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Search for dark matter produced in association with a Higgs boson decaying to a τ lepton pair in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

Abstract

A search for dark matter particles produced in association with a Higgs boson decaying into a pair of τ leptons is performed using data collected in proton-proton collisions at a center-of-mass energy of 13 TeV with the CMS detector. The analysis is based on a data set corresponding to an integrated luminosity of $101\,\text{fb}^{-1}$ collected in 2017–2018. No significant excess over the expected standard model background is observed. This result is interpreted within the frameworks of the 2HDM+a and baryonic Z' benchmark simplified models. The 2HDM+a model is a type-II two-Higgs-doublet model featuring a heavy pseudoscalar with an additional light pseudoscalar. Upper limits at 95% confidence level are set on the product of the production cross section and the branching fraction for each of these two simplified models. Heavy pseudoscalar boson masses between 400 and 700 GeV are excluded for a light pseudoscalar mass of 100 GeV. For the baryonic Z' model, a statistical combination is made with an earlier search based on a data set of $36\,\text{fb}^{-1}$ collected in 2016. In this model, Z' boson masses up to 1050 GeV are excluded for a dark matter particle mass of 1 GeV.

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*See Appendix A for the list of collaboration members

1 Introduction

Evidence for dark matter (DM) and its influence on the observed large-scale structure of the universe is well supported by numerous studies [1–4]. This evidence, along with the hypothesis that DM consists of long-lived weakly interacting massive particles, drives the search for potential DM production at the CERN LHC. Given the stringent constraints on weak interactions between DM and standard model (SM) particles, models incorporating beyond-the-SM (BSM) scalar sectors are of significant interest.

If DM is produced at the LHC, it is likely to escape direct detection because of its rare interaction with the matter that makes up the detectors. However, if DM candidates are produced alongside SM particles, such as the 125 GeV Higgs boson, they may create an imbalance in recorded momentum, resulting in a large amount of missing transverse momentum (p_T^{miss}). Such signatures are generically called "mono-Higgs". This paper reports on a search for the production of DM particles (χ) recoiling against a Higgs boson, which is reconstructed through its decay into a pair of τ leptons in both leptonic and hadronic decays. The data set used in this analysis was collected from proton-proton (pp) collisions at a center-of-mass energy of 13 TeV by the CMS experiment in 2017 and 2018, corresponding to an integrated luminosity of 101 fb^{-1}. A statistical combination is performed considering a model probed by an earlier search, conducted at the same center-of-mass energy with 36 fb^{-1} of data collected in 2016 [5].

The "mono-Higgs" signature arises from new interactions between DM and SM particles. Several models suggest enhanced couplings between BSM particles and scalar bosons [6–8]. Although the Higgs boson could theoretically be radiated from initial-state quarks, this process is highly suppressed because of small Yukawa couplings or loop processes [9–11]. This analysis considers two simplified benchmark models for DM+h production [12]. The 2HDM+a model [13, 14] is a canonical two Higgs doublet model with an additional pseudoscalar singlet interacting with DM particles. This model features five Higgs bosons: one SM-like Higgs boson (h), two charged Higgs bosons ($H^{\pm}$), one heavier neutral scalar (H), and one heavier neutral pseudoscalar (A), as well as an additional pseudoscalar (a). The Feynman diagram describing DM production in this model is shown in Fig. 1 (left). The baryonic Z' model [9] predicts a new massive vector mediator Z' that can emit a Higgs boson and then decay to a pair of Dirac fermionic DM particles, leading to the Feynman diagram shown in Fig. 1 (right).

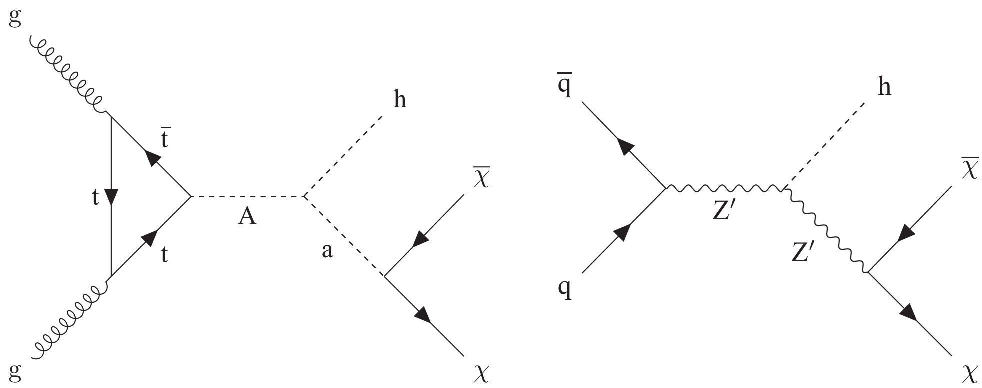

Figure 1: Representative Feynman diagrams for leading order DM-associated production of a Higgs boson in the 2HDM+a (left) and baryonic Z' (right) models.

According to Ref. [12], a benchmark scenario is defined by fixing several model parameters based on both electroweak and flavor measurements and phenomenological considerations, such as the requirement that the Higgs potential is stable. Assuming the alignment of the 2HDM+a model and the decoupling limits, m_h is set to 125 GeV. From electroweak precision constraints, the masses of the heavier Higgs bosons ($H^{\pm}$, H, A) are set to be equal, leaving five free parameters of the model: the mass of the light pseudoscalar m_{a}, the mass of the heavy pseudoscalar m_{A}, the mass of the DM candidate, m_{χ}, $\sin\theta$, where θ is the mixing angle of the two CP-odd weak spin-0 eigenstates, and the ratio of the vacuum expectation values of the two Higgs doublets, $\tan\beta$. The variations of the $\sin\theta$ and $\tan\beta$ parameters change the signal strength and have a prominent impact on the shapes of the p_{T}^{miss} distribution of the mono-Higgs production.

In the baryonic Z′ model [9], the baryonic gauge boson Z′ arises from a new $U(1)_{B}$ baryon number symmetry. A baryonic Higgs boson (h_{B}) is introduced to break this symmetry spontaneously, generating the Z′ boson mass via a coupling dependent on the h_{B} vacuum expectation value. The Z′ boson couplings to quarks and DM particles are proportional to the $U(1)_{B}$ gauge couplings. There is a mixing between h_{B} and the 125 GeV Higgs boson (h), allowing the Z′ to radiate an h. The coupling strength between the Z′ boson and h is $g_{hZ'Z'} = (m_{Z'}^{2} \sin\zeta)/v_{B}$, where the parameter $\sin\zeta$ governs the mixing angle between the h_{B} and h, and v_{B} is the vacuum expectation value of h_{B}. In this model, stable baryonic states are the candidate DM particles. This paper considers a Z′ resonance with a mass between 10 and 2500 GeV, and DM particle masses between 1 and 800 GeV. As suggested in Ref. [15], the mediator-DM coupling is fixed to 1, and the mediator-quark coupling to 0.25 to avoid the constraints from dijet searches at the LHC.

Although the branching ratio of the SM Higgs boson to two τ leptons is lower than that to $b\overline{b}$, this analysis takes advantage of several distinct benefits of the h that decays to a τ pair. It benefits from small SM backgrounds and does not rely on p_{T}^{miss} triggers. As a result, the $\tau\tau$ channel serves as a complementary approach to the bb channel, enabling the exploration of dark matter scenarios with lower p_{T}^{miss} values.

SM processes can also give rise to a signature with p_{T}^{miss} and two τ leptons consistent with the decay products of a Higgs boson. One such important SM process is the production of a Higgs boson in association with a Z boson that decays into neutrinos. Although this process has a relatively low cross section, it may produce final states indistinguishable from the signal. Other SM processes that can result in final states with p_{T}^{miss} and two τ lepton decays include the production of a Z boson, a pair of vector bosons (WW, WZ, ZZ), a top quark-antiquark pair, or a Higgs boson in association with a W boson. Separating the signal from these processes is challenging because of their higher cross sections, finite detector resolution, acceptance limitations, and the inherent uncertainty introduced by the presence of two neutrinos, which can potentially mimic signal events.

The previous search in the same final state by the CMS experiment [5] was based on data collected at a center-of-mass energy of 13 TeV and corresponding to an integrated luminosity of 36 fb^{-1}. These results were interpreted in terms of the baryonic Z′ model. A similar search was conducted by the ATLAS experiment at a center-of-mass energy of 13 TeV, using a data set corresponding to an integrated luminosity of 139 fb^{-1} [16]. The results of this search were interpreted in terms of a 2HDM+a model featuring two scalar Higgs doublets and a pseudoscalar singlet field. No significant excess over the SM prediction was observed in either study.

The analysis reported here benefits from a larger data set and employs a method based on control samples in data, known as the "misidentification factor (MF) method", described in Refs. [17, 18]. This method collectively estimates background events with quark- or gluon-jets misidentified as hadronically decaying τ leptons (τ_{h}), instead of measuring this background separately for W+jets and multijet events arising from quantum chromodynamics (QCD).

The remainder of this paper is organized as follows. In Section 2, the CMS detector and the reconstruction of the objects and event variables used in the analysis are introduced. Section 3 details the data set and the Monte Carlo (MC) simulated samples used in the analysis. Section 4 describes the event selection and analysis strategy for the study, while Section 5 outlines the systematic uncertainties affecting the analysis. Finally, Section 6 presents the results and their interpretation, and a summary is provided in Section 7. The tabulated results are also provided in the HEPData record [19].

2 The CMS detector and event reconstruction

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 extend the pseudorapidity 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. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about 4 μs [20]. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to a few kHz before data storage [21, 22]. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Refs. [23, 24].

The particle-flow (PF) algorithm [25] combines information from all the different parts of the CMS detector to identify and reconstruct individual particles. These particles, called PF candidates, can be charged or neutral hadrons, electrons, photons, or muons. The reconstructed track vertex with the largest value of summed physics-object p_{T}^2, where p_{T} is the transverse momentum of the objects, is taken to be the primary vertex (PV) of the pp interaction. Any other collision vertices in the event are associated with additional mostly soft inelastic pp collisions called pileup (PU). In the 2017–2018 data sets the average number of interactions per bunch crossing was 32.

Electron candidates are reconstructed by combining clusters of energy deposits in the ECAL with hits in the silicon tracker [26]. The momentum resolution for electrons with $p_{\mathrm{T}} \approx 45$ GeV from $\mathrm{Z} \to \mathrm{ee}$ decays ranges from 1.6 to 5%. Electron identification is performed using a multivariate discriminant derived from track quality, shower shape, and kinematic quantities. For this analysis, a medium working point with an identification efficiency of 90% is used, with a misidentification rate of $\approx$1% from jets in the relevant kinematic region [26]. Muons are measured using detection planes that employ three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers [27]. Muons in the event are reconstructed by performing a simultaneous track fit to hits in the tracker and in the muon chambers. The momentum resolution, for muons with p_{T} up to 100 GeV, is 1% in the barrel and 3% in the endcaps. The p_{T} resolution in the barrel is better than 7% for muons with p_{T} up to 1 TeV. For this study, muon identification requirements with an efficiency of approximately 99% are chosen, with a misidentification rate below 0.2% for pions [26].

The contribution of backgrounds with misidentified electrons or muons can further be minimized by isolating the corresponding lepton candidate from any hadronic activity. The isolation variable, defined by the following Eq. (1), is used:

$$I^{\ell}_{\text{rel}} = \frac{1}{p^{\ell}_{\text{T}}} \left[\Sigma p^{\text{charged}}_{\text{T}} + \max\left(0, \Sigma E^{\text{neutral}}_{\text{T}} + \Sigma E^{\gamma}_{\text{T}} - p^{\text{PU}}_{\text{T}}\right) \right], \tag{1}$$

where lepton ℓ refers to either an electron or muon, p^{ℓ}_{T} corresponds to the lepton p_{T}, $\Sigma p^{\text{charged}}_{\text{T}}$ corresponds to the p_{T} sum of all charged particles, and $\Sigma E^{\text{neutral}}_{\text{T}}$ and $\Sigma E^{\gamma}_{\text{T}}$ correspond to the transverse energy E_{T} sum of neutral hadrons and photons, respectively. This isolation is predefined in a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ around the lepton direction at the PV, where $\Delta\eta$ and $\Delta\phi$ (measured in radians) correspond to the angular distances of the particle to the lepton in the η and ϕ directions, respectively. The cone sizes for electrons and muons are $\Delta R = 0.3$ and 0.4, respectively. The lepton itself is excluded from the isolation calculation. To mitigate the contamination from PU, only those charged particles whose tracks are associated with the PV are taken into account. For neutral hadrons and photons, it is hard to determine whether they originate from the PV or from PU. To account for this, an estimated contribution from PU (p^{PU}_{T}) is subtracted from the total measured energy of neutral hadrons and photons. For electrons, this is estimated from the mean energy flow per unit area, while for muons it is obtained from tracks not associated with the PV. The isolation criteria mentioned in Section 4.1 have an efficiency for isolated electrons and muons from τ lepton decays well above 95%.

For each event, hadronic jets are reconstructed from the PF candidates using the infrared- and collinear-safe anti-k_{T} algorithm [28, 29] with a distance parameter R of 0.4. Jet momentum is determined as the vector sum of all particle momenta in the jet, and is found from simulation to be, on average, within 5 to 10% of the true momentum over the entire p_{T} spectrum and detector acceptance [30]. In 2017, the ECAL endcaps were subject to an increased noise level affecting the reconstruction of jets. Jets with $p_{\text{T}} < 50\,\text{GeV}$ in the range of $2.65 < |\eta| < 3.14$ have been excluded from the analysis. Jets resulting from the hadronization of b quarks are used to separate signal from top quark-antiquark pair ($\text{t}\bar{\text{t}}$) events. These are tagged by exploiting the neural net based DEEPCSV algorithm as described in Refs. [31, 32]. The medium working point for DEEPCSV is chosen, which achieves approximately 66% efficiency with a 1% misidentification probability. Jets with $p_{\text{T}} > 30\,\text{GeV}$ and $|\eta| < 4.7$ and b jets with $p_{\text{T}} > 20\,\text{GeV}$ and $|\eta| < 2.5$ are used.

Jet energy corrections are derived from simulation to bring the measured response of jets to that of particle-level jets on average. In situ measurements of the momentum balance in dijet, γ+jet, Z+jet, and multijet events are used to account for any residual differences in the jet energy scale (JES) and jet energy resolution (JER) in data and simulation [30]. The JER amounts typically to 15–20% at 30 GeV, 10% at 100 GeV, and 5% at 1 TeV [30]. Additional selection criteria [33] are applied to each jet to remove jets potentially dominated by anomalous contributions from various subdetector components or reconstruction failures.

Hadronic τ lepton decays (τ_{h}) are reconstructed from jets using the hadrons-plus-strips algorithm [34], which combines one or three tracks with energy deposits in the calorimeters to identify the decay modes. Neutral pions are reconstructed by clustering the PF electrons and photons falling in η-ϕ regions, called the strips, with a dynamic size in η-ϕ, where the strip size varies as a function of the p_{T} of the electron or photon candidate. To distinguish genuine τ_{h} decays from jets originating from the hadronization of quarks or gluons, and from electrons, or muons, the DEEPTAU algorithm is used [35]. Information from all individual reconstructed particles near the τ_{h} axis is combined with properties of the τ_{h} candidate and the event. The input variables to the neural net include variables related to the τ_{h}, four-momentum, charge, lifetime, isolation, the compatibility of the τ_{h} track with the PV, observables associated with the

η and ϕ distributions of the energy reconstructed in the strips, and other variables. The thresholds on the output discriminants [35], dependent on p_T, are chosen to define several working points, which provide good τ_h identification efficiencies. Table 1 shows the target τ_h identification efficiences for the different working points that are used in the analysis to discriminate against electrons (D_e), muons (D_μ), and jets (D_{jet}). The probability of a jet to be misidentified as a τ_h candidate by the DEEPTAU algorithm depends on the p_T and quark flavor of the jet. In simulated events from W boson production in association with jets, it has been estimated to be 0.43% for a genuine τ_h identification efficiency of 70%. The misidentification rate for electrons (muons) is 2.60 (0.03)% for a genuine τ_h identification efficiency of 80 (>99)%.

Table 1: Target τ_h identification efficiencies for the different working points defined for the three different discriminants that are used in the analysis. These identification efficiencies are evaluated for genuine τ_h candidates in simulated $H \to \tau\tau$ events with $p_T \in [30, 70]$ GeV for τ_h.

	Tight	Medium	VLoose	VVVLoose
D_e	80%	—	—	99.5%
D_μ	99.5%	—	99.95%	—
D_{jet}	—	70%	—	98%

The negative vector sum of the transverse momenta ($\vec{p}_T^{miss}$) is computed from all the PF candidates in an event, and its magnitude is denoted as p_T^{miss} [36]. The value of $\vec{p}_T^{miss}$ is adjusted to account for corrections to the energy scale and resolution of the reconstructed jets in the event. Anomalous high-p_T^{miss} events can arise from various issues such as reconstruction failures, detector malfunctions, or non-collision backgrounds. These events are rejected by dedicated filters that are designed to eliminate more than 85–90% of the spurious high-p_T^{miss} events with a signal efficiency exceeding 99.9% [36]. The p_T^{miss} is used for the discrimination of W boson production in association with jets (W+jets) from signal by exploiting the transverse mass:

$$m_T^\ell = \sqrt{2 p_T^\ell p_T^{miss} (1 - \cos \Delta\phi)}, \tag{2}$$

where ℓ stands for an electron or a muon, and $\Delta\phi$ is the azimuthal angular separation between p_T^ℓ and p_T^{miss}.

3 Data and simulated samples

The analysis is performed with pp collision data at $\sqrt{s} = 13$ TeV collected with the CMS detector in 2017 and 2018. The data correspond to an integrated luminosity of 101 fb^{-1}. The analysis strategy and event selection were optimized using simulated samples of associated DM+h ($\tau\tau$) production via the two benchmark models discussed in Section 1. The MADGRAPH5_aMC@NLO v2.6.0 [37] generator is used to generate both the 2HDM+a and baryonic Z′ signals at leading order (LO). The decay of the SM-like Higgs boson is simulated by PYTHIA 8.205 [38] using the CP2 tune [39].

The simulation is performed for mass values scanning the available phase space in the (m_a,m_A) plane, for the 2HDM+a model (see Table 2), and in the (m_χ,$m_{Z'}$) plane for the baryonic Z′ model (see Table 3).

The largest backgrounds are $Z/\gamma^* \to \ell\ell/\tau\tau$, W+jets, $t\bar{t}$, single top quark, and multiboson processes. The MADGRAPH5_aMC@NLO v2.4.2 generator is used for the $Z/\gamma^* \to \ell\ell/\tau\tau$ and W+jets processes, which are generated at LO in perturbative QCD with the MLM jet matching

Table 2: Mass values scanning the available phase space in the (m_a,m_A) plane, used in the simulation for the 2HDM+a model. The phase space is limited by $m_A - m_a < 125\,\text{GeV}$, where 125 GeV is the Higgs mass.

m_A [GeV]	m_a [GeV] $\tan\beta = 1$, $\sin\theta = 0.35$, $m_\chi = 10\,\text{GeV}$									
225	100									
250		125								
300	100		150							
400	100		150	200	250					
500			150	200	250	300		375		
600	100		150	200	250	300	350		400	500
700	100			200	250	300	350		400	
800	100		150	200	250	300	350			500
900	100		150	200	250	300	350		400	500
1000	100		150		250		350			
1200			150		250		350			

Table 3: Mass values scanning the available phase space in the (m_χ,$m_{Z'}$) plane, used in the simulation for the baryonic Z′ model. The phase space is limited by $m_{Z'} - 2m_\chi < 125\,\text{GeV}$, where 125 GeV is the Higgs mass, and by $m_\chi < m_{Z'}/2$.

$m_{Z'}$ [GeV]	m_χ [GeV]											
200	1											
300	1	50										
350			100									
500	1	50	100									
650		50	100	150								
700						225						
750						225						
800		50		150	200		250	300	325			
900				150								
1000	1	50	100									
1100		50										
1500	1	50	100		200					400	600	
2000	1		100		200					400		800
2500	1											

and merging scheme [40]. The $Z/\gamma^* \rightarrow \ell\ell/\tau\tau$ background is normalized to the cross section calculated at next-to-next-to-LO (NNLO) precision [41] and is corrected for differences in the dilepton invarient mass ($m^{\ell\ell/\tau\tau}$) and transverse momentum ($p_T^{\ell\ell/\tau\tau}$) distributions using dimuon events in data [42].

The reducible SM backgrounds with genuine Higgs bosons are produced via different processes: gluon-gluon fusion (ggh), vector boson fusion (VBF), in association with a vector boson (Vh), or in association with a pair of top quarks ($t\bar{t}h$). These Higgs boson samples are all generated using POWHEG 2.0 [43–46] at next-to-LO (NLO) in perturbative QCD. The $t\bar{t}$ and single top quark processes are generated at NLO with the POWHEG 2.0 generator. The FxFx [47] merging scheme is used to generate diboson backgrounds with the MADGRAPH5_aMC@NLO generator at NLO.

All simulated samples mentioned above use the NNPDF 3.1 NNLO parton distribution function (PDF) sets [48, 49] with the perturbative order matching that used in the matrix element calculations. For parton showering and hadronization, as well as for τ lepton decays, the samples are interfaced with PYTHIA using the CP5 tune [39]. The MC samples are processed through a full simulation of the CMS detector based on GEANT4 [50] and are reconstructed with the same algorithms that are used for data. Minimum-bias collision events generated with PYTHIA are added to the simulated samples to reproduce the PU effects in the data.

4 Analysis strategy

The search is conducted by categorizing events on the basis of the decay modes of the τ leptons. This analysis focuses on the three τ lepton pair final states with the highest branching fractions: $e\tau_h$, $\mu\tau_h$, and $\tau_h\tau_h$. In the $e\tau_h$ and $\mu\tau_h$ channels, one τ lepton decays leptonically to an electron or a muon along with two neutrinos, while the other τ lepton decays hadronically (τ_h) with one neutrino. In the $\tau_h\tau_h$ channel, both τ leptons decay hadronically, each with one neutrino. The $e\mu$, ee, and $\mu\mu$ final states are excluded because of the low branching fraction of $\tau\tau$ pairs to purely leptonic final states. Additionally, the ee and $\mu\mu$ final states are heavily dominated by the Drell–Yan production of lepton pairs. The search is performed separately for the 2017 and 2018 data sets and then combined statistically for the two data-taking years, as well as with the published 2016 results [5].

4.1 Event selection

To select events in the $e\tau_h$ and $\mu\tau_h$ channels, triggers based on the presence of a single electron or muon are employed. Additionally, in the $e\tau_h$ channel, a trigger relying on the presence of an electron and a τ_h candidate is also used. For the $\tau_h\tau_h$ channel, the triggers require the presence of two isolated τ_h objects. Each offline reconstructed τ_h candidate must be matched to a τ_h candidate at the trigger level with a ΔR separation of less than 0.5. The efficiency of the online selection generally exceeds 90% after the offline selection described below, and it does not exhibit strong kinematic dependencies for the leptons selected for the offline analysis, as verified with independent triggers. Events in each channel must satisfy the respective offline selection criteria for p_T, η, and $I_{rel}^{e(\mu)}$, as described in Table 4. These criteria are chosen to be efficient with respect to the online selection.

For the $e\tau_h$ channel, events are selected based on the presence of at least one electron and one τ_h candidate. The electron must satisfy a multivariate identification criterion with 90% efficiency [26]. It is also required to be isolated from any hadronic activity in the detector, with a relative isolation requirement of $I_{rel}^{e} < 0.15$. Additionally, the electron and τ_h candidate must have opposite charge and be separated by $\Delta R > 0.5$ in the η-ϕ plane. The τ_h candidate must pass the "Medium" DEEPTAU discriminant against jets. To reduce the contribution from background processes where an electron or muon is misidentified as a τ_h, the selected τ_h candidate must satisfy the anti-lepton discriminators, "Tight" against electrons, and "VLoose" against muons, as detailed in Table 1.

Table 4: Offline selection requirements applied to e, μ, and τ_h candidates used for the selection of τ pairs. The expressions "first lepton" and "second lepton" refer to the lepton order of the final state in the first column.

Final state	Observable	First lepton	Second lepton
$e\tau_h$	$p_T >$	25 GeV	30 GeV
	$\lvert\eta\rvert <$	2.1	2.3
	$I^{e}_{rel} <$	0.15	—
$\mu\tau_h$	$p_T >$	29 GeV	30 GeV
	$\lvert\eta\rvert <$	2.4	2.3
	$I^{\mu}_{rel} <$	0.15	—
$\tau_h\tau_h$	$p_T >$	55 GeV	45 GeV
	$\lvert\eta\rvert <$	2.1	2.1

Similarly, for the $\mu\tau_h$ channel, events are selected based on the presence of at least one muon and one τ_h candidate. The muon must satisfy a PF-based identification criterion with ≈95% efficiency [27]. It is also required to be isolated from any hadronic activity in the detector, with a relative isolation requirement of $I^{\mu}_{rel} < 0.15$. Additionally, the muon and τ_h candidate must have opposite charge and be separated by $\Delta R > 0.5$ in the η-ϕ plane. The τ_h candidate must pass the "Medium" DEEPTAU discriminant against jets, the "VVVLoose" discriminant against electrons, and the "Tight" discriminant against muons, as detailed in Table 1.

Two types of vetoes are implemented in the $e\tau_h$ and $\mu\tau_h$ channels to reject backgrounds. First, events containing b-tagged jets with $p_T > 25$ GeV and $|\eta| < 2.4$ are vetoed to suppress contributions from $t\bar{t}$ and single top quark processes. Second, to mitigate contributions from backgrounds with multiple leptons, events containing additional electrons or muons, each with $p_T > 10$ GeV and $|\eta| < 2.4$, aside from the τ candidates, are excluded from further analysis. The additional electron or muon must satisfy similar identification criteria as the leading lepton but without the isolation requirement.

In the $\tau_h\tau_h$ channel, events are selected based on the presence of two oppositely charged τ_h leptons. The two τ_h candidates must be separated in the η-ϕ plane by $\Delta R > 0.5$. Both the τ_h candidates must pass the "Medium" DEEPTAU discriminant against jets, the "VVVLoose" discriminant against electrons, and the "VLoose" discriminant against muons, as detailed in Table 1.

In addition, for all three τ pair categories, p_T^{miss} is required to be greater than 105 GeV and the visible p_T of the $\tau\tau$ system must exceed 65 GeV. These stringent criteria reduce the need for isolation in the $\tau_h\tau_h$ channel. Additionally, the visible mass of the $\tau\tau$ system must be less than 125 GeV to ensure that the $\tau\tau$ system is compatible with an SM Higgs boson. To minimize diboson and W+jets contributions, the two τ candidates must pass a loose criterion of $\Delta R_{\tau\tau} < 2.0$. Furthermore, a selection on the total transverse mass (M_T^{tot}) greater than 100 GeV is required. The M_T^{tot} distribution is used to extract the signal for this analysis and is defined as:

$$M_T^{tot} = \sqrt{(E_T^{\tau_1} + E_T^{\tau_2} + p_T^{miss})^2 - (p_x^{\tau_1} + p_x^{\tau_2} + p_x^{miss})^2 - (p_y^{\tau_1} + p_y^{\tau_2} + p_y^{miss})^2}, \tag{3}$$

where $p_x^{\rm miss}$ and $p_y^{\rm miss}$ are the magnitudes of the x and y components of $\vec{p}_{\rm T}^{\rm miss}$. Here τ_1 and τ_2 are the leading and the subleading electrons, muons, or $\tau_{\rm h}$ candidates in all three channels. This selection reduces the background contributions from the Drell–Yan backgrounds in the leptonic channels and is chosen to maximize the expected significance of the analysis.

During the 2017 data taking, a gradual shift in the timing of the inputs of the ECAL L1 trigger in the region at $|\eta| > 2.0$ caused a specific trigger inefficiency. For events containing in this region an electron or a photon with $p_{\rm T} \geq 50\,{\rm GeV}$, or a jet with $p_{\rm T} \geq 100\,{\rm GeV}$, the efficiency loss is up to $\approx 10-20\%$, depending on $p_{\rm T}$, η, and time [20]. Correction factors are computed from data and applied to the acceptance evaluated from simulation for the 2017 samples. Finally, a section of the HCAL was not functioning during a part of the 2018 data-taking period corresponding to 65% of the total integrated luminosity recorded in that year, leading to irrecoverable mismeasurements in a localized region of the detector ($-1.57 < \phi < -0.87, -3.0 < \eta < -1.3$). To avoid contamination from such mismeasurements, events where any jet with $p_{\rm T} > 30\,{\rm GeV}$ is found in the corresponding η-ϕ region are rejected in the analysis of the corresponding partial 2018 data set.

On top of JES corrections to $\vec{p}_{\rm T}^{\rm miss}$, this analysis adopts an additional correction similar to that in Ref. [42]. The differences between data and simulation are applied as corrections to the direction and magnitude of the $\vec{p}_{\rm T}^{\rm miss}$ in simulated events. Simulated $\rm Z \to \mu\mu$ events are used to estimate the hadronic recoil, which is then compared with selected $\rm Z \to \mu\mu$ events in data. This correction to $\vec{p}_{\rm T}^{\rm miss}$ is applied to Z+jets events. More details on this method can be found in Ref. [36]. Additionally, for simulated $\rm t\bar{t}$ events, a top quark $p_{\rm T}$ reweighing is applied to match the $p_{\rm T}$ distribution observed in data [51].

4.2 Signal extraction and background estimation

Backgrounds are estimated using a combination of simulated samples and control samples in data. The major backgrounds arising from jets misidentified as $\tau_{\rm h}$ candidates, including events from W+jets, QCD multijet, and $\rm t\bar{t}$ production, are estimated using data, with a so-called "misidentification factor method". The other backgrounds, from Z+jets, SM Higgs boson, single top quark, diboson production processes, and the background from $\rm t\bar{t}$ production with two real τ leptons, are estimated from simulation. The measurements of the cross sections for Drell–Yan [18] and single top quark [52] processes at the LHC are consistent with the NNLO theoretical predictions, within the quoted uncertainties, supporting the use of theory-based normalizations for these backgrounds.

The background with jets misidentified as $\tau_{\rm h}$ candidates, called the "mis-ID background", is obtained with a method similar to that in Ref. [53]. The method is based on measuring two quantities: the number of events where jets pass the nominal $\tau_{\rm h}$ identification (ID) criteria (called isolated), corresponding to the signal region (SR) selection of the corresponding analysis, and the number of events where jets satisfy a set of loose ID criteria, but fail the nominal $\tau_{\rm h}$ ID criteria (referred to as "antiisolated" in the following).

The MF is defined as the ratio of the two numbers:

$$\mathrm{MF} = \frac{\text{number of events passing preselection and Medium } D_{\rm jet} \text{ ID discriminant}}{\text{number of events passing preselection and failing the Medium } D_{\rm jet} \text{ ID discriminant}} \tag{4}$$

and is applied as a weight to events that pass the corresponding SR selection except that the events are required to select $\tau_{\rm h}$ candidates satisfying the loose preselection criteria, but failing the nominal $\tau_{\rm h}$ ID criteria (application region). The MF is estimated as a function of the jet multiplicity (0 or ≥ 1), separately for the QCD multijet, W+jets, and $\rm t\bar{t}$ backgrounds. A control region (CR) enriched in QCD multijet events is obtained by applying the same selection as used in the analysis, except that the two τ leptons are required to be of the same sign (SS) instead of the opposite sign (OS). A CR enriched in W+jets events is obtained by applying the same selection as used in the analysis, except that the Higgs boson p_{T}, which is the visible p_{T} of the τ lepton pair, is required to be less than 65 GeV and m_{T}, which is the transverse mass of the lepton and the $p_{\mathrm{T}}^{\mathrm{miss}}$, is required to be greater than 70 GeV. Finally, a CR enriched in $\mathrm{t\bar{t}}$ events is obtained by applying the same selection as used in the analysis, except that the number of b-tagged jets is required to be at least 1.

The following steps are performed successively to estimate the mis-ID background:

1. Measure the MFs as a function of the $p_{\mathrm{T}}^{\tau_{\mathrm{h}}}$: The MFs are derived as the ratio of isolated to antiisolated τ_{h} candidates in QCD, W+jets, and $\mathrm{t\bar{t}}$ events in dedicated CRs, and are fitted with a linear function.

2. Correct the MFs as a function of the p_{T} of the lepton that is not misidentified: The correction is derived by comparing the distributions of isolated events in the CR with antiisolated events in the CR, reweighted with the raw MFs derived in the previous step.

3. Correct the MFs for differences in selection between the CRs and the SR: The correction in the QCD CR (OS/SS correction), and the differences in the selection of the Higgs boson p_{T} and the m_{T} in the W+jets CR. The correction for the inversion of the Higgs boson p_{T} and m_{T} selections in the W+jets CR is determined through simulations by comparing the isolated events in the CR to the weighted antiisolated events as a function of m_{T}. The correction for the sign inversion in the QCD CR is computed using data. It is determined as a function of visible mass of the $\tau\tau$ system in a CR with antiisolated lepton i.e $0.1 < I_{\mathrm{rel}}^{\mathrm{e}} < 0.2$ ($0.15 < I_{\mathrm{rel}}^{\mu} < 0.25$) in the $\mathrm{e}\tau_{\mathrm{h}}$ ($\mu\tau_{\mathrm{h}}$) final state. The MF is computed by using step 1 and step 2 and is applied as a weight to OS events with an antiisolated tau and antiisolated lepton. These weighted events are then compared with OS events with antiisolated lepton and an isolated tau to obtain the correction.

4. Determine the relative fraction of QCD, W+jets, and $\mathrm{t\bar{t}}$ events: The $\mathrm{t\bar{t}}$ and W+jets yields are estimated using simulations, whereas the QCD yield is estimated by subtracting all the backgrounds from data in the antiisolated region.

5. Apply the MFs weighted by the corresponding fractions, to obtain the mis-ID background from the simulated events in the SR.

The signal is extracted with a binned maximum likelihood fit to the $M_{\mathrm{T}}^{\mathrm{tot}}$ distributions (Eq. (3)) in the different channels for the SR.

Figure 2 shows the comparison of data and expected backgrounds for the $M_{\mathrm{T}}^{\mathrm{tot}}$ distributions after the simultaneous likelihood fit to data in the SRs. Table 5 shows the post-fit yields extracted from the $M_{\mathrm{T}}^{\mathrm{tot}}$ distribution for the expected number of background events and the number of events observed in 2017 and 2018 data combined. The observed number of events is in good agreement with the estimated number of events by the SM backgrounds.

5 Systematic uncertainties

All systematic uncertainties affecting the analysis are summarized along in Table 6, with their correlations between data sets from different years and different final states. These uncertain-

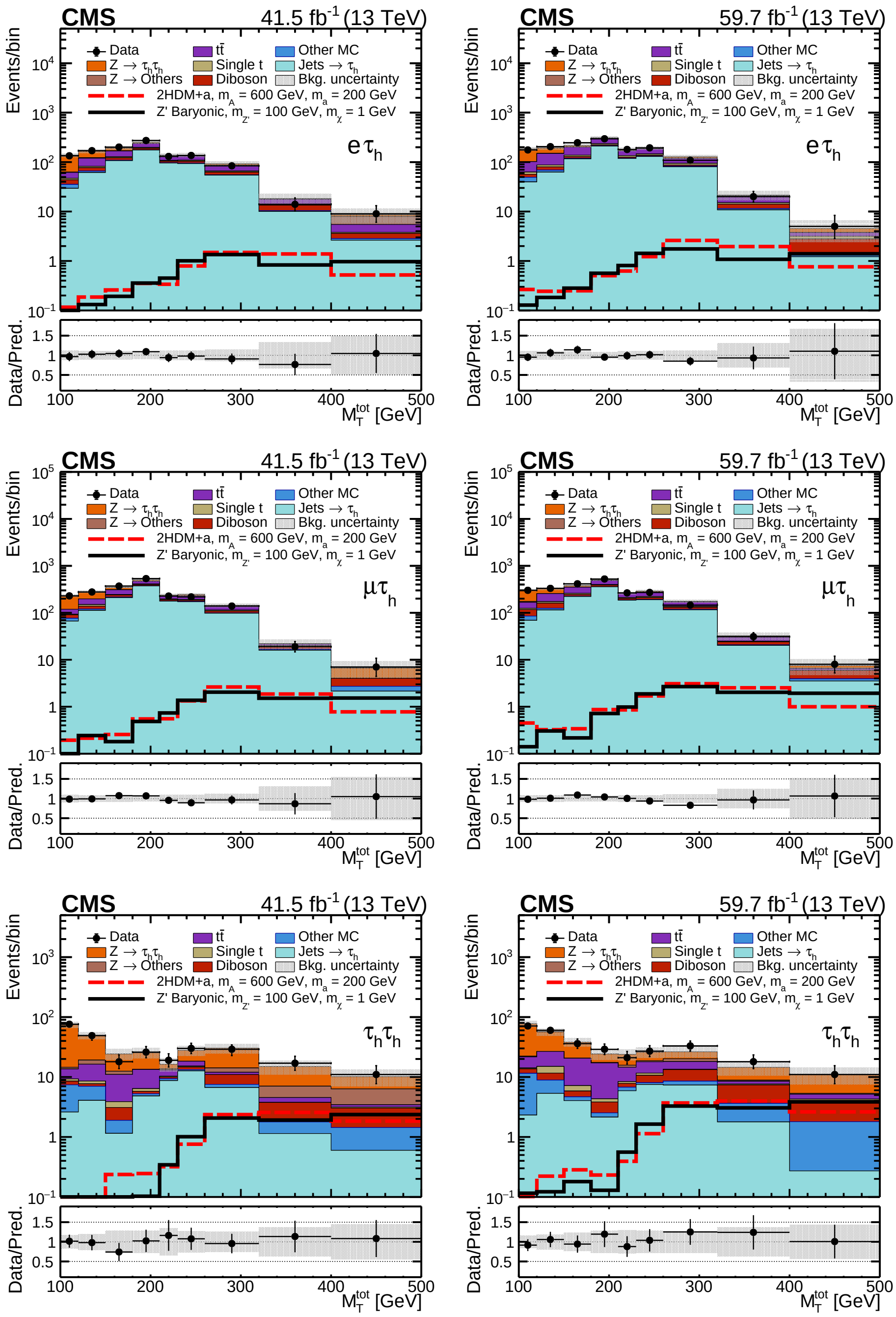

Figure 2: Distributions of the total transverse mass $M_{\mathrm{T}}^{\mathrm{tot}}$ in the SRs, for observed data and SM prediction in the $\mathrm{e}\tau_{\mathrm{h}}$ (upper), $\mu\tau_{\mathrm{h}}$ (center), and $\tau_{\mathrm{h}}\tau_{\mathrm{h}}$ (lower) final states in 2017 (left) and 2018 (right) after the simultaneous maximum likelihood fit. Representative signal distributions are shown for the 2HDM+a (dashed red curve) and baryonic Z′ (solid black curve) models. The data points are shown with their statistical uncertainties, and the last bin includes overflow. The "Other MC" background contribution includes events from ggh, VBF, Wh, Zh, and electroweak vector boson production. The uncertainty band accounts for all systematic and statistical sources of uncertainty, after the fit to the data.

ties are considered as nuisance parameters within the likelihood function. The selection efficiency correction factors are applied to the signal and all the background processes estimated

Table 5: The post-fit estimated background yields and the observed number of events for the $M_{\mathrm{T}}^{\mathrm{tot}}$ distribution in the SR, combined for the 2017 and 2018 data. The "Other MC" background contribution includes events from ggh, VBF, Wh, Zh, $\mathrm{Z} \rightarrow$ Others, and electroweak vector boson production. The uncertainties in the total expected yields include both statistical and systematic contributions.

Expected Backgrounds	$\mathrm{e}\tau_{\mathrm{h}}$	$\mu\tau_{\mathrm{h}}$	$\tau_{\mathrm{h}}\tau_{\mathrm{h}}$
$\mathrm{Z} \rightarrow \tau_{\mathrm{h}}\tau_{\mathrm{h}}$	339 ± 49	557 ± 73	297 ± 38
$\mathrm{t\bar{t}}$	542 ± 48	744 ± 61	99 ± 10
Single Top	94.9 ± 8.6	122 ± 10	11.8 ± 1.2
Diboson	133 ± 11	279 ± 27	34.5 ± 3.0
Other MC	64.4 ± 6.5	84.4 ± 7.0	50.7 ± 4.8
Jets $\rightarrow \tau_{\mathrm{h}}$	1400 ± 68	2508 ± 95	79.1 ± 5.9
Total Background	2573 ± 98	4294 ± 138	572 ± 40
Data	2582	4311	581

through simulations, and uncertainties are included that account for differences between simulation and observation in the reconstruction and identification efficiencies for various particle candidates.

The uncertainty in the τ_{h} identification efficiency is considered as a $p_{\mathrm{T}}^{\tau_{\mathrm{h}}}$- and decay-mode-dependent uncertainty ranging from 3 to 5% [35]. An additional shape-based uncertainty on the $M_{\mathrm{T}}^{\mathrm{tot}}$ distribution in the range 10–15% is added for τ_{h} candidates with $p_{\mathrm{T}} > 100\,\mathrm{GeV}$. The uncertainty in the τ_{h} trigger efficiency is also $p_{\mathrm{T}}^{\tau_{\mathrm{h}}}$-dependent and ranges from 4 to 9%. Since both the τ_{h} identification and τ_{h} trigger uncertainties are statistically dominated, they are considered as uncorrelated across data-taking years.

An uncertainty covers the misidentification of electrons or muons as τ_{h} candidates. It is dependent on $p_{\mathrm{T}}^{\tau_{\mathrm{h}}}$, η, and the decay mode. It is also considered as uncorrelated between the samples of different data-taking years. The uncertainty in the τ_{h} energy scale is in the range 0.7–1.2%, depending on $p_{\mathrm{T}}^{\tau_{\mathrm{h}}}$ and on the τ_{h} decay mode. It is treated as uncorrelated between data-taking years and decay modes. An additional uncertainty of 1% is also considered for the energy scale of the misidentified leptons and it is considered uncorrelated across the data-taking years.

The uncertainty in the electron and muon reconstruction, efficiency, and identification is 2% for all years, uncorrelated across data-taking years [26, 27, 54]. The electron energy scale uncertainties are also derived event-by-event and are treated as shape uncertainties. Since they are systematically dominated [26], these uncertainties are treated as correlated across data-taking years. The uncertainty related to the muon energy scale is between 0.4 and 2.7%, and correlated between data-taking years. A shape-based uncertainty depending on p_{T} and η for the electron and muon triggers is considered.

For the background processes, cross section uncertainties of 5% for diboson and single top quark [52, 55–57], 4% for Drell–Yan [18, 41], and 6% for $\mathrm{t\bar{t}}$ backgrounds are also considered [55, 58]. An additional uncertainty of 1-2% to account for the L1 trigger ECAL timing shift is also considered. The uncertainties related to the integrated luminosities for the data-taking period 2017-2018 amounts to 2.3-2.5%, while overall uncertainty for total Run-2 period is 1.6% [59, 60]. In simulated Z+jets events, a shape uncertainty of 10% of the Z boson p_{T} reweighting correction, to account for higher-order effects, is used. A shape-based uncertainty is applied to the $\mathrm{t\bar{t}}$ process to correct the top quark p_{T} distribution. For the Drell–Yan process, where $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ recoil

Table 6: Systematic uncertainties with their source, magnitude and correlations between data samples from either different data-taking years or different final states

Uncertainty	Magnitude	Correlation years	Correlation final states
τ_h identification	p_T-dependent	0%	100 (0)% for $\ell\tau_h$ ($\tau_h\tau_h$)
τ_h ID, for high $p_T^{\tau_h}$	Event-dependent	100%	100%
τ_h energy scale	0.7–1.2%	0%	100%
Electron misidentified as τ_h	Event-dependent	0%	0%
Muon misidentified as τ_h	Event-dependent	0%	0%
Electron/muon identification	2%	0%	0%
Energy scale for lepton mis-ID as τ_h	1%	0%	0%
Trigger	Event-dependent	0%	0%
Electron energy scale	Event-dependent	100%	100%
Muon energy scale	0.4–2.7%	100%	100%
b jet veto	Event-dependent	partial	100%
Integrated luminosity	2–3%	partial	100%
$t\bar{t}$ cross section	6%	100%	100%
Diboson cross section	5%	100%	100%
Single top quark cross section	5%	100%	100%
Drell–Yan cross section	4%	100%	100%
L1 mistiming	Event-dependent	0%	100%
Z boson p_T reweighting	10%	100%	100%
Top quark p_T reweighting	Event-dependent	100%	100%
JES	Event-dependent	100%	100%
JER	Event-dependent	100%	100%
$\vec{p}_T^{miss}$ unclustered ES	Event-dependent	0%	100%
$\vec{p}_T^{miss}$ recoil corrections	Event-dependent	0%	100%
MF in $\ell\tau_h$	Event-dependent	partial	0%
MF in $\tau_h\tau_h$	Event-dependent	partial	0%
MF in $\tau_h\tau_h$, for $p_T^{\tau_h} > 100\,\mathrm{GeV}$	Event-dependent	0%	0%

corrections are applied, an uncertainty in the calibration and resolution of the hadronic recoil are applied [36]. For all other background processes estimated from simulation, an uncertainty in $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ related to unclustered energy is taken into account. The $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ uncertainties are considered as uncorrelated across data-taking years. Uncertainties in the JES are included on an event-by-event basis and considered as correlated across data-taking years.

For the background with jets misidentified as τ_{h} candidates, different sources of uncertainty are considered. The MFs are parameterized linearly as function of $p_{\mathrm{T}}^{\tau_{\mathrm{h}}}$. Two uncertainties per fit function are considered. They are obtained by uncorrelating the fit uncertainties in the slope and intercept of the fit functions obtained in the three CRs, i.e, the W+jets, QCD multijet, and $\mathrm{t\bar{t}}$ CRs. A shape-based uncertainty for the lepton p_{T} correction for all three CRs is considered. An additional shape-based uncertainty to cover the OS/SS correction in the QCD CR is applied. A shape-based uncertainty is considered for τ_{h} candidates with $p_{\mathrm{T}} > 100\,\mathrm{GeV}$, following Ref. [61].

6 Results

The results are extracted from a maximum likelihood fit, using the CMS statistical analysis tool COMBINE [62]. No significant excess of data above the SM background expectation is observed. Interpretations in the 2HDM+a and baryonic Z′ models are provided.

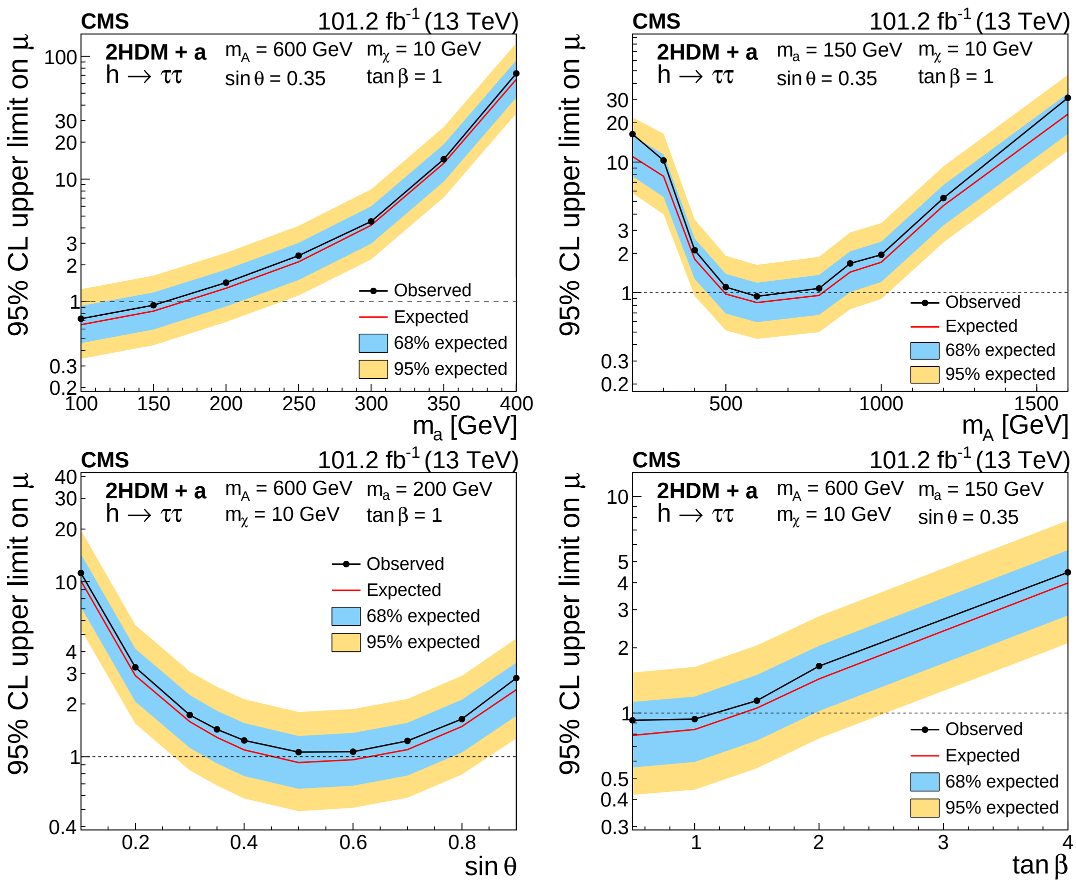

Figure 3: The 95% CL upper limits on μ for the 2HDM+a model as a function of m_{a} (upper let), m_{A} (upper right), $\sin\theta$ (lower left) and $\tan\beta$ (lower right). The values assumed for the other parameters are shown on each figure. The interpolation between the points is linear.

The signal upper limits are determined with the signal strength modifier $\mu = \sigma/\sigma_{\text{theory}}$, where σ_{theory} is the predicted production cross section of the particular model considered, calculated using the parameter choices described in Section 1, and σ corresponds to the upper limit on the observed cross section.

Upper limits are obtained using the data set collected in 2017–2018. They are calculated at 95% confidence level (CL) using the CLs criterion [63, 64] computed with an asymptotic approximation [65] by using the profile likelihood ratio modified for upper limits.

For the 2HDM+a model, the one-dimensional upper limits on μ as a function of the lighter pseudoscalar mass m_{a} are shown in Fig. 3 (upper left), using $\sin\theta = 0.35$, $m_{\text{A}} = 600\,\text{GeV}$, $\tan\beta = 1$, and $m_{\chi} = 10\,\text{GeV}$. Similar limits as functions of m_{A} are shown in Fig. 3 (upper right), using $\sin\theta = 0.35$, $m_{\text{a}} = 150\,\text{GeV}$, $\tan\beta = 1$, and $m_{\chi} = 10\,\text{GeV}$. Upper limits on μ as a function of $\sin\theta$ ($\tan\beta$) are shown in Fig. 3 lower left (lower right), using $m_{\text{a}} = 200\,\text{GeV}$, $m_{\text{A}} = 600\,\text{GeV}$, $\tan\beta = 1$, and $m_{\chi} = 10\,\text{GeV}$ ($m_{\text{a}} = 150\,\text{GeV}$, $m_{\text{A}} = 600\,\text{GeV}$, $\sin\theta = 0.35$, and $m_{\chi} = 10\,\text{GeV}$).

Two-dimensional limits in the (m_{A},m_{a}) plane, using $\sin\theta = 0.35$, $\tan\beta = 1$, and $m_{\chi} = 10\,\text{GeV}$ are shown in Fig. 4. Masses of m_{A} between 400 and 700 GeV are excluded for small values of m_{a} ($m_{\text{a}} \approx 100\,\text{GeV}$).

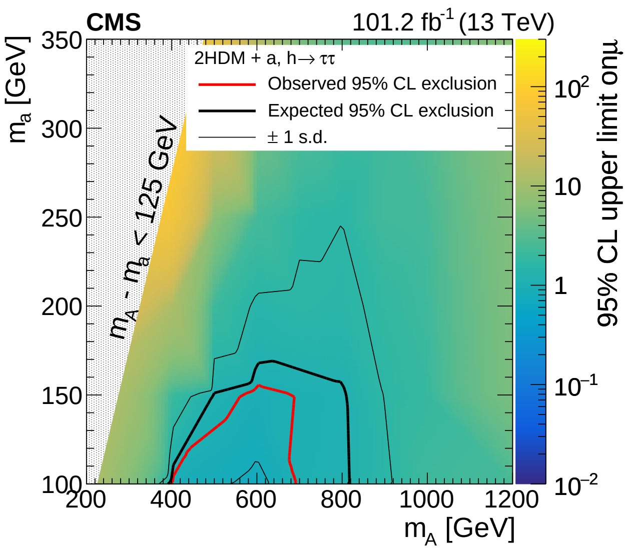

Figure 4: The 95% CL upper limits on μ in the (m_{A},m_{a}) plane for the 2HDM+a model. The regions inside the red and black curves correspond to the observed and expected exclusions at 95% CL, respectively.

The one-dimensional upper limits on μ for the baryonic Z$'$ model, as a function of $m_{Z'}$ are shown in Fig. 5 (left), using $138\,\text{fb}^{-1}$ of data collected in 2016–2018. The two-dimensional limits on μ in the ($m_{Z'}$,m_{χ}) plane are shown in Fig. 5 (right). In the previous result based on 2016 data, the observed exclusion region for the mediator mass reached 450 GeV for a DM mass of 1 GeV. After combination with the search based on 2017 and 2018 data presented in this paper, the observed (expected) exclusion region for $m_{Z'}$ extends to around 1050 (1150) GeV for the same DM mass.

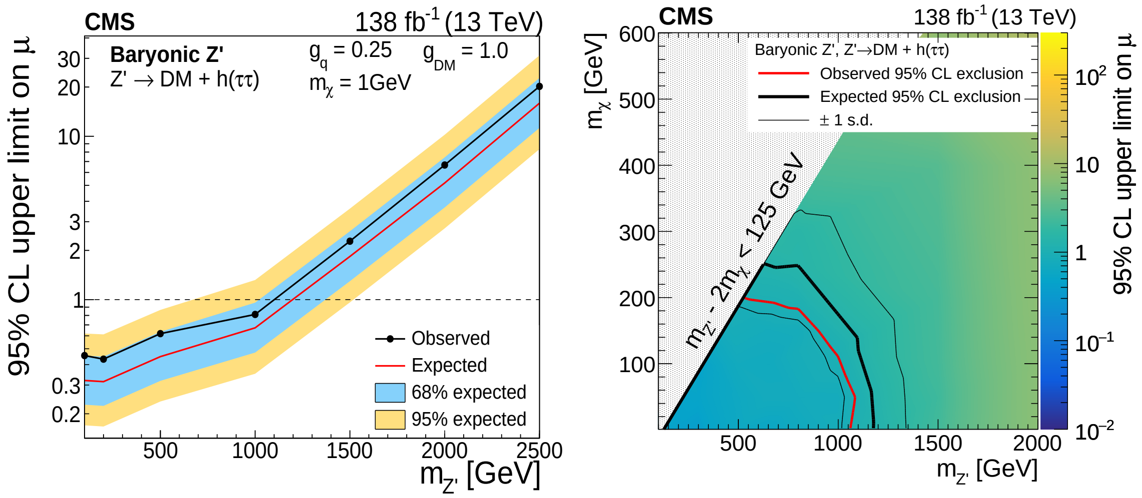

Figure 5: The 95% CL upper limits on μ for the baryonic Z′ model. Left: Observed and expected 95% CL upper limits on μ as a function of $m_{Z'}$, using $m_\chi = 1$ GeV. Right: 95% CL upper limits on μ in the ($m_{Z'}$,m_χ) plane. The regions inside the red and black curve correspond to the observed and expected exclusions at 95% CL, respectively.

7 Summary

A search for dark matter produced in association with a Higgs boson decaying to a pair of τ leptons has been performed using a data set of proton-proton collisions at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 101 fb^{-1}. The results are interpreted within the framework of two benchmark simplified models: the 2HDM+a model, where a heavy pseudoscalar couples to a Higgs boson and a lighter pseudoscalar that decays to dark matter particles, and the baryonic Z′ model, where a high mass resonance (Z′) decays into a pair of dark matter particles and a standard model Higgs boson. Upper limits at the 95% confidence level are set on the product of the production cross section and branching fraction for both models. In the 2HDM+a model, heavy pseudoscalar masses between 400 and 700 GeV are excluded for a light pseudoscalar mass around 100 GeV. For the baryonic Z′ model, the results are combined with those of an earlier search using an independent data set collected at the same center-of-mass energy, corresponding to an integrated luminosity of 36 fb^{-1}. Z′ masses up to 1050 GeV are excluded for a dark matter particle mass of 1 GeV, based on a data sample corresponding to a total integrated luminosity of 138 fb^{-1}.

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A The CMS Collaboration

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

Institut für Hochenergiephysik, Vienna, Austria
W. Adam, J.W. Andrejkovic, L. Benato, 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[2], D. Schwarz, M. Sonawane, W. Waltenberger, C.-E. Wulz[2]

Universiteit Antwerpen, Antwerpen, Belgium
T. Janssen, H. Kwon, 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, Y. Hong, 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, I. De Bruyn, G. De Lentdecker, H. Evard, L. Favart, P. Gianneios, A. Khalilzadeh, F.A. Khan, K. Lee, A. Malara, M.A. Shahzad, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer

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

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Bein, A. Benecke, A. Bethani, G. Bruno, 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. Turkcapar

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

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[6], E.M. Da Costa, G.G. Da Silveira[7], D. De Jesus Damiao, S. Fonseca De Souza, R. Gomes De Souza, T. Laux Kuhn[7], M. Macedo, J. Martins, K. Mota Amarilo, 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[7], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, I. Maietto Silverio, P.G. Mercadante, S.F. Novaes, B. Orzari, Sandra S. Padula, V. Scheurer

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
A. Aleksandrov, G. Antchev, 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

Institute of High Energy Physics, Beijing, China
G.M. Chen[8], H.S. Chen[8], M. Chen[8], F. Iemmi, C.H. Jiang, A. Kapoor[9], H. Liao, Z.-A. Liu[10], R. Sharma[11], J.N. Song[10], J. Tao, C. Wang[8], J. Wang, Z. Wang[8], H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. Ban, A. Carvalho Antunes De Oliveira, S. Deng, B. Guo, C. Jiang, A. Levin, C. Li, Q. Li, Y. Mao, S. Qian, S.J. Qian, X. Qin, X. Sun, D. Wang, H. Yang, 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[12], B. Li[13], H. Wang, K. Yi[14], J. Zhang

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

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

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
J. Jaramillo, 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, A. Starodumov[15],

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

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

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

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
B. El-mahdy, S. Khalil[16], E. Salama[17,18]

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, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

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

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

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

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, 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[19], 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, T.D. Cuisset, 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, S. Obraztsov, C. Ochando, R. Salerno, J.B. Sauvan, Y. Sirois, G. Sokmen, L. Urda Gómez, E. Vernazza, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[20], 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[21], 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[15], I. Lomidze, Z. Tsamalaidze[15]

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, 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, F. Torres Da Silva De Araujo[22], 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[23], K. Borras[24], A. Campbell, A. Cardini, F. Colombina, M. De Silva, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, E. Gallo[23], 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[25], W. Lohmann[26], 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, J. Park, E. Ranken, A. Raspereza, D. Rastorguev, J. Rübenach, L. Rygaard, M. Scham[27,24], S. Schnake[24], P. Schütze, C. Schwanenberger[23], D. Selivanova, K. Sharko, M. Shchedrolosiev, D. Stafford, F. Vazzoler, A. Ventura Barroso, R. Walsh, D. Wang, Q. Wang, K. Wichmann, L. Wiens[24], C. Wissing, Y. Yang, S. Zakharov, A. Zimermmane Castro Santos

University of Hamburg, Hamburg, Germany
A. Albrecht, S. Albrecht, M. Antonello, S. Bollweg, M. Bonanomi, P. Connor, K. El Morabit, Y. Fischer, E. Garutti, A. Grohsjean, J. Haller, D. Hundhausen, 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, B. Wiederspan, M. Wolf

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
S. Brommer, E. Butz, T. Chwalek, A. Dierlamm, G.G. Dincer, U. Elicabuk, N. Faltermann, M. Giffels, A. Gottmann, F. Hartmann[28], R. Hofsaess, M. Horzela, U. Husemann, J. Kieseler, M. Klute, O. Lavoryk, J.M. Lawhorn, M. Link, A. Lintuluoto, S. Maier, S. Mitra, M. Mormile, Th. Müller, M. Neukum, M. Oh, E. Pfeffer, M. Presilla, G. Quast, K. Rabbertz, B. Regnery, R. Schmieder, N. Shadskiy, I. Shvetsov, H.J. Simonis, L. Sowa, L. Stockmeier, K. Tauqeer, M. Toms, B. Topko, N. Trevisani, T. Voigtländer, R.F. Von Cube, J. Von Den Driesch, 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[28], A. Stakia

National and Kapodistrian University of Athens, Athens, Greece
G. Melachroinos, Z. Painesis, 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
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[29,30], K. Márton, A.J. Rádl[31], F. Sikler, V. Veszpremi

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanád, K. Farkas, A. Fehérkuti[32], M.M.A. Gadallah[33], Á. Kadlecsik, P. Major, G. Pásztor, G.I. Veres

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

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

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
T. Csorgo[32], F. Nemes[32], T. Novak

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra[34], A. Kaur, A. Kaur, H. Kaur, M. Kaur, S. Kumar, T. Sheokand, J.B. Singh, A. Singla

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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
S. Baradia, S. Barman[35], 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[36], D. Kumar[36], T. Mishra, B. Parida[37], 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, M. Shelake, P. Suryadevara

Tata Institute of Fundamental Research-B, Mumbai, India
A. Bala, S. Banerjee, S. Bhowmik, R.M. Chatterjee, M. Guchait, Sh. Jain, A. Jaiswal, B.M. Joshi, 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[38], C. Kar, D. Maity[39], P. Mal, K. Naskar[39], A. Nayak[39], S. Nayak, K. Pal, P. Sadangi, S.K. Swain, S. Varghese[39], D. Vats[39]

Indian Institute of Science Education and Research (IISER), Pune, India
S. Acharya[40], A. Alpana, S. Dube, B. Gomber[40], P. Hazarika, B. Kansal, A. Laha, B. Sahu[40], S. Sharma, K.Y. Vaish

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[41], A. Jafari[42], M. Zeinali[43]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Bashiri, S. Chenarani[44], S.M. Etesami, Y. Hosseini, M. Khakzad, E. Khazaie, M. Mohammadi Najafabadi, S. Tizchang[45]

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,46], N. Ferrara[a,b], 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,47], M. Lorusso[a,b], L. Lunerti[a], S. Marcellini[a], G. Masetti[a], F.L. Navarria[a,b], G. Paggi[a,b], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], S. Rossi Tisbeni[a,b], T. Rovelli[a,b], G.P. Siroli[a,b]

INFN Sezione di Catania[a], Università di Catania[b], Catania, Italy
S. Costa[a,b,48], A. Di Mattia[a], A. Lapertosa[a], R. Potenza[a,b], A. Tricomi[a,b,48]

INFN Sezione di Firenze[a], Università di Firenze[b], Firenze, Italy
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[49], D. Piccolo

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

INFN Sezione di Milano-Bicocca[a], Università di Milano-Bicocca[b], Milano, Italy
A. Benaglia[a], F. Brivio[a], 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], G. Lavizzari[a,b], M.T. Lucchini[a,b], M. Malberti[a], S. Malvezzi[a], A. Massironi[a], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], S. Palluotto[a,b], D. Pedrini[a], A. Perego[a,b], 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,50], P. Paolucci[a,28], B. Rossi[a]

INFN Sezione di Padova[a], Università di Padova[b], Padova, Italy; Universita degli Studi di Cagliari[c], Cagliari, Italy
R. Ardino[a], P. Azzi[a], N. Bacchetta[a,51], D. Bisello[a,b], P. Bortignon[a], G. Bortolato[a,b], A.C.M. Bulla[a], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a,52], U. Gasparini[a,b], S. Giorgetti[a], E. Lusiani[a], M. Margoni[a,b], G. Maron[a,53], A.T. Meneguzzo[a,b], M. Migliorini[a,b], J. Pazzini[a,b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], M. Tosi[a,b], A. Triossi[a,b], S. Ventura[a], M. Zanetti[a,b], P. Zotto[a,b], A. Zucchetta[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia[a], Università di Pavia[b], Pavia, Italy
A. Braghieri[a], S. Calzaferri[a], 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], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,54], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a], T. Tedeschi[a,b]

INFN Sezione di Pisa[a], Università di Pisa[b], Scuola Normale Superiore di Pisa[c], Pisa, Italy; Università di Siena[d], Siena, Italy
C. Aimè[a], 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,b], D. Matos Figueiredo[a], A. Messineo[a,b], S. Mishra[a], V.K. Muraleedharan Nair Bindhu[a,b,39], M. Musich[a,b], S. Nandan[a], 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
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], R. Gargiulo[a,b], E. Longo[a,b], L. Martikainen[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],

V. Vladimirov[a,b]

INFN Sezione di Torino[a], Università di Torino[b], Torino, Italy; Università del Piemonte Orientale[c], Novara, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a], R. Bellan[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, 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[55], 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
Y. Kang, H. S. Kim, Y. Kim, S. Lee

Seoul National University, Seoul, Korea
J. Almond, J.H. Bhyun, J. Choi, J. Choi, W. Jun, J. Kim, Y.W. Kim, S. Ko, 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, 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, K. Hwang, B. Kim, 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[56], 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[57], 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, F.E. Neri Huerta, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

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

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

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

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

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
P. Fokow, K. Pozniak, W. Zabolotny

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

Faculty of Physics, University of Belgrade, Belgrade, Serbia

P. Adzic, P. Milenovic

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

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
J. Alcaraz Maestre, Cristina F. Bedoya, J.A. Brochero Cifuentes, 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, J. Llorente Merino, C. Martin Perez, E. Martin Viscasillas, D. Moran, C. M. Morcillo Perez, Á. Navarro Tobar, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, 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, P. Leguina, E. Palencia Cortezon, J. Prado Pico, 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. Blanco Fernández, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, G. Gomez, C. Lasaosa García, R. Lopez Ruiz, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, E. Navarrete Ramos, J. Piedra Gomez, L. Scodellaro, I. Vila, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
B. Kailasapathy[58], D.D.C. Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G.D. Dharmaratna[59], 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, A. Bragagnolo, E. Brondolin, C.E. Brown, 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, M. Glowacki, J. Hegeman, J.K. Heikkilä, B. Huber, V. Innocente, T. James, P. Janot, O. Kaluzinska, O. Karacheban[26], G. Karathanasis, S. Laurila, P. Lecoq, E. Leutgeb, C. Lourenço, M. Magherini, 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, F. Riti, M. Rovere, H. Sakulin, R. Salvatico, S. Sanchez Cruz, S. Scarfi, C. Schwick, M. Selvaggi, A. Sharma, K. Shchelina, P. Silva, P. Sphicas[60], A.G. Stahl Leiton, A. Steen, S. Summers, D. Treille, P. Tropea, D. Walter, J. Wanczyk[61], J. Wang, S. Wuchterl, P. Zehetner, P. Zejdl, W.D. Zeuner

PSI Center for Neutron and Muon Sciences, Villigen, Switzerland

T. Bevilacqua[62], L. Caminada[62], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli[62], L. Noehte[62], T. Rohe, A. Samalan

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
T.K. Aarrestad, M. Backhaus, G. Bonomelli, A. Calandri, C. Cazzaniga, K. Datta, P. De Bryas Dexmiers D'archiac[61], 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, A. Mascellani[61], F. Nessi-Tedaldi, F. Pauss, V. Perovic, S. Pigazzini, B. Ristic, R. Seidita, J. Steggemann[61], A. Tarabini, D. Valsecchi, R. Wallny

Universität Zürich, Zurich, Switzerland
C. Amsler[63], 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, J. Motta, A. Reimers, P. Robmann, M. Senger, E. Shokr, F. Stäger, R. Tramontano

National Central University, Chung-Li, Taiwan
C. Adloff[64], D. Bhowmik, C.M. Kuo, W. Lin, P.K. Rout, P.C. Tiwari[36]

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

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

Tunis El Manar University, Tunis, Tunisia
Y. Maghrbi

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
D. Agyel, F. Boran, F. Dolek, I. Dumanoglu[65], E. Eskut, Y. Guler[66], E. Gurpinar Guler[66], C. Isik, O. Kara, A. Kayis Topaksu, Y. Komurcu, G. Onengut, K. Ozdemir[67], A. Polatoz, B. Tali[68], U.G. Tok, E. Uslan, I.S. Zorbakir

Middle East Technical University, Physics Department, Ankara, Turkey
M. Yalvac[69]

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

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak[65,73], S. Sen[74]

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

Yildiz Technical University, Istanbul, Turkey
S. Cerci, B. Isildak[77], 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, J. Goldstein, H.F. Heath, M.-L. Holmberg, L. Kreczko, S. Paramesvaran, L. Robertshaw, V.J. Smith, 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, O. Buchmuller, C.A. Carrillo Montoya, G.S. Chahal[79], D. Colling, J.S. Dancu, I. Das, P. Dauncey, G. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, A. Howard, G. Iles, C.R. Knight, P. Krueper, J. Langford, K.H. Law, J. León Holgado, L. Lyons, A.-M. Magnan, B. Maier, 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, T. Virdee[28], M. Vojinovic, N. Wardle, D. Winterbottom

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

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

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

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[81], 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. Barone, G. Benelli, D. Cutts, L. Gouskos, M. Hadley, U. Heintz, K.W. Ho, J.M. Hogan[82], T. Kwon, G. Landsberg, K.T. Lau, J. Luo, S. Mondal, T. Russell, S. Sagir[83], X. Shen, M. Stamenkovic, N. Venkatasubramanian

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

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

University of California, San Diego, La Jolla, California, USA
A. Aportela, A. Arora, J.G. Branson, S. Cittolin, S. Cooperstein, 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, D. Primosch, M. Quinnan, 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, M.M. Hussain, 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, X. Yan, D. Zhang

California Institute of Technology, Pasadena, California, USA
S. Bhattacharya, A. Bornheim, O. Cerri, 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, M. Kanemura, 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, 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, X. Chen, D.J. Cranshaw, J. Dickinson, 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, I. Dutta, V.D. Elvira, J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, A. Grummer, S. Grünendahl, D. Guerrero, O. Gutsche, R.M. Harris, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, C. Lee, D. Lincoln, R. Lipton, T. Liu, K. Maeshima, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, D. Noonan, S. Norberg, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[84], F. Ravera,

A. Reinsvold Hall[85], 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, 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, S. Butalla, S. Das, T. Elkafrawy[18], M. Hohlmann, E. Yanes

University of Illinois Chicago, Chicago, Illinois, 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, C. Mills, S. Nanda, G. Oh, B. Ozek, D. Pilipovic, R. Pradhan, E. Prifti, T. Roy, S. Rudrabhatla, N. Singh, 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[86], L. Emediato, G. Karaman, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[87], O. Neogi, H. Ogul[88], Y. Onel, A. Penzo, C. Snyder, E. Tiras[89]

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[90], C. Rogan, C. Royon, 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[91], A. Shevelev, L. Wang, L. Zhang

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
C. Baldenegro Barrera, J. Bendavid, S. Bright-Thonney, 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, 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, A. Rohilla, 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, S. Rappoccio, H. Rejeb Sfar, A. Williams, P. Young

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

Northwestern University, Evanston, Illinois, USA
S. Dittmer, K.A. Hahn, D. Li, Y. Liu, M. Mcginnis, 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. 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[15], 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, M. Carrigan, L.S. Durkin, C. Hill, M. Joyce, M. Nunez Ornelas, K. Wei, D.A. Wenzl, B.L. Winer, B. R. Yates

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

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

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, J.F. Schulte, 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, A. Agrawal, 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[91], 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, P. Saha, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, J. Vora

University of Tennessee, Knoxville, Tennessee, USA
D. Ally, A.G. Delannoy, S. Fiorendi, 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, K. Androsov[61], O. Bouhali[92], R. Eusebi, J. Gilmore, T. Huang, T. Kamon[93], H. Kim, S. Luo, R. Mueller, D. Overton, A. Safonov

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

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

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

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

University of Wisconsin - Madison, Madison, Wisconsin, USA
A. Aravind, S. Banerjee, K. Black, T. Bose, E. Chavez, S. Dasu, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Herve, C.K. Koraka, 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 international laboratory covered by a cooperation agreement with CERN
S. Afanasiev, V. Alexakhin, D. Budkouski, I. Golutvin[†], I. Gorbunov, V. Karjavine, O. Kodolova[94,91], V. Korenkov, A. Lanev, A. Malakhov, V. Matveev[95], A. Nikitenko[96,94], 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

Authors affiliated with an institute formerly covered by a cooperation agreement with CERN
G. Gavrilov, V. Golovtcov, Y. Ivanov, V. Kim[95], 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, K. Ivanov, V. Gavrilov, N. Lychkovskaya, V. Popov, A. Zhokin, R. Chistov[95], M. Danilov[95], S. Polikarpov[95], V. Andreev, M. Azarkin, M. Kirakosyan, A. Terkulov, E. Boos, V. Bunichev, M. Dubinin[84], L. Dudko, A. Ershov, V. Klyukhin, M. Perfilov, S. Petrushanko, V. Savrin, P. Volkov, V. Blinov[95], T. Dimova[95], A. Kozyrev[95], O. Radchenko[95], Y. Skovpen[95], V. Kachanov, S. Slabospitskii, A. Uzunian, A. Babaev, V. Borshch, D. Druzhkin

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

[40] Also at University of Hyderabad, Hyderabad, India
[41] Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
[42] Also at Isfahan University of Technology, Isfahan, Iran
[43] Also at Sharif University of Technology, Tehran, Iran
[44] Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
[45] Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran
[46] Also at Helwan University, Cairo, Egypt
[47] Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
[48] Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
[49] Also at Università degli Studi Guglielmo Marconi, Roma, Italy
[50] Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
[51] Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
[52] Also at Lulea University of Technology, Lulea, Sweden
[53] Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy
[54] Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
[55] Also at Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
[56] Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
[57] Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
[58] Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
[59] Also at Saegis Campus, Nugegoda, Sri Lanka
[60] Also at National and Kapodistrian University of Athens, Athens, Greece
[61] Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
[62] Also at Universität Zürich, Zurich, Switzerland
[63] Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
[64] Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
[65] Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
[66] Also at Konya Technical University, Konya, Turkey
[67] Also at Izmir Bakircay University, Izmir, Turkey
[68] Also at Adiyaman University, Adiyaman, Turkey
[69] Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
[70] Also at Marmara University, Istanbul, Turkey
[71] Also at Milli Savunma University, Istanbul, Turkey
[72] Also at Kafkas University, Kars, Turkey
[73] Now at Istanbul Okan University, Istanbul, Turkey
[74] Also at Hacettepe University, Ankara, Turkey
[75] Also at Erzincan Binali Yildirim University, Erzincan, Turkey
[76] Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
[77] Also at Yildiz Technical University, Istanbul, Turkey
[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 Università di Torino, Torino, Italy
[82] Also at Bethel University, St. Paul, Minnesota, USA

[83]Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
[84]Also at California Institute of Technology, Pasadena, California, USA
[85]Also at United States Naval Academy, Annapolis, Maryland, USA
[86]Also at Bingol University, Bingol, Turkey
[87]Also at Georgian Technical University, Tbilisi, Georgia
[88]Also at Sinop University, Sinop, Turkey
[89]Also at Erciyes University, Kayseri, Turkey
[90]Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania
[91]Now at another institute formerly covered by a cooperation agreement with CERN
[92]Also at Texas A&M University at Qatar, Doha, Qatar
[93]Also at Kyungpook National University, Daegu, Korea
[94]Also at Yerevan Physics Institute, Yerevan, Armenia
[95]Also at another institute formerly covered by a cooperation agreement with CERN
[96]Also at Imperial College, London, United Kingdom
[97]Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan