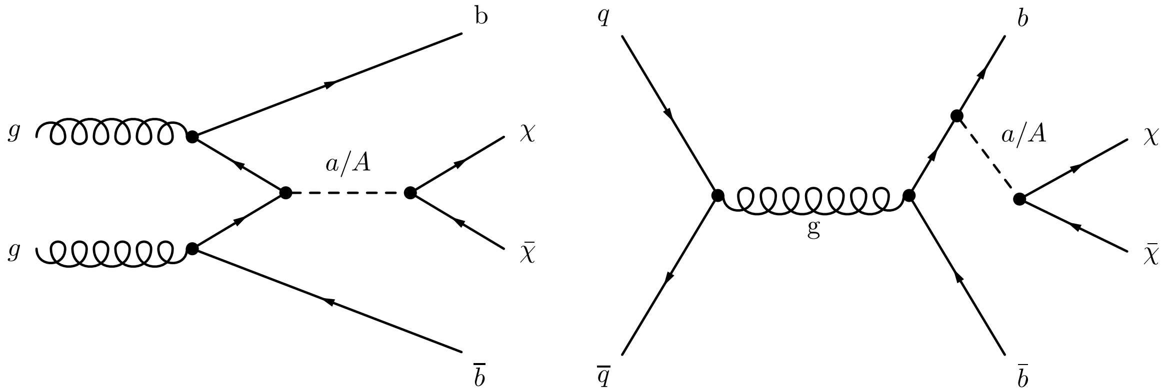

Figure 1: Leading Feynman diagrams for the $\mathrm{b\bar{b}} + \chi\bar{\chi}$ process in the 2HDM+a model.

The production cross section is dominantly driven by the lighter mediator a as well as $\tan\beta$ and $\sin\theta$, and does not depend on the mass of A. Furthermore, as shown in Fig. 2, the distribution of $p_{\mathrm{T}}^{\mathrm{miss}}$ strongly depends on m_{a}. On the other hand, $\tan\beta$, $\sin\theta$, and m_χ marginally change the $p_{\mathrm{T}}^{\mathrm{miss}}$ distribution, as also shown in Fig. 2 for m_χ. Hence, signal events are generated with $m_{\mathrm{A}} = 600\,\mathrm{GeV}$, $\tan\beta = 35$, $\sin\theta = 0.7$, and $m_\chi = 1\,\mathrm{GeV}$ for different m_{a} values using MADGRAPH5_aMC@NLO v2.6.0 [21] and the 5-flavor scheme at leading order (LO) in quantum chromodynamics (QCD) with no additional jets at the matrix element level.

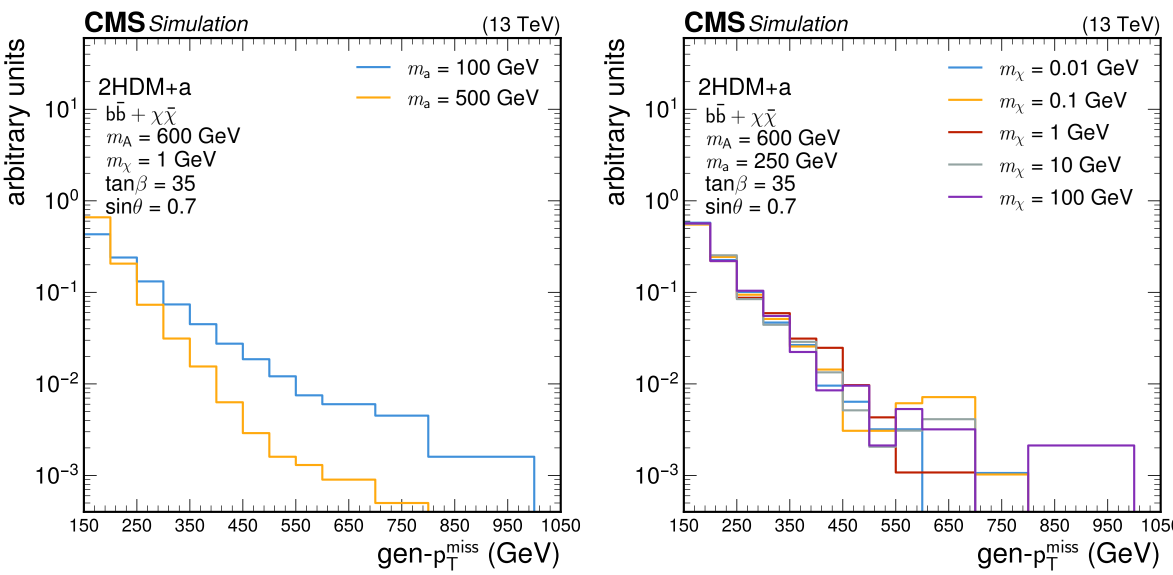

Figure 2: Normalized (to unity) shape of generator-level $p_{\mathrm{T}}^{\mathrm{miss}}$ distribution for two illustrative lighter pseudoscalar masses m_{a} (left) and for five illustrative DM masses m_χ (right).

A lower threshold of 150 GeV is set on $p_{\mathrm{T}}^{\mathrm{miss}}$ at the generator level to constrain the kinematic phase space of simulated events to the region where the analysis is conducted. Various SM processes have a similar final state and higher production cross sections. The dominant background comes from the $Z(\nu\nu) + \text{jets}$ production (≈60–70% of the total background), when the Z boson is produced in association with one or two b jets and decays to neutrinos. The $t\bar{t}$ (lepton + jets) and $W(\ell\nu) + \text{jets}$ backgrounds are the next largest backgrounds, where a lepton coming from these processes is either lost or not reconstructed properly in the detector. Dileptonic and hadronic $t\bar{t}$ decays, as well as single top quark and diboson (WW, WZ, ZZ) production events, are smaller contributions to the total background.

The $Z(\nu\nu) + \text{jets}$, $Z(\ell\ell) + \text{jets}$, and $W(\ell\nu) + \text{jets}$ background processes ($\ell = e, \mu, \tau$) are simulated using MADGRAPH5_aMC@NLO v2.4.2 [21] at next-to-LO (NLO) in QCD. The $t\bar{t}$ and single top quark production events are simulated using the POWHEG v2 generator [22, 23] at NLO in QCD. Diboson events are generated at LO in QCD using the PYTHIA 8.212 generator [24]. The SM Higgs boson with a mass of 125 GeV produced in association with a vector boson is considered as a background and is simulated using the POWHEG generator at NLO in QCD. The NNPDF3.1 parton distribution functions (PDFs) [25] are used, depending on the QCD order of the generator for each physics process. Parton showering, fragmentation, and hadronization are simulated with PYTHIA 8.230 (8.212 for 2016) using the CP5 (CUETP8M1 for 2016) underlying event tune [26, 27].

Interactions of the resulting final state particles with the CMS detector are simulated using the GEANT4 software [28] and reconstructed using the same algorithms used for the data. Additional inelastic pp interactions in the same or a neighboring bunch crossing (pileup) are included in the simulation. The pileup distribution is adjusted to match the corresponding distribution observed in data.

3 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters, made of steel and quartz fibers, extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid.

Events of interest are selected using a two-tiered trigger system [29]. The first level, composed of custom hardware processors (L1), uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz in a fixed time interval of approximately 4 μs. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage.

A more detailed description of the CMS detector, along with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [30].

4 Data samples and event reconstruction

This search uses data collected in pp collisions between 2016 and 2018. In particular, physics data sets for which the events pass the p_T^{miss} and single-electron triggers at the HLT, and electron-photon and calo-p_T^{miss} triggers at L1 are used for final analysis.

A global "particle-flow" (PF) algorithm [31] aims to reconstruct all individual particles in an event, combining information provided by the inner tracker ECAL, HCAL, and muon detectors. The reconstructed particles are used to build τ leptons, jets, and missing transverse momentum [32–34]. The primary vertex is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone, as described in Section 9.4.1 of Ref. [35].

Jets are clustered using the anti-k_{T} jet clustering algorithm [36] with a distance parameter ($\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$) of 0.4 ("AK4 jets"). Jet calibration [33] is used to account for the energy deposits of neutral particles and full nonlinear hadronic response of the detector. Pileup effects from the charged hadrons are mitigated by removing them from pileup interactions, with a technique called "charged-hadron subtraction" (CHS) [37]. For mitigation of neutral PU particles, a new technique, pileup per particle identification (PUPPI) [38] is used, which builds on the existing CHS algorithm. Furthermore, to ensure that the energy and momentum of the reconstructed jet matches that of the quark/gluon-initiated jet, jet energy corrections are applied to the reconstructed jets. In this search, jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 2.5$ are considered. To remove any overlap with leptons, all jets within $\Delta R = 0.4$ with leptons are removed.

Jets originating from bottom quark hadronization, b jets, are identified with the DEEPCSV algorithm [39], which uses a deep neural network (DNN) with 4 hidden layers and exploits the discriminating power of variables such as the position of the secondary vertex, the lifetime of the bottom quark, and the mass of b hadrons. Three working points are defined on the basis of the output of the DeepCSV algorithm. The loose working point corresponds to a 10% misidentification ("mistag") rate with 84% efficiency. The medium working point gives a 1% mistag rate with 68% efficiency, and the tight working point gives a 0.1% mistag rate with 50% efficiency.

The hadron-plus-strips algorithm is employed to reconstruct hadronically decaying τ leptons, denoted as τ_{h} [32]. Jets reconstructed using AK4 jet clustering are used as an input to the algorithm and τ_{h} candidates are reconstructed on the basis of the number of charged hadrons and energy deposits in strips in the ECAL, which originate from the photon candidates and their electron-positron conversions. In order to minimize the misidentification rate of τ_{h} from quark and gluon jets, a convolutional discriminator based on a DNN called DeepTau [40] is employed. Events with a τ_{h} candidate with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and $|\eta| < 2.3$ are vetoed.

Shower shape and isolation variables, as defined in Section 7.1 of Ref. [41], are used to identify electrons and photons. Isolated electrons and photons used in this analysis have $p_{\mathrm{T}} > 10$ and $15\,\mathrm{GeV}$, respectively, and $|\eta| < 2.5$. Isolated muons have $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ and $|\eta| < 2.4$. Two parameters are considered while identifying the muons, namely the number of measurements in the tracker-muon system and the track reconstruction quality [42].

As mentioned in Section 1, the negative vectorial p_{T} sum of all PF candidates is used to calculate $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ with all jet energy corrections are applied. Events with anomalous $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ can occur because of reconstruction failures, detector artifacts, or noncollision backgrounds [34]. Dedicated event filters, which can identify more than 90% of such events, are used, with a mistagging rate of less than 0.1%.

5 Analysis strategy and event selection

The final states reconstructed in this analysis consist of one or two b-tagged jets and large $p_{\mathrm{T}}^{\mathrm{miss}}$, which could arise from DM particles. The data are split into two categories based on the number of b-tagged jets: the 1b category contains events with only one b-tagged jet and is composed of one signal region (SR), called SR1, and two control regions (CRs), while the 2b category contains events with two b-tagged jets and is composed of one SR (SR2) and two CRs. Events that contain at least one well identified and isolated electron and muon with $p_T > 10\,\text{GeV}$ are vetoed from the SRs to reduce the background from the $t\bar{t}$ and $W(\ell\nu)$ + jets processes. These regions are illustrated in Fig. 3. The three dominant background sources $Z(\nu\nu)$ + jets, $t\bar{t}(\ell\nu)$, and $W(\ell\nu)$ + jets are estimated by performing a simultaneous fit of the SRs and CRs, as detailed in Section 7.

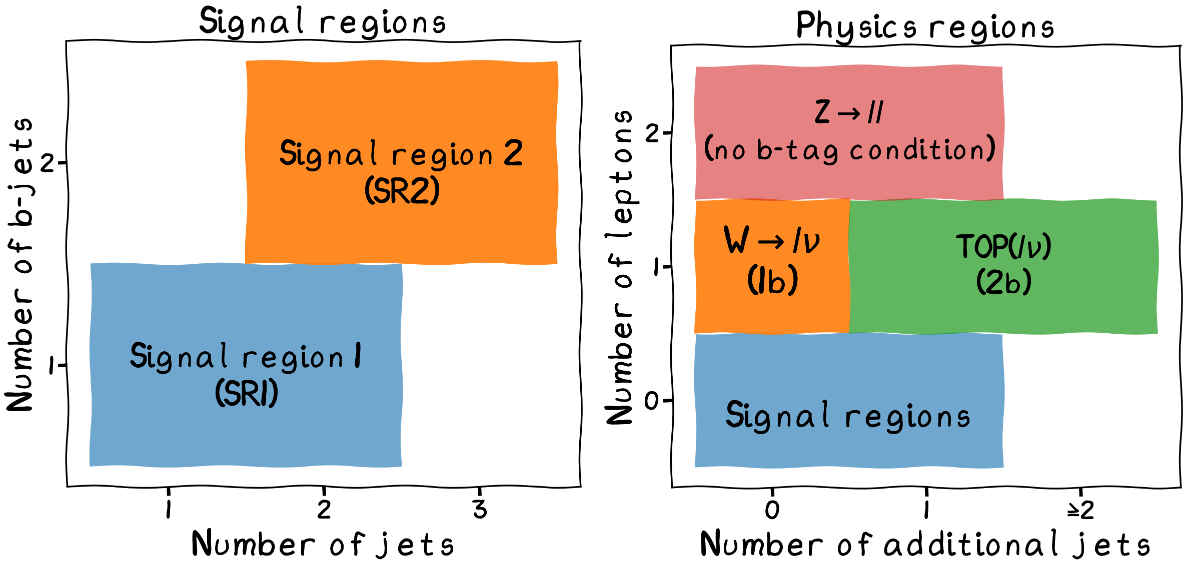

Figure 3: Definition of SR1 and SR2 in terms of jet multiplicity (left), and CR and SR definition in the lepton multiplicity and additional jet multiplicity plane (right). The categories depend on the number and flavor of leptons, and the number of jets in an event.

In the CRs, p_T^{miss} is replaced by the the absolute value of the transverse momentum recoil, $\vec{U}$, to mimic the variation observed in p_T^{miss} within the SRs because of the presence of leptons. The recoil is defined as:

$$U = |\vec{U}| = \left| -\left(\vec{p}_T^{\,miss} + \sum \vec{p}_T^{\,lep}\right) \right| \tag{1}$$

In the 2b category, the p_T^{miss} distribution for signal events is similar to that of background events, such that there is little separation power for signal and background. The angular variable $\cos\Theta^*$ [43], defined as

$$\cos\Theta^* = \left| \tanh\left(\frac{\eta_1 - \eta_2}{2}\right) \right|, \tag{2}$$

where η_1 and η_2 are the pseudorapidities of the leading and subleading jets, gives an optimal discrimination between the signal and backgrounds in this category. In the longitudinally boosted frame, $\cos\Theta^*$ is the cosine of the polar angle between each jet and the beam axis, where the pseudorapidities of the jets are equal and opposite.

Events in the SRs and CRs are selected such that they are mutually exclusive. The events in the SRs and muon-based CRs are selected by a logical 'OR' of p_T^{miss} triggers with different thresholds (90, 100, 110, 120, or 140 GeV), whereas events in the electron-based CRs are selected by using a logical 'OR' of single electron triggers with minimum threshold of 27, 32, or 35 GeV [29]. Events are preselected using a set of requirements common to the SRs and CRs. In the CRs, the selection criteria incorporate U to mimic the variation observed in $p_{\mathrm{T}}^{\mathrm{miss}}$ within the SRs because of the presence of leptons.

The event selection procedure starts with the preselection, which requires events passing trigger thresholds, followed by an offline selection of $p_{\mathrm{T}}^{\mathrm{miss}}$ or recoil $> 250\,\mathrm{GeV}$. Events must include at least one jet, with the leading jet having $p_{\mathrm{T}} > 100\,\mathrm{GeV}$, as optimized based on signal sensitivity. Events with a photon with $p_{\mathrm{T}} > 15\,\mathrm{GeV}$ and $|\eta| < 2.5$ are rejected to suppress photon-induced backgrounds ($\mathrm{Z}(\ell\ell) + \gamma + \mathrm{jet}$, $\mathrm{W}(\ell\nu) + \gamma + \mathrm{jet}$).

QCD multijet events can mimic the signal signature when the jet momentum is mismeasured, giving rise to high $p_{\mathrm{T}}^{\mathrm{miss}}$. The QCD multijet background is reduced by requiring the minimum $\Delta\phi$ between any jet and $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ ($\min(\Delta\phi(\mathrm{jet}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}))$) to be higher than 0.5 radians. This ensures that $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is not aligned with any jet, which is a common feature in events with mismeasured jets. The QCD multijet background is further reduced by requiring the relative difference in the value of $p_{\mathrm{T}}^{\mathrm{miss}}$ measured with the PF algorithm and with calorimeter only information to be less than 0.5. This quantity is defined as

$$\Delta p_{\mathrm{T}}^{\mathrm{miss}}(\text{PF - calorimeter}) = \begin{cases} \left|p_{\mathrm{T}}^{\mathrm{miss}}(\mathrm{PF})\,/\,p_{\mathrm{T}}^{\mathrm{miss}}(\mathrm{calorimeter}) - 1\right|, & \text{in the SRs and} \\ \left|p_{\mathrm{T}}^{\mathrm{miss}}(\mathrm{PF})\,/\,U(\mathrm{calorimeter}) - 1\right|, & \text{in the CRs.} \end{cases}$$

Table 1 summarizes the requirements to preselect the events for all three data-taking years. A dedicated event selection for the SRs and CRs is applied on top of the preselection.

Table 1: Preselection criteria applied to all the events entering the SRs and CRs.

Selection	Cut Value
Trigger	$p_{\mathrm{T}}^{\mathrm{miss}}$ or single electron
$p_{\mathrm{T}}^{\mathrm{miss}}$ (U in CR)	$>250\,\mathrm{GeV}$
Jets	multiplicity ≥ 1, $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.5$
Leading jet	$p_{\mathrm{T}} > 100\,\mathrm{GeV}$
Overlap removal	no overlap with e, μ, τ_{h}, γ
γ	veto photon with $p_{\mathrm{T}} > 15\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.5$
$\min(\Delta\phi(\mathrm{jet}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}))$	>0.5
$\Delta p_{\mathrm{T}}^{\mathrm{miss}}$(PF - calorimeter)	<0.5

Events in SR2 have two jets tagged as originating from bottom quarks (using the medium working point) and large $p_{\mathrm{T}}^{\mathrm{miss}}$. Furthermore, up to one additional jet with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, not b-tagged, is allowed in events entering this region. SR1 is foreseen to catch signal events where one of the b jets is lost because it is outside of the detector acceptance or is not tagged correctly, requiring exactly one b-tagged jet and up to one additional jet. This category helps to recover some lost signal efficiency at the cost of a relatively higher background.

6 Background estimation

To estimate the $\mathrm{Z}(\nu\nu) + \mathrm{jets}$ background, two CRs, targeting the $\mathrm{Z} \to \mathrm{e}^-\mathrm{e}^+$ and $\mathrm{Z} \to \mu^-\mu^+$ processes, are defined. In these CRs, out of exactly two leptons in the event, the leading lepton must have $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, the invariant mass of the dilepton candidate must be between 70 and 110 GeV, and there is no b tagging requirement on the jets. The CRs dedicated to the $\mathrm{W}(\ell\nu) + \mathrm{jets}$ and $\mathrm{t\bar{t}}$ backgrounds are built for SR1 and SR2, respectively. They require a single lepton (electron or muon) with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and a transverse mass $\mathrm{m_T} = \sqrt{2 p_{\mathrm{T}}^{\mathrm{miss}} p_{\mathrm{T}}^{l} (1 - \cos[\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\,l})])}$ less than 160 GeV, together with the same b tagging requirements as in the SRs. In addition, events in the $\mathrm{t\bar{t}}$ CR have at least 2 additional non b-tagged jets, while, for the $\mathrm{W}(\ell\nu)+$jets CR, exactly one additional non b-tagged jet is required and $p_{\mathrm{T}}^{\mathrm{miss}}$ must be greater than 100 GeV.

To estimate the QCD multijet background, a QCD CR is defined using the same selection as the SR except for requiring $\min(\Delta\phi(\mathrm{jet}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})) < 0.5$. The QCD background in the CR is estimated as the difference between data and other simulated backgrounds, and is plotted against the $\min(\Delta\phi)$ threshold, i.e., for each entry of $\min(\Delta\phi)$ on the x axis, the y axis corresponds to the number of events passing the $\min(\Delta\phi)$ requirement. This distribution is plotted for each bin of $p_{\mathrm{T}}^{\mathrm{miss}}$ or $\cos\Theta^*$ and then fitted with a function that describes the behavior of the distribution. The QCD contribution exhibits an exponential decrease with $\min(\Delta\phi)$, as shown for one example in Fig. 4. The QCD background is fitted with an exponential in the $\min(\Delta\phi)$ range between 0 to 0.3, and the resulting function is validated in the $\min(\Delta\phi)$ range between 0.3 to 0.5. The QCD contribution in the SR is calculated as the integral of the function for $\min(\Delta\phi(\mathrm{jet}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})) > 0.5$.

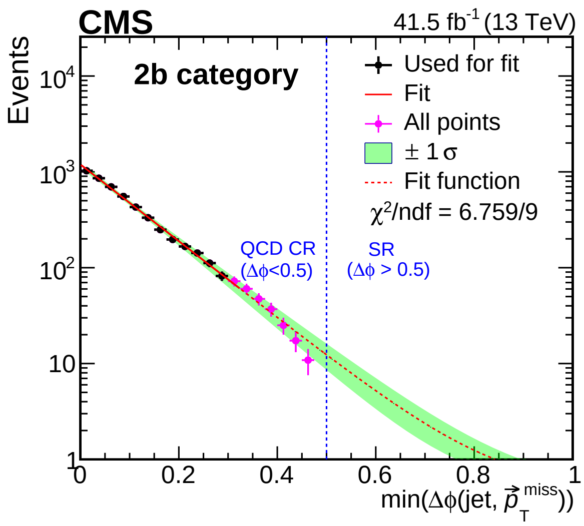

Figure 4: QCD background contribution in the QCD CR (black and pink dots) in the 2b category using 2017 data. The exponential is fitted in the range $\min(\Delta\phi(\mathrm{jet}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})) < 0.3$, checked to fit well in the range $0.3 < \min(\Delta\phi(\mathrm{jet}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})) < 0.5$, and extrapolated to the SRs for $\min(\Delta\phi(\mathrm{jet}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})) > 0.5$. The process is performed for the 1b as well as 2b categories for all years.

7 Signal extraction

The fit for the 1b category is performed using $p_{\mathrm{T}}^{\mathrm{miss}}$ in SR1 and U in corresponding CRs as observables, therefore, both SR1 and the corresponding CRs enter simultaneously in a binned profile likelihood fit to estimate the signal. Each bin of $p_{\mathrm{T}}^{\mathrm{miss}}$ in SR1 is tied to the corresponding bin of U in the CR via a scale factor, treating the systematic uncertainties as nuisance parameters in the fit. A variable binning is used for $p_{\mathrm{T}}^{\mathrm{miss}}$ and U with bin edges 250, 300, 400, 550, and 1000 GeV.

In the 2b category, the variable $\cos\Theta^*$ is used with bins of 0.25 width from 0.0 to 1.0, and a similar procedure is used to constrain the backgrounds using equivalent bins in the CRs. For each category, the electron and muon CRs are combined to form a single CR for each background estimated from data.

8 Systematic uncertainties

The background and signal predictions are affected by systematic uncertainties. Only the systematic uncertainties that have an impact of at least half a percent are taken into account in the signal extraction fit. Some uncertainties affect only the normalization of the various processes, while some affect their distributions too.

Shape-based uncertainties in the b tagging efficiency are calculated separately for true b jets (having b flavor at the particle level) and incorrectly b-tagged jets for each event. The uncertainty in the integrated luminosity amounts to 1.2–2.5%, depending on the data-taking year [44–46], while the overall uncertainty for the 2016–2018 period is 1.6%.

The $p_{\mathrm{T}}^{\mathrm{miss}}$-based trigger efficiency scale factors are measured in a phase space with single-muon and dimuon events, and the difference in the scale factors is considered as the systematic uncertainty. A shape-based systematic uncertainty of the order of 1% is applied to all the simulated samples in the SRs and muon CRs. The electron trigger efficiency scale factors are calculated using a tag-and-probe method [47] and a shape-based uncertainty is applied to all the simulated samples in the electron CRs. The overall effect is of the order of 2–3% on the normalization.

Shape uncertainties arising from jet energy corrections are applied to the simulations, separating different sources of uncertainty. The average effect is of the order of 2–3%.

An uncertainty in the total inelastic cross section of 4.6% [48] is used as a shape-based uncertainty to account for the effects of pileup modeling.

For the single top quark, diboson, and SM Higgs boson processes, a normalization uncertainty of 10%, 20%, and 20%, respectively, is used [49–51]. The systematic uncertainty in the SM Higgs boson cross section due to the renormalization and factorization scales is taken into account, using the envelope of the distributions treated as the shape uncertainty. The uncertainty related to the modeling of PDFs is estimated using the replicas provided in the corresponding PDF sets for the different backgrounds [25, 52–54].

For the QCD multijet background, the total uncertainty comes from the combination of the uncertainty obtained from the 95% confidence intervals of the fitted extrapolation function and a flat uncertainty of 20% that covers the statistical uncertainty. The total effect on the QCD background estimation is about 50%. The magnitude and categories of systematic uncertainties are detailed in Table 2.

9 Results

Figures 5 and 6 present the expected distributions of $p_{\mathrm{T}}^{\mathrm{miss}}$ for SR1 and U for the $\mathrm{Z}(\ell\ell) + \text{jets}$ and $\mathrm{W}(\ell\nu) + \text{jets}$ CRs in the 1b category, as well as $\cos\Theta^*$ for the SR and CRs in the 2b category. These distributions are shown both before (prefit) and after (postfit) the maximum likelihood fit, with the observed data superimposed. No excess with respect to the SM prediction is observed.

Upper limits on the signal strength modifier $\mu = \sigma/\sigma_{\text{theory}}$ are extracted, where σ_{theory} is the production cross section of DM candidates in association with two bottom quarks as predicted by the theoretical model, and σ represents the upper limit on the observed cross section. The upper limits are calculated at the 95% confidence level (CL) using a modified frequen-

Table 2: Systematic uncertainties affecting the shape and normalization (lnN) of the signal and background predictions with an impact greater than 0.5%.

Systematics	Type	Size
Pileup reweighting	shape	3%
b tag efficiency	shape	3–8%
Incorrectly b-tagged jets	shape	1–7%
Electron identification	shape	5–7%
Electron reconstruction efficiency	shape	3–5%
Muon identification	shape	$<$1%
Muon isolation	shape	$<$1%
Electron trigger	shape	1%
$p_{\mathrm{T}}^{\mathrm{miss}}$ trigger	shape	1%
Jet energy correction	shape	3%
L1 prefiring	shape	0.5%
Muon prefiring	lnN	0.5%
τ_{h} veto	lnN	6%
Integrated luminosity	lnN	2.5%
Cross section diboson	lnN	20%
Cross section Drell–Yan	lnN	5%
Cross section Higgs boson	lnN	20%
Cross section single top quark	lnN	10%
QCD normalization	lnN	20%
Renormalization and factorization scales	shape	16–42%
PDF	shape	25–50%

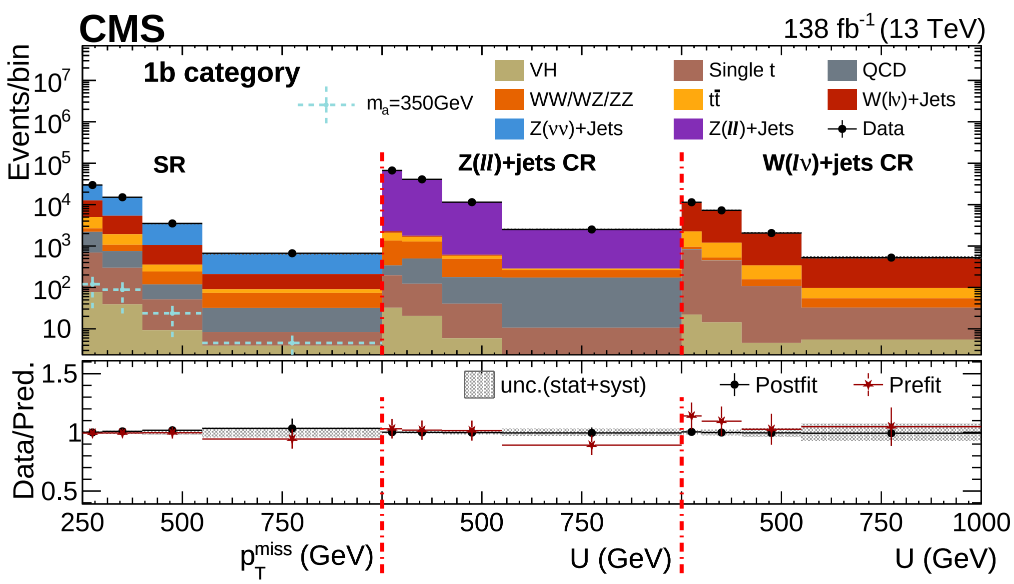

Figure 5: Observed and predicted $p_{\mathrm{T}}^{\mathrm{miss}}$ (U) distributions in the 1b category. The red lines divide the plot into three parts: the first part shows the SR, the second part the $\mathrm{Z}(\ell\ell) + \text{jets}$ CR, and the third part the $\mathrm{W}(\ell\nu) + \text{jets}$ CR. The bottom plot shows the ratio of observed and predicted (both postfit and prefit) distributions along with an uncertainty band that includes both the systematic and statistical components.

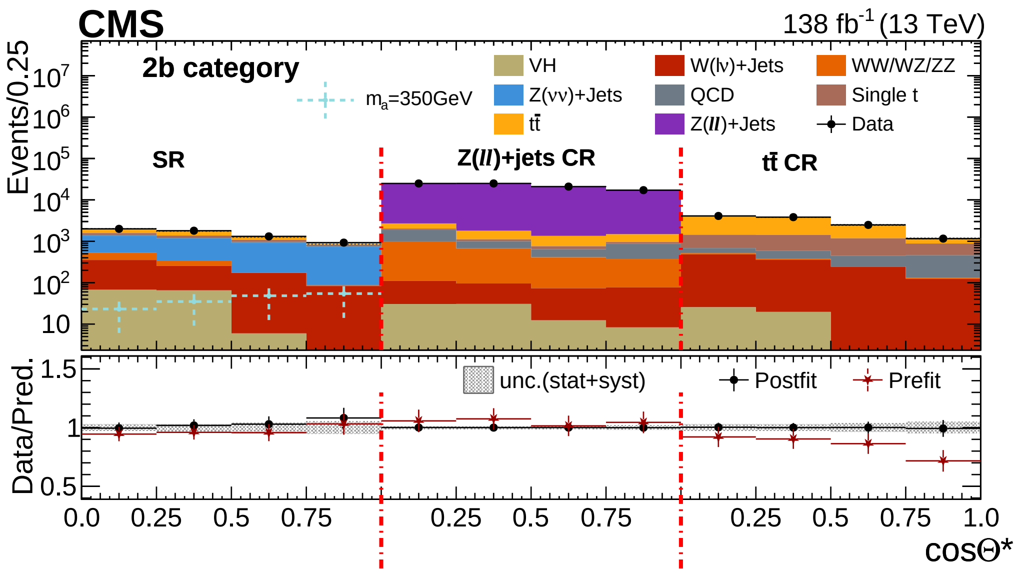

Figure 6: Observed and predicted $\cos\Theta^*$ distributions in the 2b category. The red lines divide the plot into three parts: the first part shows the SR, the second part the $Z(\nu\nu) +$ jets CR, and the third part the $t\bar{t}$ CR. The bottom plot shows the ratio of observed and predicted (both postfit and prefit) distributions along with an uncertainty band that includes both the systematic and statistical components.

tist method [55–57] computed with an asymptotic approximation [58]. The combined limit is shown in Fig. 7. The observed exclusion range for m_a is up to 260 GeV, for $m_A = 600$ GeV, $\tan\beta = 35$, $\sin\theta = 0.7$, and $m_\chi = 1$ GeV. The two-dimensional limit in the plane of m_a-$\tan\beta$, using $m_A = 600$ GeV, $\sin\theta = 0.7$ and $m_\chi = 1$ GeV, is shown in Fig. 8 (upper left). The two-dimensional limit in the plane of m_a-$\sin\theta$, using $m_A = 600$ GeV, $\tan\beta = 35$ and $m_\chi = 1$ GeV, is shown in Fig. 8 (upper right). The two-dimensional limit in the plane of m_a–m_χ, using $\tan\beta = 35$, $\sin\theta = 0.7$, and $m_A = 600$ GeV is shown in Fig. 8 (lower).

Tabulated results are provided in the HEPData record for this analysis [59].

10 Summary

A search for dark matter produced in association with a pair of bottom quarks is performed using data collected by the CMS detector in 2016–2018, corresponding to an integrated luminosity of 138 fb^{-1}. The analysis searches for a possible signal by using two independent categories with different multiplicities of jets reconstructed as originating from a bottom quark. The results are interpreted in the framework of a simplified model, namely a type-II two-Higgs-doublet model with an additional pseudoscalar singlet (2HDM+a). It is the first search at the LHC to probe dark matter (DM) produced in association with two nonresonant bottom quarks in this model. This search performs best in the high-$\tan\beta$ phase space, where the signal production cross section is enhanced. This provides a complementary search to constrain the 2HDM+a model parameter phase space in the region where other DM searches are less sensitive. The lighter pseudoscalar mass below 260 GeV is excluded at 95% confidence level for $\tan\beta = 35$, $\sin\theta = 0.7$, and $m_A = 600$ GeV.

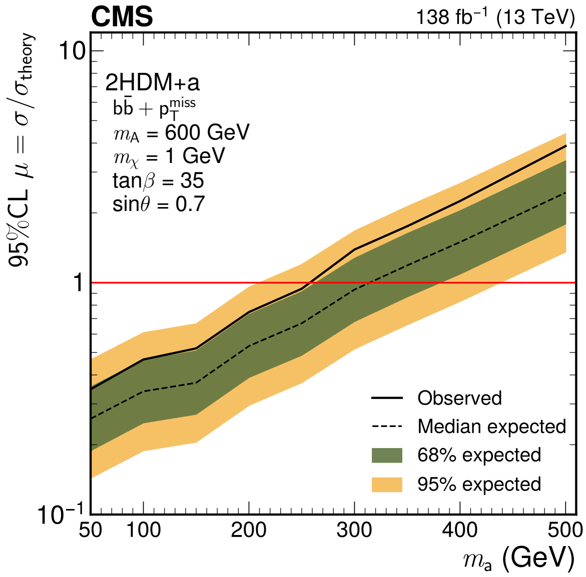

Figure 7: The 95% CL upper limit on the signal strength modifier of DM produced in association with a pair of bottom quarks for $m_A = 600$ GeV, $\sin\theta = 0.7$, $m_\chi = 1$ GeV, and $\tan\beta = 35$, for the combination of SR1 and SR2. The green and yellow bands show the ± 1 and ± 2 standard deviations from expected limits. The mass points below the red line are excluded.

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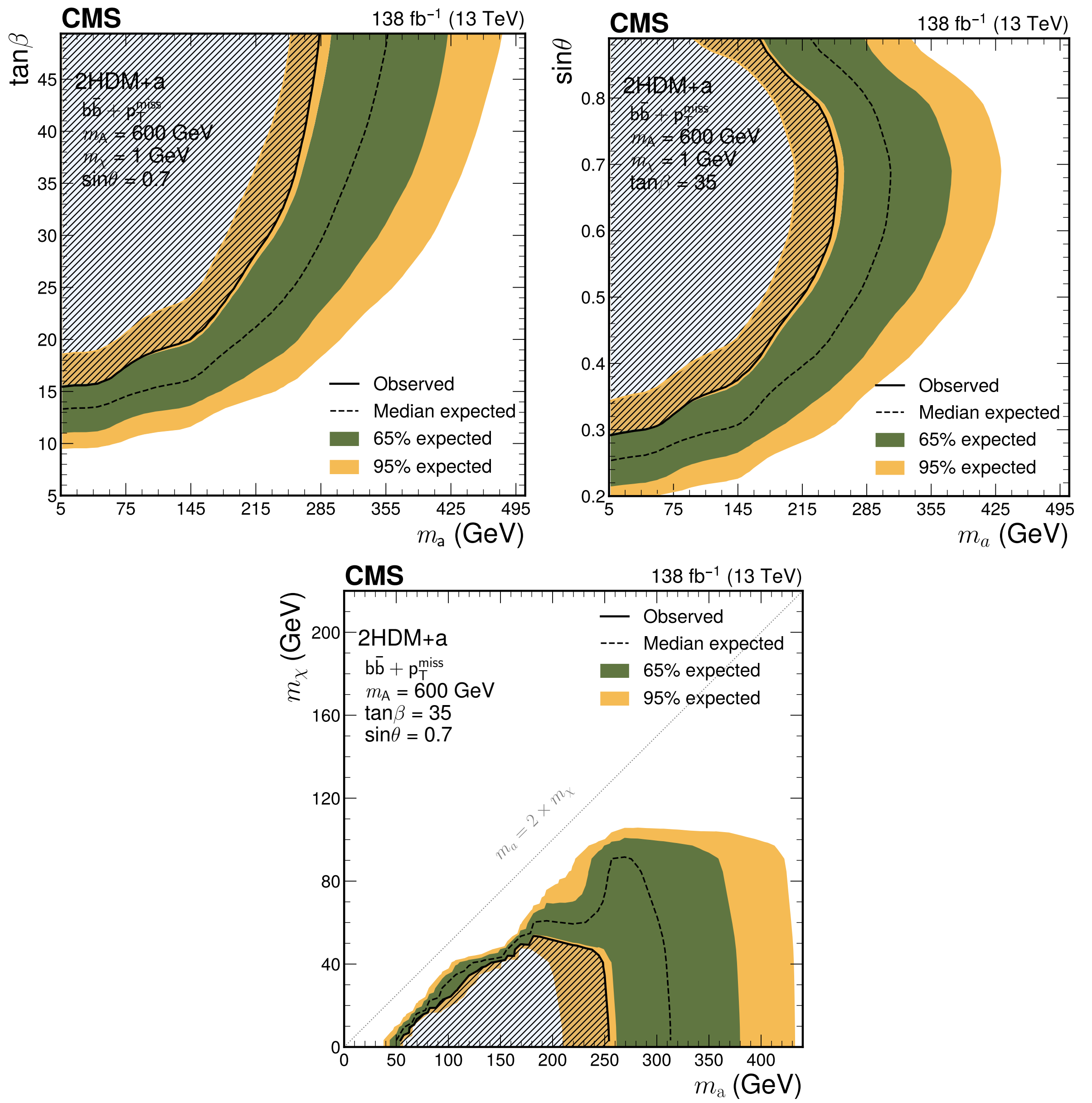

Figure 8: Observed and expected upper limits at 95% CL on the signal strength in the m_a– $\tan\beta$ (upper left), m_a– $\sin\theta$ (upper right), and m_a– m_χ (lower) planes. The shaded area bounded by solid black line is excluded, with, the dotted grey line ($m_a = 2m_\chi$) separating on-shell and off-shell productions for the lower plot.

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References

[1] N. Deruelle and J.-P. Uzan, "The Lambda-CDM model of the hot Big Bang", *OUP Academic* (2018) doi:10.1093/oso/9780198786399.003.0059.

[2] Planck Collaboration, "Planck 2018 results. I. Overview and the cosmological legacy of Planck", *Astron. Astrophys.* **641** (2020) A1, doi:10.1051/0004-6361/201833880, arXiv:1807.06205.

[3] K. Freese, "Status of Dark Matter in the Universe", *Int. J. Mod. Phys.* **1** (2017) 325, doi:10.1142/S0218271817300129, arXiv:1701.01840.

[4] J. L. Feng, "Dark Matter Candidates from Particle Physics and Methods of Detection", *Ann. Rev. Astron. Astrophys.* **48** (2010) 495, doi:10.1146/annurev-astro-082708-101659, arXiv:1003.0904.

[5] V. Trimble, "Existence and nature of dark matter in the universe", *Annual Review of Astronomy and Astrophysics.* **25** (1987) 425, doi:10.1146/annurev.aa.25.090187.002233.

[6] G. Jungman, M. Kamionkowski, and K. Griest, "Supersymmetric dark matter", *Phys. Rept.* **267** (1996) 195, doi:10.1016/0370-1573(95)00058-5, arXiv:hep-ph/9506380.

[7] CMS Collaboration, "Dark sector searches with the CMS experiment", 2024. arXiv:2405.13778. Submitted to *Phys. Rept.*

[8] CMS Collaboration, "Search for dark matter produced in association with a single top quark or a top quark pair in proton-proton collisions at $\sqrt{s} = 13$ TeV", *JHEP* **03** (2019) 141, doi:10.1007/JHEP03(2019)141, arXiv:1901.01553.

[9] CMS Collaboration, "Search for dark matter particles produced in association with a top quark pair at $\sqrt{s} = 13$ TeV", *Phys. Rev. Lett.* **122** (2019) 011803, doi:10.1103/PhysRevLett.122.011803, arXiv:1807.06522.

[10] CMS Collaboration, "Search for dark matter produced in association with heavy-flavor quark pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV", *Eur. Phys. J. C* **77** (2017), no. 12, 845, doi:10.1140/epjc/s10052-017-5317-4, arXiv:1706.02581.

[11] CMS Collaboration, "Searches for physics beyond the standard model with the M_{T2} variable in hadronic final states with and without disappearing tracks in proton-proton collisions at $\sqrt{s} = 13$ TeV", *Eur. Phys. J. C* **80** (2020) 3, doi:10.1140/epjc/s10052-019-7493-x, arXiv:1909.03460.

[12] ATLAS Collaboration, "Search for dark matter produced in association with bottom or top quarks in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector", *Eur. Phys. J. C* **78** (2018) 18, doi:10.1140/epjc/s10052-017-5486-1, arXiv:1710.11412.

[13] D. Abercrombie et al., "Dark Matter benchmark models for early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum", *Phys. Dark Univ.* **27** (2020) 100371, doi:10.1016/j.dark.2019.100371, arXiv:1507.00966.

[14] M. Bauer, U. Haisch, and F. Kahlhoefer, "Simplified dark matter models with two Higgs doublets: I. Pseudoscalar mediators", *JHEP* **05** (2017) 138, doi:10.1007/JHEP05(2017)138, arXiv:1701.07427.

[15] T. Abe et al., "LHC Dark Matter Working Group: Next-generation spin-0 dark matter models", *Phys. Dark Univ.* **27** (2020) 100351, doi:10.1016/j.dark.2019.100351, arXiv:1810.09420.

[16] CMS Collaboration, "Search for dark matter produced in association with a Higgs boson decaying to a pair of bottom quarks in proton–proton collisions at $\sqrt{s} = 13$ TeV", *Eur. Phys. J. C* **79** (2019), no. 3, 280, doi:10.1140/epjc/s10052-019-6730-7, arXiv:1811.06562.

[17] ATLAS Collaboration, "Search for heavy ZZ resonances in the $\ell^+\ell^-\ell^+\ell^-$ and $\ell^+\ell^-\nu\bar{\nu}$ final states using proton –proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector", *Eur. Phys. J. C* **78** (2018) 293, doi:10.1140/epjc/s10052-018-5686-3, arXiv:1712.06386.

[18] ATLAS Collaboration, "Search for heavy resonances decaying into WW in the $e\nu\mu\nu$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector", *Eur. Phys. J. C* **78** (2018) 24, doi:10.1140/epjc/s10052-017-5491-4, arXiv:1710.01123.

[19] CMS Collaboration, "Search for beyond the standard model Higgs bosons decaying into a $b\bar{b}$ pair in pp collisions at $\sqrt{s} = 13$ TeV", *JHEP* **08** (2018) 113, doi:10.1007/JHEP08(2018)113, arXiv:1805.12191.

[20] ATLAS Collaboration, "Constraints on mediator-based dark matter and scalar dark energy models using $\sqrt{s} = 13$ TeV pp collision data collected by the ATLAS detector", *JHEP* **05** (2019) 142, doi:10.1007/JHEP05(2019)142, arXiv:1903.01400.

[21] J. Alwall et al., "The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations", *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.

[22] S. Frixione, P. Nason, and C. Oleari, "Matching NLO QCD computations with Parton Shower simulations: the POWHEG method", *JHEP* **11** (2007) 070, doi:10.1088/1126-6708/2007/11/070, arXiv:0709.2092.

[23] S. Alioli, P. Nason, C. Oleari, and E. Re, "A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX", *JHEP* **06** (2010) 043, doi:10.1007/JHEP06(2010)043, arXiv:1002.2581.

[24] T. Sjöstrand et al., "An introduction to PYTHIA 8.2", *Computer Physics Communications* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.

[25] NNPDF Collaboration, "Parton distributions for the LHC Run II", *JHEP* **04** (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849.

[26] CMS Collaboration, "Event generator tunes obtained from underlying event and multiparton scattering measurements", *Eur. Phys. J. C* **76** (2016) 155, doi:10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.

[27] P. Skands, S. Carrazza, and J. Rojo, "Tuning PYTHIA 8.1: the Monash 2013 tune", *Eur. Phys. J. C* **74** (2014) 3024, doi:10.1140/epjc/s10052-014-3024-y, arXiv:1404.5630.

[28] GEANT4 Collaboration, "GEANT4—a simulation toolkit", *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.

[29] CMS Collaboration, "The CMS trigger system", *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.

[30] CMS Collaboration, "The CMS Experiment at the CERN LHC", *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[31] CMS Collaboration, "Particle-flow reconstruction and global event description with the CMS detector", *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.

[32] CMS Collaboration, "Performance of reconstruction and identification of τ leptons decaying to hadrons and ν_τ in pp collisions at $\sqrt{s} = 13$ TeV", *JINST* **13** (2018) P10005, doi:10.1088/1748-0221/13/10/P10005, arXiv:1809.02816.

[33] CMS Collaboration, "Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV", *JINST* **12** (2017) P02014, doi:10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.

[34] CMS Collaboration, "Performance of missing transverse momentum reconstruction in proton-proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector", *JINST* **14** (2019) P07004, doi:10.1088/1748-0221/14/07/P07004, arXiv:1903.06078.

[35] D. Contardo et al., "Technical Proposal for the Phase-II Upgrade of the CMS Detector", technical report, Geneva, 2015. doi:10.17181/CERN.VU8I.D59J.

[36] M. Cacciari, G. P. Salam, and G. Soyez, “The anti-k_{T} jet clustering algorithm”, *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.

[37] CMS Collaboration, “Pileup mitigation at CMS in 13 TeV data”, *JINST* **15** (2020) P09018, doi:10.1088/1748-0221/15/09/P09018, arXiv:2003.00503.

[38] D. Bertolini, P. Harris, M. Low, and N. Tran, “Pileup Per Particle Identification”, *JHEP* **10** (2014) 059, doi:10.1007/JHEP10(2014)059, arXiv:1407.6013.

[39] CMS Collaboration, “Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV”, *JINST* **13** (2018) P05011, doi:10.1088/1748-0221/13/05/P05011, arXiv:1712.07158.

[40] CMS Collaboration, “Identification of hadronic tau lepton decays using a deep neural network”, *JINST* **17** (2022) P07023, doi:10.1088/1748-0221/17/07/P07023, arXiv:2201.08458.

[41] CMS Collaboration, “Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC”, *JINST* **16** (2021) P05014, doi:10.1088/1748-0221/16/05/P05014, arXiv:2012.06888.

[42] CMS Collaboration, “Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **13** (2018) P06015, doi:10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.

[43] A. J. Barr, “Measuring slepton spin at the LHC”, *JHEP* **02** (2006) 042, doi:10.1088/1126-6708/2006/02/042, arXiv:hep-ph/0511115.

[44] CMS Collaboration, “Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS”, *Eur. Phys. J. C* **81** (2021) 800, doi:10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.

[45] CMS Collaboration, “CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s}$ = 13 TeV”, CMS Physics Analysis Summary CMS-PAS-LUM-17-004, 2018.

[46] CMS Collaboration, “CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s}$ = 13 TeV”, CMS Physics Analysis Summary CMS-PAS-LUM-18-002, 2019.

[47] CMS Collaboration, “Measurements of Inclusive W and Z Cross Sections in pp Collisions at $\sqrt{s} = 7$ TeV”, *JHEP* **01** (2011) 080, doi:10.1007/JHEP01(2011)080, arXiv:1012.2466.

[48] CMS Collaboration, “Measurement of the inelastic proton-proton cross section at $\sqrt{s} = 13$ TeV”, *JHEP* **07** (2018) 161, doi:10.1007/JHEP07(2018)161, arXiv:1802.02613.

[49] CMS Collaboration, “Observation of the associated production of a single top quark and a W boson in pp collisions at $\sqrt{s}$ =8 TeV”, *Phys. Rev. Lett.* **112** (2014) 231802, doi:10.1103/PhysRevLett.112.231802, arXiv:1401.2942.

[50] CMS Collaboration, “Measurement of the ZZ production cross section and Z $\rightarrow \ell^+\ell^-\ell'^+\ell'^-$ branching fraction in pp collisions at $\sqrt{s}$=13 TeV”, *Phys. Lett. B* **763** (2016) 280, doi:10.1016/j.physletb.2016.10.054, arXiv:1607.08834. [Erratum: doi:Phys.Lett.B772,884--884(2017)].

[51] CMS Collaboration, "Measurement of the inclusive and differential WZ production cross sections, polarization angles, and triple gauge couplings in pp collisions at $\sqrt{s}$ = 13 TeV", *JHEP* **07** (2022) 032, doi:10.1007/JHEP07(2022)032, arXiv:2110.11231.

[52] J. Butterworth et al., "PDF4LHC recommendations for LHC Run II", *J. Phys. G: Nucl. Part. Phys.* **43** (2016), no. 2, 023001, doi:10.1088/0954-3899/43/2/023001, arXiv:1510.03865.

[53] S. Dulat et al., "New parton distribution functions from a global analysis of quantum chromodynamics", *Phys. Rev. D* **93** (2016), no. 3, 033006, doi:10.1103/PhysRevD.93.033006, arXiv:1506.07443.

[54] L. A. Harland-Lang, A. D. Martin, P. Motylinski, and R. S. Thorne, "Parton distributions in the LHC era: MMHT 2014 PDFs", *Eur. Phys. J. C* **75** (2015), no. 5, 204, doi:10.1140/epjc/s10052-015-3397-6, arXiv:1412.3989.

[55] LHC Higgs Cross Section Working Group, "Handbook of LHC Higgs cross sections: 3. Higgs properties", CERN Report CERN-2013-004, 2013. doi:10.5170/CERN-2013-004, arXiv:1307.1347.

[56] T. Junk, "Confidence level computation for combining searches with small statistics", *Nucl. Instrum. Meth. A* **434** (1999) 435, doi:10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.

[57] A. L. Read, "Presentation of search results: the CL_s technique", *J. Phys. G* **28** (2002), no. 10, 2693, doi:10.1088/0954-3899/28/10/313.

[58] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, "Asymptotic formulae for likelihood-based tests of new physics", *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727. [Erratum: doi:10.1140/epjc/s10052-013-2501-z].

[59] HEPData record for this analysis, 2024. doi:10.17182/hepdata.152385.

A The CMS Collaboration

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

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

Universiteit Antwerpen, Antwerpen, Belgium
T. Janssen, T. Van Laer, P. Van Mechelen

Vrije Universiteit Brussel, Brussel, Belgium
N. Breugelmans, J. D'Hondt, S. Dansana, A. De Moor, M. Delcourt, F. Heyen, S. Lowette, I. Makarenko, D. Müller, 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, G. De Lentdecker, H. Evard, L. Favart, P. Gianneios, J. Jaramillo, A. Khalilzadeh, F.A. Khan, K. Lee, M. Mahdavikhorrami, A. Malara, S. Paredes, M.A. Shahzad, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer

Ghent University, Ghent, Belgium
M. De Coen, D. Dobur, G. Gokbulut, Y. Hong, J. Knolle, L. Lambrecht, D. Marckx, K. Mota Amarilo, A. Samalan, K. Skovpen, N. Van Den Bossche, J. van der Linden, L. Wezenbeek

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
A. Benecke, A. Bethani, G. Bruno, C. Caputo, J. De Favereau De Jeneret, C. Delaere, I.S. Donertas, A. Giammanco, A.O. Guzel, Sa. Jain, V. Lemaitre, J. Lidrych, P. Mastrapasqua, T.T. Tran, S. Wertz

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, M. Alves Gallo Pereira, E. Coelho, G. Correia Silva, C. Hensel, T. Menezes De Oliveira, C. Mora Herrera[4], A. Moraes, P. Rebello Teles, M. Soeiro, A. Vilela Pereira[4]

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[5], E.M. Da Costa, G.G. Da Silveira[6], D. De Jesus Damiao, S. Fonseca De Souza, R. Gomes De Souza, M. Macedo, J. Martins[7], L. Mundim, H. Nogima, J.P. Pinheiro, A. Santoro, A. Sznajder, M. Thiel

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil
C.A. Bernardes[6], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, I. Maietto Silverio, P.G. Mercadante, S.F. Novaes, B. Orzari, Sandra S. Padula

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

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

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

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

Department of Physics, Tsinghua University, Beijing, China
Z. Hu, Z. Liang, J. Liu, K. Yi[8,9]

Institute of High Energy Physics, Beijing, China
G.M. Chen[10], H.S. Chen[10], M. Chen[10], F. Iemmi, C.H. Jiang, A. Kapoor[11], H. Liao, Z.-A. Liu[12], R. Sharma[13], J.N. Song[12], J. Tao, C. Wang[10], J. Wang, Z. Wang[10], H. Zhang, J. Zhao

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

Guangdong Provincial Key Laboratory of Nuclear Science and Guangdong-Hong Kong Joint Laboratory 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[14], B. Li, J. Zhang

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
X. Gao[15], Y. Li

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

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

Universidad de Antioquia, Medellin, Colombia
F. Ramirez, 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
D. Giljanovic, 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, S. Mishra, A. Starodumov[16], T. Susa

University of Cyprus, Nicosia, Cyprus
A. Attikis, K. Christoforou, A. Hadjiagapiou, C. Leonidou, J. Mousa, 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., A. Kveton

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
A.A. Abdelalim[17,18], S. Elgammal[19], A. Ellithi Kamel[20]

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

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

Department of Physics, University of Helsinki, Helsinki, Finland
H. Kirschenmann, K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
S. Bharthuar, N. Bin Norjoharuddeen, E. Brücken, F. Garcia, P. Inkaew, K.T.S. Kallonen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, L. Martikainen, M. Myllymäki, M.m. Rantanen, H. Siikonen, J. Tuominiemi

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

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, M. Kumar, V. Lohezic, J. Malcles, F. Orlandi, L. Portales, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[21], 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, A. Cappati, C. Charlot, M. Chiusi, F. Damas, O. Davignon, A. De Wit, I.T. Ehle, B.A. Fontana Santos Alves, S. Ghosh, A. Gilbert, R. Granier de Cassagnac, A. Hakimi, B. Harikrishnan, L. Kalipoliti, G. Liu, M. Nguyen, C. Ochando, R. Salerno, J.B. Sauvan, Y. Sirois, L. Urda Gómez, E. Vernazza, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[22], J. Andrea, D. Apparu, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, S. Falke, U. Goerlach, R. Haeberle, A.-C. Le Bihan, M. Meena, O. Poncet, G. Saha, M.A. Sessini, P. Van Hove, 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, C. Dozen[23], H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, C. Greenberg, G. Grenier, B. Ille, E. Jourd'huy, I.B. Laktineh, M. Lethuillier, L. Mirabito, S. Perries, A. Purohit, M. Vander Donckt, P. Verdier, J. Xiao

Georgian Technical University, Tbilisi, Georgia
A. Khvedelidze[16], I. Lomidze, Z. Tsamalaidze[16]

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

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
S. Diekmann, A. Dodonova, N. Eich, D. Eliseev, F. Engelke, J. Erdmann, M. Erdmann, P. Fackeldey, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, A. Jung, M.y. Lee, F. Mausolf, M. Merschmeyer, A. Meyer, S. Mukherjee, D. Noll, F. Nowotny, A. Pozdnyakov, Y. Rath, W. Redjeb, F. Rehm, H. Reithler, V. Sarkisovi, A. Schmidt, C. Seth, A. Sharma, J.L. Spah, A. Stein, F. Torres Da Silva De Araujo[24], S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
C. Dziwok, G. Flügge, T. Kress, A. Nowack, O. Pooth, A. Stahl, T. Ziemons, A. Zotz

Deutsches Elektronen-Synchrotron, Hamburg, Germany
H. Aarup Petersen, M. Aldaya Martin, J. Alimena, S. Amoroso, Y. An, J. Bach, S. Baxter, M. Bayatmakou, H. Becerril Gonzalez, O. Behnke, A. Belvedere, F. Blekman[25], K. Borras[26], A. Campbell, A. Cardini, C. Cheng, F. Colombina, M. De Silva, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, O. Filatov, E. Gallo[25], A. Geiser, V. Guglielmi, M. Guthoff, A. Hinzmann, L. Jeppe, B. Kaech, M. Kasemann, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, W. Lange, D. Leyva Pernia, K. Lipka[27], W. Lohmann[28], F. Lorkowski, 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, Y. Otarid, J. Park, E. Ranken, A. Raspereza, D. Rastorguev, J. Rübenach, L. Rygaard, A. Saggio, M. Scham[29,26], S. Schnake[26], P. Schütze, C. Schwanenberger[25], D. Selivanova, K. Sharko, M. Shchedrolosiev, D. Stafford, F. Vazzoler, A. Ventura Barroso, R. Walsh, D. Wang, Q. Wang, Y. Wen, K. Wichmann, L. Wiens[26], C. Wissing, Y. Yang, A. Zimermmane Castro Santos

University of Hamburg, Hamburg, Germany
A. Albrecht, S. Albrecht, M. Antonello, S. Bein, L. Benato, S. Bollweg, M. Bonanomi, P. Connor, K. El Morabit, Y. Fischer, E. Garutti, A. Grohsjean, J. Haller, H.R. Jabusch, G. Kasieczka, P. Keicher, R. Klanner, W. Korcari, T. Kramer, C.c. Kuo, V. Kutzner, F. Labe, J. Lange, A. Lobanov, C. Matthies, L. Moureaux, M. Mrowietz, A. Nigamova, Y. Nissan, A. Paasch, K.J. Pena Rodriguez, T. Quadfasel, B. Raciti, M. Rieger, D. Savoiu, J. Schindler, P. Schleper, M. Schröder, J. Schwandt, M. Sommerhalder, H. Stadie, G. Steinbrück, A. Tews, M. Wolf

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
S. Brommer, M. Burkart, E. Butz, T. Chwalek, A. Dierlamm, A. Droll, U. Elicabuk, N. Faltermann, M. Giffels, A. Gottmann, F. Hartmann[30], R. Hofsaess,

M. Horzela, U. Husemann, J. Kieseler, M. Klute, R. Koppenhöfer, J.M. Lawhorn, M. Link, A. Lintuluoto, B. Maier, S. Maier, S. Mitra, M. Mormile, Th. Müller, M. Neukum, M. Oh, E. Pfeffer, M. Presilla, G. Quast, K. Rabbertz, B. Regnery, N. Shadskiy, I. Shvetsov, H.J. Simonis, L. Sowa, L. Stockmeier, K. Tauqeer, M. Toms, N. Trevisani, R.F. Von Cube, M. Wassmer, S. Wieland, F. Wittig, R. Wolf, X. Zuo

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, A. Kyriakis, A. Papadopoulos[30], A. Stakia

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

National Technical University of Athens, Athens, Greece
G. Bakas, T. Chatzistavrou, G. Karapostoli, K. Kousouris, I. Papakrivopoulos, E. Siamarkou, G. Tsipolitis, A. Zacharopoulou

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

HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
C. Hajdu, D. Horvath[31,32], K. Márton, A.J. Rádl[33], F. Sikler, V. Veszpremi

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanád, K. Farkas, A. Fehérkuti[34], M.M.A. Gadallah[35], Á. Kadlecsik, P. Major, G. Pásztor, G.I. Veres

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

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

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
F. Nemes[34], T. Novak

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, K. Sandeep, T. Sheokand, J.B. Singh, A. Singla

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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
S. Baradia, S. Barman[37], 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.C. Behera, S. Chatterjee, G. Dash, P. Jana, P. Kalbhor, S. Kamble, J.R. Komaragiri[38], D. Kumar[38], P.R. Pujahari, N.R. Saha, A. Sharma, A.K. Sikdar, R.K. Singh, P. Verma, S. Verma, A. Vijay

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

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

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India
S. Bahinipati[39], C. Kar, D. Maity[40], P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu[40], K. Naskar[40], A. Nayak[40], S. Nayak, K. Pal, P. Sadangi, S.K. Swain, S. Varghese[40], D. Vats[40]

Indian Institute of Science Education and Research (IISER), Pune, India
S. Acharya[41], A. Alpana, S. Dube, B. Gomber[41], P. Hazarika, B. Kansal, A. Laha, B. Sahu[41], S. Sharma, K.Y. Vaish

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[42], A. Jafari[43], 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[46], M. Mohammadi Najafabadi, S. Tizchang[47]

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], A. Colaleo[a,b], D. Creanza[a,c], B. D'Anzi[a,b], N. De Filippis[a,c], M. De Palma[a,b], W. Elmetenawee[a,b,17], L. Fiore[a], G. Iaselli[a,c], 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], 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], A. Castro[†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], L. Giommi[a,b], C. Grandi[a], L. Guiducci[a,b], S. Lo Meo[a,48], 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,49], A. Di Mattia[a], A. Lapertosa[a], R. Potenza[a,b], A. Tricomi[a,b,49], C. Tuve[a,b]

INFN Sezione di Firenze[a], Università di Firenze[b], Firenze, Italy
P. Assiouras[a], G. Barbagli[a], G. Bardelli[a,b], B. Camaiani[a,b], A. Cassese[a], R. Ceccarelli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[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[50], D. Piccolo

INFN Sezione di Genova[a], Università di Genova[b], Genova, Italy
P. Chatagnon[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], 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.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], B.S. Pinolini[a], 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], A. Cagnotta[a,b], F. Carnevali[a,b], N. Cavallo[a,c], F. Fabozzi[a,c], A.O.M. Iorio[a,b], L. Lista[a,b,51], P. Paolucci[a,30], B. Rossi[a]

INFN Sezione di Padova[a], Università di Padova[b], Padova, Italy; Università di Trento[c], Trento, Italy
R. Ardino[a], P. Azzi[a], N. Bacchetta[a,52], D. Bisello[a,b], P. Bortignon[a], G. Bortolato[a,b], A. Bragagnolo[a,b], A.C.M. Bulla[a], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a], F. Gasparini[a,b], U. Gasparini[a,b], E. Lusiani[a], M. Margoni[a,b], A.T. Meneguzzo[a,b], M. Michelotto[a], M. Migliorini[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
C. Aimè[a], A. Braghieri[a], S. Calzaferri[a], D. Fiorina[a], P. Montagna[a,b], 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. Fanò[a,b], M. Magherini[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.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], R. Castaldi[a], M.A. Ciocci[a,b], M. Cipriani[a,b], V. D'Amante[a,d], R. Dell'Orso[a], S. Donato[a], A. Giassi[a], F. Ligabue[a,c], A.C. Marini[a], D. Matos Figueiredo[a], A. Messineo[a,b], M. Musich[a,b], F. Palla[a], A. Rizzi[a,b], G. Rolandi[a,c], S. Roy Chowdhury[a], T. Sarkar[a], A. Scribano[a], P. Spagnolo[a], 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
C. Baldenegro Barrera[a,b], P. Barria[a], C. Basile[a,b], F. Cavallari[a], L. Cunqueiro Mendez[a,b], D. Del Re[a,b], E. Di Marco[a,b], M. Diemoz[a], F. Errico[a,b], E. Longo[a,b], J. Mijuskovic[a,b], G. Organtini[a,b], F. Pandolfi[a], R. Paramatti[a,b], C. Quaranta[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], L. Soffi[a]

INFN Sezione di Torino[a], Università di Torino[b], Torino, Italy; Università del Piemonte Orientale[c], Novara, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a], R. Bellan[a,b], A. Bellora[a,b], 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], F. Legger[a], F. Luongo[a,b], C. Mariotti[a], L. Markovic[a,b], S. Maselli[a], A. Mecca[a,b], L. Menzio[a,b], P. Meridiani[a], E. Migliore[a,b], M. Monteno[a], R. Mulargia[a], M.M. Obertino[a,b], G. Ortona[a], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[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], 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]

Kyungpook National University, Daegu, Korea
S. Dogra, J. Hong, B. Kim, J. Kim, D. Lee, H. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, M.S. Ryu, 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

Hanyang University, Seoul, Korea
E. Asilar, J. Choi, D. Kim, T.J. Kim, J.A. Merlin, Y. Ryou

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

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

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

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

University of Seoul, Seoul, Korea
W. Jang, D.Y. Kang, Y. Kang, 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
S. Ha, H.D. Yoo

Sungkyunkwan University, Suwon, Korea
M. Choi, M.R. Kim, H. Lee, 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, A. Gaile, C. Munoz Diaz, D. Osite, G. Pikurs, A. Potrebko, M. Seidel,

D. Sidiropoulos Kontos

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

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

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Yusuff[54], Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, H.A. Encinas Acosta, L.G. Gallegos Maríñez, M. León Coello, J.A. Murillo Quijada, A. Sehrawat, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
G. Ayala, H. Castilla-Valdez, H. Crotte Ledesma, E. De La Cruz-Burelo, I. Heredia-De La Cruz[55], R. Lopez-Fernandez, J. Mejia Guisao, C.A. Mondragon Herrera, 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, 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, H.R. Hoorani, W.A. Khan

AGH University of Krakow, Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland
V. Avati, L. Grzanka, M. Malawski

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, 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
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, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, G.B. Marozzo, T. Niknejad, A. Petrilli, M. Pisano, J. Seixas, J. Varela, J.W. Wulff

Faculty of Physics, University of Belgrade, Belgrade, Serbia
P. Adzic, P. Milenovic

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

D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
J. Alcaraz Maestre, Cristina F. Bedoya, Oliver M. Carretero, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, D. Fernández Del Val, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, E. Martin Viscasillas, D. Moran, C. M. Morcillo Perez, Á. Navarro Tobar, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, S. Sánchez Navas, J. Sastre, 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. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, P. Leguina, E. Palencia Cortezon, J. Prado Pico, C. Ramón Álvarez, V. Rodríguez Bouza, A. Soto Rodríguez, A. Trapote, C. Vico Villalba, P. Vischia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
S. Bhowmik, S. Blanco Fernández, J.A. Brochero Cifuentes, 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, L. Scodellaro, I. Vila, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
B. Kailasapathy[56], D.D.C. Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G.D. Dharmaratna[57], K. Liyanage, N. Perera

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, C. Amendola, E. Auffray, G. Auzinger, J. Baechler, D. Barney, A. Bermúdez Martínez, M. Bianco, A.A. Bin Anuar, A. Bocci, L. Borgonovi, C. Botta, E. Brondolin, C. Caillol, G. Cerminara, N. Chernyavskaya, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, G. Franzoni, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, J. Hegeman, J.K. Heikkilä, B. Huber, V. Innocente, T. James, P. Janot, O. Kaluzinska, O. Karacheban[28], S. Laurila, P. Lecoq, E. Leutgeb, C. Lourenço, L. Malgeri, M. Mannelli, M. Matthewman, A. Mehta, F. Meijers, S. Mersi, E. Meschi, V. Milosevic, F. Monti, F. Moortgat, M. Mulders, I. Neutelings, S. Orfanelli, F. Pantaleo, G. Petrucciani, A. Pfeiffer, M. Pierini, H. Qu, D. Rabady, B. Ribeiro Lopes, M. Rovere, H. Sakulin, S. Sanchez Cruz, S. Scarfi, C. Schwick, M. Selvaggi, A. Sharma, K. Shchelina, P. Silva, P. Sphicas[58], A.G. Stahl Leiton, A. Steen, S. Summers, D. Treille, P. Tropea, D. Walter, J. Wanczyk[59], J. Wang, K.A. Wozniak[60], S. Wuchterl, P. Zehetner, P. Zejdl, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
T. Bevilacqua[61], L. Caminada[61], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli[61], L. Noehte[61],

T. Rohe

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
T.K. Aarrestad, K. Androsov[59], M. Backhaus, G. Bonomelli, A. Calandri, C. Cazzaniga, K. Datta, P. De Bryas Dexmiers D'archiac[59], A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, M. Galli, K. Gedia, F. Glessgen, C. Grab, N. Härringer, T.G. Harte, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, M. Marchegiani, L. Marchese, C. Martin Perez, A. Mascellani[59], F. Nessi-Tedaldi, F. Pauss, V. Perovic, S. Pigazzini, B. Ristic, F. Riti, R. Seidita, J. Steggemann[59], A. Tarabini, D. Valsecchi, R. Wallny

Universität Zürich, Zurich, Switzerland
C. Amsler[62], P. Bärtschi, M.F. Canelli, K. Cormier, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, F. Meng, U. Molinatti, J. Motta, A. Reimers, P. Robmann, M. Senger, E. Shokr, F. Stäger, R. Tramontano

National Central University, Chung-Li, Taiwan
C. Adloff[63], D. Bhowmik, C.M. Kuo, W. Lin, P.K. Rout, P.C. Tiwari[38], S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
L. Ceard, K.F. Chen, P.s. Chen, Z.g. Chen, A. De Iorio, W.-S. Hou, T.h. Hsu, Y.w. Kao, S. Karmakar, R. Khurana, 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, V. Wachirapusitanand

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
D. Agyel, F. Boran, F. Dolek, I. Dumanoglu[64], E. Eskut, Y. Guler[65], E. Gurpinar Guler[65], C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir[66], A. Polatoz, B. Tali[67], U.G. Tok, S. Turkcapar, E. Uslan, I.S. Zorbakir

Middle East Technical University, Physics Department, Ankara, Turkey
G. Sokmen, M. Yalvac[68]

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

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak[64,72], G.G. Dincer[64], Y. Komurcu, S. Sen[73]

Istanbul University, Istanbul, Turkey
O. Aydilek[74], B. Hacisahinoglu, I. Hos[75], B. Kaynak, S. Ozkorucuklu, O. Potok, H. Sert, C. Simsek, C. Zorbilmez

Yildiz Technical University, Istanbul, Turkey
S. Cerci[67], B. Isildak[76], D. Sunar Cerci, T. Yetkin

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

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

L. Levchuk

University of Bristol, Bristol, United Kingdom
D. Anthony, J.J. Brooke, A. Bundock, F. Bury, E. Clement, D. Cussans, H. Flacher, M. Glowacki, J. Goldstein, H.F. Heath, M.-L. Holmberg, L. Kreczko, S. Paramesvaran, L. Robertshaw, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou[77], K. Walkingshaw Pass

Rutherford Appleton Laboratory, Didcot, United Kingdom
A.H. Ball, K.W. Bell, A. Belyaev[78], C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, A. Elliot, K.V. Ellis, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, 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, C.E. Brown, O. Buchmuller, V. Cacchio, C.A. Carrillo Montoya, G.S. Chahal[79], D. Colling, J.S. Dancu, I. Das, P. Dauncey, G. Davies, J. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, A. Howard, G. Iles, C.R. Knight, J. Langford, J. León Holgado, L. Lyons, A.-M. Magnan, S. Mallios, M. Mieskolainen, J. Nash[80], M. Pesaresi, P.B. Pradeep, B.C. Radburn-Smith, A. Richards, A. Rose, K. Savva, C. Seez, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, L.H. Vage, T. Virdee[30], M. Vojinovic, N. Wardle, D. Winterbottom

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

Baylor University, Waco, Texas, USA
S. Abdullin, A. Brinkerhoff, E. Collins, M.R. Darwish[81], J. Dittmann, K. Hatakeyama, J. Hiltbrand, B. McMaster, J. Samudio, S. Sawant, C. Sutantawibul, J. Wilson

Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez, C. Huerta Escamilla, A.E. Simsek, R. Uniyal, A.M. Vargas Hernandez

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

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

Brown University, Providence, Rhode Island, USA
G. Benelli, D. Cutts, L. Gouskos, M. Hadley, U. Heintz, J.M. Hogan[83], T. Kwon, G. Landsberg, K.T. Lau, D. Li, J. Luo, S. Mondal, N. Pervan, T. Russell, S. Sagir[84], X. Shen, F. Simpson, M. Stamenkovic, N. Venkatasubramanian, X. Yan

University of California, Davis, Davis, California, USA
S. Abbott, C. Brainerd, R. Breedon, H. Cai, M. Calderon De La Barca Sanchez,

M. Chertok, M. Citron, J. Conway, P.T. Cox, R. Erbacher, F. Jensen, O. Kukral, G. Mocellin, M. Mulhearn, S. Ostrom, W. Wei, S. Yoo, F. Zhang

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

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

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

University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA
A. Barzdukas, L. Brennan, C. Campagnari, K. Downham, C. Grieco, J. Incandela, J. Kim, A.J. Li, P. Masterson, H. Mei, J. Richman, S.N. Santpur, U. Sarica, R. Schmitz, F. Setti, J. Sheplock, D. Stuart, T.Á. Vámi, S. Wang, D. Zhang

California Institute of Technology, Pasadena, California, USA
S. Bhattacharya, A. Bornheim, O. Cerri, A. Latorre, J. Mao, H.B. Newman, G. Reales Gutiérrez, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
J. Alison, S. An, P. Bryant, M. Cremonesi, V. Dutta, T. Ferguson, T.A. Gómez Espinosa, A. Harilal, A. Kallil Tharayil, C. Liu, 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, G. Karathanasis, N. Manganelli, 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, S. Bright-Thonney, X. Chen, D.J. Cranshaw, J. Fan, X. Fan, S. Hogan, P. Kotamnives, J. Monroy, M. Oshiro, J.R. Patterson, M. Reid, A. Ryd, J. Thom, P. Wittich, R. Zou

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, G. Cummings, J. Dickinson, I. Dutta, V.D. Elvira, Y. Feng, J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, A. Grummer, S. Grünendahl, D. Guerrero, O. Gutsche, R.M. Harris, R. Heller, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, D. Lincoln, R. Lipton, T. Liu, C. Madrid, K. Maeshima, C. Mantilla, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, D. Noonan, S. Norberg, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[85], 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, 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, K. Matchev, N. Menendez, G. Mitselmakher, K. Mohrman, A. Muthirakalayil Madhu, N. Rawal, S. Rosenzweig, Y. Takahashi, J. Wang

Florida State University, Tallahassee, Florida, USA
T. Adams, A. Al Kadhim, A. Askew, S. Bower, V. Hagopian, R. Hashmi, R.S. Kim, S. Kim, T. Kolberg, G. Martinez, H. Prosper, P.R. Prova, M. Wulansatiti, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, Florida, USA
B. Alsufyani, M.M. Baarmand, S. Butalla, S. Das, T. Elkafrawy[87], M. Hohlmann, E. Yanes

University of Illinois Chicago, Chicago, USA, Chicago, USA
M.R. Adams, A. Baty, C. Bennett, R. Cavanaugh, R. Escobar Franco, O. Evdokimov, C.E. Gerber, M. Hawksworth, A. Hingrajiya, D.J. Hofman, J.h. Lee, D. S. Lemos, A.H. Merrit, C. Mills, S. Nanda, G. Oh, B. Ozek, D. Pilipovic, R. Pradhan, E. Prifti, T. Roy, S. Rudrabhatla, M.B. Tonjes, N. Varelas, M.A. Wadud, Z. Ye, J. Yoo

The University of Iowa, Iowa City, Iowa, USA
M. Alhusseini, D. Blend, K. Dilsiz[88], L. Emediato, G. Karaman, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[89], O. Neogi, H. Ogul[90], Y. Onel, A. Penzo, C. Snyder, E. Tiras[91]

Johns Hopkins University, Baltimore, Maryland, USA
B. Blumenfeld, L. Corcodilos, J. Davis, A.V. Gritsan, L. Kang, S. Kyriacou, P. Maksimovic, M. Roguljic, J. Roskes, S. Sekhar, 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, M. Pitt, S. Popescu[92], C. Rogan, C. Royon, R. Salvatico, S. Sanders, C. Smith, G. Wilson

Kansas State University, Manhattan, Kansas, USA
B. Allmond, R. Gujju Gurunadha, A. Ivanov, K. Kaadze, Y. Maravin, J. Natoli, D. Roy, G. Sorrentino

University of Maryland, College Park, Maryland, USA
A. Baden, A. Belloni, J. Bistany-riebman, Y.M. Chen, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, B. Kronheim, Y. Lai, S. Lascio, A.C. Mignerey, S. Nabili, C. Palmer, C. Papageorgakis, M.M. Paranjpe, E. Popova[93], A. Shevelev, L. Wang

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
J. Bendavid, I.A. Cali, P.c. Chou, M. D'Alfonso, J. Eysermans, C. Freer, G. Gomez-Ceballos, M. Goncharov, G. Grosso, P. Harris, D. Hoang, 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, G.S.F. Stephans,

Z. Wang, B. Wyslouch, T. J. Yang

University of Minnesota, Minneapolis, Minnesota, USA
B. Crossman, B.M. Joshi, C. Kapsiak, M. Krohn, D. Mahon, J. Mans, B. Marzocchi, M. Revering, R. Rusack, R. Saradhy, N. Strobbe

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

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

Northeastern University, Boston, Massachusetts, USA
G. Alverson, E. Barberis, J. Bonilla, M. Campana, J. Dervan, Y. Haddad, Y. Han, A. Krishna, J. Li, M. Lu, G. Madigan, R. Mccarthy, D.M. Morse, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari, D. Wood

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

University of Notre Dame, Notre Dame, Indiana, USA
G. Agarwal, R. Band, R. Bucci, S. Castells, A. Das, R. Goldouzian, M. Hildreth, K.W. Ho, K. Hurtado Anampa, T. Ivanov, C. Jessop, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, C. Moore, Y. Musienko[16], H. Nelson, M. Osherson, A. Piccinelli, R. Ruchti, A. Townsend, Y. Wan, M. Wayne, H. Yockey, M. Zarucki, L. Zygala

The Ohio State University, Columbus, Ohio, USA
A. Basnet, B. Bylsma, M. Carrigan, L.S. Durkin, C. Hill, M. Joyce, M. Nunez Ornelas, K. Wei, B.L. Winer, B. R. Yates

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

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

Purdue University, West Lafayette, Indiana, USA
A.S. Bakshi, S. Chandra, R. Chawla, A. Gu, L. Gutay, M. Jones, A.W. Jung, A.M. Koshy, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, V. Scheurer, J.F. Schulte, M. Stojanovic, J. Thieman, A. K. Virdi, F. Wang, A. Wildridge, W. Xie, Y. Yao

Purdue University Northwest, Hammond, Indiana, USA
J. Dolen, N. Parashar, A. Pathak

Rice University, Houston, Texas, USA
D. Acosta, T. Carnahan, K.M. Ecklund, P.J. Fernández Manteca, S. Freed, P. Gardner, F.J.M. Geurts, I. Krommydas, W. Li, J. Lin, O. Miguel Colin, B.P. Padley,

R. Redjimi, J. Rotter, E. Yigitbasi, Y. Zhang

University of Rochester, Rochester, New York, USA
A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, N. Parmar, P. Parygin[93], R. Taus

Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
B. Chiarito, J.P. Chou, S.V. Clark, D. Gadkari, Y. Gershtein, E. Halkiadakis, M. Heindl, C. Houghton, D. Jaroslawski, S. Konstantinou, I. Laflotte, A. Lath, R. Montalvo, K. Nash, J. Reichert, H. Routray, P. Saha, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, J. Vora, H. Wang

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

Texas A&M University, College Station, Texas, USA
D. Aebi, M. Ahmad, T. Akhter, O. Bouhali[94], R. Eusebi, J. Gilmore, T. Huang, T. Kamon[95], H. Kim, S. Luo, R. Mueller, D. Overton, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, Texas, USA
N. Akchurin, J. Damgov, N. Gogate, V. Hegde, A. Hussain, Y. Kazhykarim, K. Lamichhane, S.W. Lee, 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, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, J. Viinikainen

University of Virginia, Charlottesville, Virginia, USA
B. Cardwell, H. Chung, B. Cox, J. Hakala, R. Hirosky, A. Ledovskoy, C. Neu

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, S. Dasu, I. De Bruyn, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Herve, C.K. Koraka, A. Lanaro, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, A. Mohammadi, S. Mondal, 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 institute or an international laboratory covered by a cooperation agreement with CERN
S. Afanasiev, V. Alexakhin, D. Budkouski, I. Golutvin†, I. Gorbunov, V. Karjavine, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev[96], V. Palichik, V. Perelygin, M. Savina, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, B.S. Yuldashev[97], A. Zarubin, I. Zhizhin, G. Gavrilov, V. Golovtcov, Y. Ivanov, V. Kim[96], P. Levchenko[98], V. Murzin, V. Oreshkin, D. Sosnov, V. Sulimov, L. Uvarov, A. Vorobyev†, Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, D. Kirpichnikov, M. Kirsanov, N. Krasnikov, I. Tlisova, A. Toropin, T. Aushev, V. Gavrilov, N. Lychkovskaya, A. Nikitenko[99,100], V. Popov, A. Zhokin, R. Chistov[96], M. Danilov[96], S. Polikarpov[96], V. Andreev, M. Azarkin, M. Kirakosyan, A. Terkulov, E. Boos, V. Bunichev, M. Dubinin[85], L. Dudko, A. Ershov, V. Klyukhin, O. Kodolova[100],

S. Obraztsov, M. Perfilov, V. Savrin, P. Volkov, G. Vorotnikov, V. Blinov[96], T. Dimova[96], A. Kozyrev[96], O. Radchenko[96], Y. Skovpen[96], V. Kachanov, D. Konstantinov, S. Slabospitskii, A. Uzunian, A. Babaev, V. Borshch, D. Druzhkin[101]

Authors affiliated with an institute formerly covered by a cooperation agreement with CERN
V. Chekhovsky, V. Makarenko

†: 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 Universidade Estadual de Campinas, Campinas, Brazil
[6]Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
[7]Also at UFMS, Nova Andradina, Brazil
[8]Also at Nanjing Normal University, Nanjing, China
[9]Now at The University of Iowa, Iowa City, Iowa, USA
[10]Also at University of Chinese Academy of Sciences, Beijing, China
[11]Also at China Center of Advanced Science and Technology, Beijing, China
[12]Also at University of Chinese Academy of Sciences, Beijing, China
[13]Also at China Spallation Neutron Source, Guangdong, China
[14]Now at Henan Normal University, Xinxiang, China
[15]Also at Université Libre de Bruxelles, Bruxelles, Belgium
[16]Also at an institute or an international laboratory covered by a cooperation agreement with CERN
[17]Also at Helwan University, Cairo, Egypt
[18]Now at Zewail City of Science and Technology, Zewail, Egypt
[19]Now at British University in Egypt, Cairo, Egypt
[20]Now at Cairo University, Cairo, Egypt
[21]Also at Purdue University, West Lafayette, Indiana, USA
[22]Also at Université de Haute Alsace, Mulhouse, France
[23]Also at Istinye University, Istanbul, Turkey
[24]Also at The University of the State of Amazonas, Manaus, Brazil
[25]Also at University of Hamburg, Hamburg, Germany
[26]Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
[27]Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
[28]Also at Brandenburg University of Technology, Cottbus, Germany
[29]Also at Forschungszentrum Jülich, Juelich, Germany
[30]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
[31]Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
[32]Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
[33]Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
[34]Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
[35]Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
[36]Also at Punjab Agricultural University, Ludhiana, India
[37]Also at University of Visva-Bharati, Santiniketan, India
[38]Also at Indian Institute of Science (IISc), Bangalore, India
[39]Also at IIT Bhubaneswar, Bhubaneswar, India
[40]Also at Institute of Physics, Bhubaneswar, India

[41]Also at University of Hyderabad, Hyderabad, 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, Isfahan University of Technology, Isfahan, Iran
[47]Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran
[48]Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
[49]Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
[50]Also at Università degli Studi Guglielmo Marconi, Roma, Italy
[51]Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
[52]Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
[53]Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
[54]Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
[55]Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
[56]Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
[57]Also at Saegis Campus, Nugegoda, Sri Lanka
[58]Also at National and Kapodistrian University of Athens, Athens, Greece
[59]Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
[60]Also at University of Vienna, Vienna, Austria
[61]Also at Universität Zürich, Zurich, Switzerland
[62]Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
[63]Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
[64]Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
[65]Also at Konya Technical University, Konya, Turkey
[66]Also at Izmir Bakircay University, Izmir, Turkey
[67]Also at Adiyaman University, Adiyaman, Turkey
[68]Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
[69]Also at Marmara University, Istanbul, Turkey
[70]Also at Milli Savunma University, Istanbul, Turkey
[71]Also at Kafkas University, Kars, Turkey
[72]Now at Istanbul Okan University, Istanbul, Turkey
[73]Also at Hacettepe University, Ankara, Turkey
[74]Also at Erzincan Binali Yildirim University, Erzincan, Turkey
[75]Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
[76]Also at Yildiz Technical University, Istanbul, Turkey
[77]Also at Vrije Universiteit Brussel, Brussel, Belgium
[78]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
[79]Also at IPPP Durham University, Durham, United Kingdom
[80]Also at Monash University, Faculty of Science, Clayton, Australia
[81]Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt
[82]Also at Università di Torino, Torino, Italy

[83]Also at Bethel University, St. Paul, Minnesota, USA
[84]Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
[85]Also at California Institute of Technology, Pasadena, California, USA
[86]Also at United States Naval Academy, Annapolis, Maryland, USA
[87]Also at Ain Shams University, Cairo, Egypt
[88]Also at Bingol University, Bingol, Turkey
[89]Also at Georgian Technical University, Tbilisi, Georgia
[90]Also at Sinop University, Sinop, Turkey
[91]Also at Erciyes University, Kayseri, Turkey
[92]Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania
[93]Now at another institute or international laboratory covered by a cooperation agreement with CERN
[94]Also at Texas A&M University at Qatar, Doha, Qatar
[95]Also at Kyungpook National University, Daegu, Korea
[96]Also at another institute or international laboratory covered by a cooperation agreement with CERN
[97]Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
[98]Also at Northeastern University, Boston, Massachusetts, USA
[99]Also at Imperial College, London, United Kingdom
[100]Now at Yerevan Physics Institute, Yerevan, Armenia
[101]Also at Universiteit Antwerpen, Antwerpen, Belgium