



Search for disappearing tracks in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

CERN, Switzerland

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ABSTRACT

A search is presented for long-lived charged particles that decay within the volume of the silicon tracker of the CMS experiment. Such particles can produce events with an isolated track that is missing hits in the outermost layers of the silicon tracker, and is also associated with little energy deposited in the calorimeters and no hits in the muon detectors. The search for events with this “disappearing track” signature is performed in a sample of proton-proton collisions recorded by the CMS experiment at the LHC with a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 101 fb^{-1} recorded in 2017 and 2018. The observation of 48 events is consistent with the estimated background of $47.8_{-2.3}^{+2.7} (\text{stat}) \pm 8.1 (\text{syst})$ events. Upper limits are set on chargino production in the context of an anomaly-mediated supersymmetry breaking model for purely wino and higgsino neutralino scenarios. At 95% confidence level, the first constraint is placed on chargino masses in the higgsino case, excluding below 750 (175) GeV for a lifetime of 3 (0.05) ns. In the wino case, the results of this search are combined with a previous CMS search to produce a result representing the complete LHC data set recorded in 2015–2018, the most stringent constraints to date. At 95% confidence level, chargino masses in the wino case are excluded below 884 (474) GeV for a lifetime of 3 (0.2) ns.

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1. Introduction

Many beyond-the-standard-model (BSM) scenarios introduce long-lived charged particles that could decay within the volume of the tracking detectors used by the CERN LHC experiments. If the decay products of such a particle are undetected, either because they have too little momentum to be reconstructed or because they interact only weakly, a “disappearing track” signature is produced. This signature is identified as an isolated particle track that extends from the interaction region but is missing hits in the outermost region of the tracking detector, and also has little associated energy deposited in the calorimeters and no associated hits in the outer muon detectors. Because standard model (SM) processes rarely produce this signature, background processes are almost entirely composed of failures of the particle reconstruction or track finding algorithms.

The disappearing track signature arises in a broad range of BSM scenarios [1–13]. For example, in anomaly-mediated supersymmetry breaking (AMSB) [14,15] the particle mass spectrum includes a chargino and neutralino (electroweakinos $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$, respectively) that are nearly degenerate in mass. In this scenario,

with a chargino-neutralino mass difference of order 100 MeV, the chargino is long-lived and can reach the CMS tracking detector before decaying to a neutralino and a pion ($\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \pi^\pm$). The produced pion does not have sufficient momentum to be reconstructed as a track, nor to contribute significantly to the energy associated with the original chargino track. The neutralino, as the lightest supersymmetric particle (LSP), is stable assuming R-parity conservation and interacts only weakly, leaving no trace in the detector. Consequently, the decay of an AMSB chargino to a weakly interacting neutralino and an unreconstructed pion would produce the disappearing track signature.

This letter presents a search for disappearing tracks in proton-proton (pp) collision data collected at $\sqrt{s} = 13$ TeV throughout 2017 and 2018, corresponding to an integrated luminosity of 101 fb^{-1} . The results of this search are presented in terms of chargino masses and lifetimes within the context of AMSB. The results are also presented more generally in a form that can be used to test any BSM scenario producing the disappearing track signature. The ATLAS experiment has previously excluded AMSB, with a purely wino LSP, for chargino masses below 460 GeV with a lifetime of 0.2 ns [16]. The CMS experiment has excluded AMSB chargino masses for a purely wino LSP below 715 GeV for a lifetime of 3 ns [17], using the data collected during 2015 and 2016. This search extends the previous CMS results to encompass the

* E-mail address: cms-publication-committee-chair@cern.ch.

entire available $\sqrt{s} = 13\text{TeV}$ data set, referred to as the Run 2 data set, corresponding to a total integrated luminosity of 140fb^{-1} . Prior to the 2017 data-taking period, a new pixel detector was installed as part of the Phase 1 upgrade [18,19]. This new detector contains a fourth inner layer at a radius of 2.9 cm from the interaction region. The addition of this new layer enables this search to accept shorter tracks that traverse fewer layers of the tracker, thereby increasing its sensitivity to shorter lifetime particles. The interpretation of the results is extended to include the direct electroweak production of charginos in the case of a purely higgsino LSP.

2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter. 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 measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

The silicon tracker measures charged particles within the pseudorapidity range $|\eta| < 2.5$. During the LHC running period when the data used in this analysis were recorded, the silicon tracker consisted of 1856 silicon pixel and 15 148 silicon strip detector modules.

Events of interest are selected using a two-tiered trigger system [20]. 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 time interval of less than $4\mu\text{s}$. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to $\mathcal{O}(1)\text{kHz}$ before data storage.

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [21].

3. Data sets

This search is based on pp collision data recorded by the CMS detector at $\sqrt{s} = 13\text{TeV}$ corresponding to an integrated luminosity of 42fb^{-1} [22] and 60fb^{-1} [23] from the 2017 and 2018 data-taking periods, respectively.

Simulated signal events are generated at leading order (LO) precision with PYTHIA 8.240 [24], using the NNPDF3.0 LO [25] parton distribution function (PDF) set with the CP5 tune [26] to describe the underlying event. Supersymmetric particle mass spectra are produced by ISAJET 7.70 [27], for chargino masses in the range 100–1100 (100–900) GeV in steps of 100 GeV for the wino (higgsino) LSP case. The ratio of the vacuum expectation values of the two Higgs doublets ($\tan\beta$) is fixed to 5, with a positive higgsino mass parameter ($\mu > 0$). The $\tilde{\chi}_1^\pm - \tilde{\chi}_1^0$ mass difference has little dependence on $\tan\beta$ and the sign of μ [28]. While this mass difference typically determines the chargino's proper decay time (the lifetime in the rest frame, τ), in these simulated signal events τ is explicitly varied from 6.67 ps to 333 ns (corresponding to a range in $c\tau$ of 0.2–10 000 cm) in logarithmic steps, to examine sensitivity to a broader range of models.

In the wino LSP case, the chargino branching fraction (\mathcal{B}) for $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \pi^\pm$ is set to 100%, and both $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ and $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ production processes are simulated. In the higgsino LSP case, the second

neutralino ($\tilde{\chi}_2^0$) is completely degenerate in mass with $\tilde{\chi}_1^0$, having equal production cross sections (σ) and branching fractions for the $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_{1,2}^0 + X$ decays. Following Ref. [29], these are taken to be 95.5% for $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_{1,2}^0 \pi^\pm$, 3% for $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_{1,2}^0 e\nu$, and 1.5% for $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_{1,2}^0 \mu\nu$ in the range of chargino masses of interest, and both $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ and $\tilde{\chi}_1^\pm \tilde{\chi}_{1,2}^0$ production processes are simulated.

Simulated signal events are normalized using cross sections calculated to next-to-leading order plus next-to-leading-logarithmic (NLO+NLL) precision, using RESUMMINO 1.0.9 [30,31] with the CTEQ6.6 [32] and MSTW2008nlo90cl [33] PDF sets, and the final numbers are calculated using the PDF4LHC recommendations [34] for the two sets of cross sections. In the wino case, the ratio of $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ to $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ production is roughly 2:1 for all chargino masses considered. In the higgsino case, the ratio of $\tilde{\chi}_1^\pm \tilde{\chi}_{1,2}^0$ to $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ production is roughly 7:2.

As an LO generator, PYTHIA is known to be deficient in modeling the rate of initial-state radiation (ISR) and the resulting hadronic recoil [35,36], so data-derived corrections for this deficiency are applied as functions of the transverse momentum (p_T) of the electroweakino pair (either $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ or $\tilde{\chi}_1^\pm \tilde{\chi}_{1,2}^0$). Similar to the method used in Ref. [36], the correction factors are derived as the ratio of the p_T of $Z \rightarrow \mu\mu$ candidates in data to simulated PYTHIA events, under the assumption that the production of ISR in Z boson and electroweakino pair events are similar, since both are electroweak processes. The ISR correction factors typically range between 1.8 and 2.0 in the kinematic region relevant for this search.

Simulated events are generated with a Monte Carlo program incorporating a full model of the CMS detector, based on GEANT4 [37], and reconstructed with the same software used for collision data. Simulated minimum bias events are superimposed on the hard interaction to describe the effect of additional inelastic pp interactions within the same or neighboring bunch crossings, known as pileup, and the samples are weighted to match the pileup distribution observed in data.

4. Event reconstruction and selection

A particle-flow (PF) algorithm [38] aims to reconstruct and identify each individual particle in an event with an optimized combination of information from the various elements of the CMS detector. The energy of photons is obtained from the ECAL measurement. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies.

For each event, hadronic jets are clustered from these reconstructed particles using the infrared- and collinear-safe anti- k_T algorithm [39,40] with a distance parameter 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. Hadronic τ lepton decays are reconstructed with the hadron-plus-strips algorithm [41], which starts from the reconstructed jets.

The missing transverse momentum vector \vec{p}_T^{miss} is computed as the negative vector sum of the transverse momenta of all the PF

candidates in an event [42], and its magnitude is denoted as p_T^{miss} . The \vec{p}_T^{miss} is modified to account for corrections to the energy scale of the reconstructed jets in the event. The related vector $\vec{p}_T^{\text{miss},\mu}$ is calculated in the same manner as \vec{p}_T^{miss} , excepting that the transverse momenta of PF muons are ignored. The magnitude of $\vec{p}_T^{\text{miss},\mu}$ is denoted by $p_T^{\text{miss},\mu}$. Signal events for this search typically have no reconstructed muons, in which case \vec{p}_T^{miss} and $\vec{p}_T^{\text{miss},\mu}$ are identical.

As tracking information is not available in the L1 trigger, events are collected by several triggers requiring large p_T^{miss} or $p_T^{\text{miss},\mu}$, which would be produced in signal events by an ISR jet recoiling against the electroweakino pair. The L1 triggers require p_T^{miss} above a threshold that was varied during the data-taking period according to the instantaneous luminosity. The HLT requires both p_T^{miss} and $p_T^{\text{miss},\mu}$ with a range of thresholds. The lowest threshold trigger, designed specially for this search, requires $p_T^{\text{miss}} > 105 \text{ GeV}$ and an isolated track with $p_T > 50 \text{ GeV}$ and at least 5 associated tracker hits at the HLT. The remaining triggers require p_T^{miss} or $p_T^{\text{miss},\mu} > 120 \text{ GeV}$ and do not have a track requirement.

After the trigger, events selected offline are required to be consistent with the topology of an ISR jet at the HLT, having $p_T^{\text{miss},\mu} > 120 \text{ GeV}$, and at least one jet with $p_T > 110 \text{ GeV}$ and $|\eta| < 2.4$. To reject events with spurious p_T^{miss} from mismeasured jets, the difference in the azimuthal angle ϕ between the direction of the highest p_T jet and \vec{p}_T^{miss} is required to be greater than 0.5 radians. For events with at least two jets, the maximum difference in ϕ between any two jets, $\Delta\phi_{\text{max}}$, is required to be less than 2.5 radians. In 2018, a 40° section of one end of the hadronic endcap calorimeter (HEM) lost power during the data-taking period. The 2018 data are therefore separated into two samples, 2018 A and B, corresponding to events before and after this loss of power, with integrated luminosities of 21 and 39 fb^{-1} , respectively. Events from the 2018 B period are rejected if the \vec{p}_T^{miss} points to the affected region, having $-1.6 < \phi(\vec{p}_T^{\text{miss}}) < -0.6$. This requirement, referred to as the ‘‘HEM veto’’, removes 31% of the events in 2018 B, and leads to a reduction in the signal acceptance of 16% for this data-taking period, as expected from geometrical considerations and as verified in simulation. The selection requirements applied to this point define the ‘‘basic selection’’, with the resulting sample dominated by $W \rightarrow \ell\nu$ events.

After the basic selection, isolated tracks with $p_T > 55 \text{ GeV}$ and $|\eta| < 2.1$ are further selected, where the isolation requirement is defined such that the scalar sum of the p_T of all other tracks within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$ of the candidate track must be less than 5% of the candidate track’s p_T . Tracks must be separated from jets having $p_T > 30 \text{ GeV}$ by $\Delta R(\text{track, jet}) > 0.5$. Tracks are also required to be associated with the primary pp interaction vertex (PV), the candidate vertex with the largest value of summed physics-object p_T^2 . The physics objects in this sum are the jets, clustered with the tracks assigned to candidate vertices as inputs, and the associated missing transverse momentum, taken as the negative vector sum of the p_T of those jets. With respect to the PV, candidate tracks must have a transverse impact parameter ($|d_0|$) less than 0.02 cm and a longitudinal impact parameter ($|d_z|$) less than 0.50 cm.

Tracks are said to have a missing hit if they are reconstructed as passing through a functional tracker layer, but no hit in that layer is associated with the track. A missing hit is described as ‘‘inner’’ if the missing layer is between the interaction point and the track’s innermost hit, ‘‘middle’’ if between the track’s innermost and outermost hits, and ‘‘outer’’ if it is beyond the track’s outermost hit. The track reconstruction algorithm generally allows

for some missing hits, to improve efficiency for tracks traversing the entire tracker. However, for shorter tracks this may result in spurious reconstructed tracks, arising not from charged particle trajectories but from pattern recognition errors. These spurious tracks are one of two sources of backgrounds considered in this search. This background is reduced by requiring tracks to have no missing inner or middle hits, and at least four hits in the pixel detector.

The other source of background is isolated, high- p_T charged leptons from SM decays of W^\pm or Z bosons, or from virtual photons. These tracks can seem to disappear if the track reconstruction fails to find all of the associated hits. Missing outer hits in lepton tracks may occur because of highly energetic bremsstrahlung in the case of electrons, or nuclear interactions with the tracker material in the case of hadronically decaying τ leptons (τ_h). Electrons or τ_h may be associated with little energy deposited in the calorimeters because of nonfunctional or noisy calorimeter channels. To mitigate this background, tracks are rejected if they are within $\Delta R(\text{track, lepton}) < 0.15$ of any reconstructed lepton candidate, whether electron, muon, or τ_h . This requirement is referred to as the ‘‘reconstructed lepton veto’’. To avoid regions of the detector known to have lower efficiency for lepton reconstruction, fiducial criteria are applied to the track selection. In the muon system, tracks within regions of incomplete detector coverage, i.e., within $0.15 < |\eta| < 0.35$ and $1.55 < |\eta| < 1.85$, are rejected. In the ECAL, tracks in the transition region between the barrel and endcap sections at $1.42 < |\eta| < 1.65$ are rejected, as are tracks whose projected entrance into the calorimeter is within $\Delta R < 0.05$ of a nonfunctional or noisy channel. Because two layers of the pixel tracker were not fully functional in certain data-taking periods, some regions exhibited low efficiency for the requirement of four or more pixel hits, and tracks within these regions are rejected. These regions correspond to the range $2.7 < \phi < \pi$ for the region $0 < \eta < 1.42$ in the 2017 data set, and to the range $0.4 < \phi < 0.8$ for the same η region in the 2018 data set. Application of this final requirement rejects approximately 20% of simulated signal tracks.

Additional regions of lower lepton reconstruction efficiency are identified using ‘‘tag-and-probe’’ (T&P) studies [43]. Candidate $Z \rightarrow \ell\ell$ objects are selected in data where the invariant mass of a tag lepton and a probe track is within 10 GeV of m_Z , the world-average mass of the Z boson [44], resulting in a sample of tracks having a high probability of being a lepton without explicitly requiring that they pass the lepton reconstruction. The efficiency of the lepton reconstruction is calculated using these probe tracks across the full coverage of the detector, and also for each local η - ϕ region of size 0.1×0.1 . Candidate tracks are rejected from the search region if they are within an η - ϕ region in which the local efficiency is less than the overall mean efficiency by at least two standard deviations. This procedure removes an additional 4% of simulated signal tracks.

Finally, two criteria define the condition by which a track is considered to have ‘‘disappeared’’: (1) the track must have at least three missing outer hits, and (2) the sum of all associated calorimeter energy within $\Delta R < 0.5$ of the track ($E_{\text{calo}}^{\Delta R < 0.5}$) must be less than 10 GeV . From the sample of tracks passing all of the requirements described above, three signal categories are defined depending on the number of tracker layers that have hits associated to the track, n_{lay} : $n_{\text{lay}} = 4$, $n_{\text{lay}} = 5$, and $n_{\text{lay}} \geq 6$. At $\eta = 0$ these categories correspond, respectively, to track lengths of approximately 20, 20–30, and $> 30 \text{ cm}$. The previous CMS search for disappearing tracks [17] required at least seven hits associated with the selected tracks, which resulted in a sensitivity comparable to that of only the $n_{\text{lay}} \geq 6$ category in this search.

Table 1
Summary of estimated values of P_{veto} . The uncertainties shown represent only the statistical component.

Data-taking period	n_{lay}	P_{veto}		
		Electrons	Muons	τ_h
2017	4	$(8.2 \pm 5.2) \times 10^{-4}$	$(0.0^{+3.9}_{-0.0}) \times 10^{-3}$	$(6.9^{+8.3}_{-5.1}) \times 10^{-2}$
	5	$(2.2 \pm 0.9) \times 10^{-4}$	$(3.2 \pm 1.3) \times 10^{-2}$	$(6.5^{+2.9}_{-2.7}) \times 10^{-2}$
	≥ 6	$(2.7 \pm 0.5) \times 10^{-5}$	$(1.2 \pm 0.5) \times 10^{-6}$	$(1.0 \pm 0.4) \times 10^{-3}$
2018 A	4	$(1.3 \pm 0.7) \times 10^{-3}$	$(1.0 \pm 1.0) \times 10^{-1}$	$(7.1^{+5.5}_{-3.8}) \times 10^{-2}$
	5	$(0.9^{+1.5}_{-0.9}) \times 10^{-4}$	$(7.4 \pm 4.2) \times 10^{-2}$	$(4.4^{+5.5}_{-4.4}) \times 10^{-2}$
	≥ 6	$(1.6 \pm 0.6) \times 10^{-5}$	$(1.9 \pm 0.8) \times 10^{-6}$	$(0.0^{+7.3}_{-0.0}) \times 10^{-4}$
2018 B	4	$(0.0^{+1.1}_{-0.0}) \times 10^{-4}$	$(4.0^{+15.0}_{-4.0}) \times 10^{-2}$	$(5.6^{+6.5}_{-5.0}) \times 10^{-2}$
	5	$(1.4 \pm 1.1) \times 10^{-4}$	$(5.8 \pm 3.8) \times 10^{-2}$	$(5.1^{+4.5}_{-3.7}) \times 10^{-2}$
	≥ 6	$(3.3 \pm 0.7) \times 10^{-5}$	$(1.5 \pm 0.6) \times 10^{-6}$	$(2.3 \pm 1.0) \times 10^{-3}$

5. Background estimation

5.1. Charged leptons

For tracks from charged, high- p_T leptons (electrons, muons, or τ_h) to be selected by the search criteria, the lepton reconstruction must fail in such a way that a track is still observed but no lepton candidate is produced, resulting in a mismeasurement of the calorimeter energy in the event. For this reconstruction failure to occur, the following conditions must be present:

- There is a reconstructed lepton track that is isolated from other tracks and has zero missing inner or middle hits. In addition, there must be no candidate lepton identified near to it, $E_{\text{calo}}^{\Delta R < 0.5}$ must be less than 10 GeV, and the track must have at least three missing outer hits.
- The resulting $p_T^{\text{miss}, \ell}$ must be large enough to pass the offline $p_T^{\text{miss}, \ell}$ requirement.
- The resulting p_T^{miss} and $p_T^{\text{miss}, \ell}$ must be large enough to pass to trigger requirement.
- In the 2018 B data-taking period, the resulting p_T^{miss} must pass the HEM veto.

The background from charged leptons is estimated by calculating the conditional probability of each of these four requirements in the given order, as described below, treating each lepton flavor independently in each of the three signal categories.

5.1.1. P_{veto}

The probability of satisfying the first condition, P_{veto} , is defined as the probability for a lepton candidate to fail to be identified as a lepton. This is estimated for electrons (muons) using a T&P study with $Z \rightarrow ee$ ($Z \rightarrow \mu\mu$) candidates. Events are selected if they satisfy a single-electron (single-muon) trigger and contain a tag electron (muon) candidate passing tight identification and isolation criteria. A probe track is required to pass the disappearing track criteria, excepting the reconstructed lepton veto for the flavor under study, the $E_{\text{calo}}^{\Delta R < 0.5}$ requirement, and the missing outer hits requirement. The tag lepton and the probed track are required to have opposite-sign electric charges and an invariant mass within 10 GeV of m_Z .

To study these probabilities for τ_h , $Z \rightarrow \tau\tau$ candidate events are selected in which one τ decays via $\tau \rightarrow e\nu\nu$ or $\tau \rightarrow \mu\nu\nu$, with the electron or muon serving as the tag lepton. The other τ in these events is selected as the probe track and, after applying the reconstructed electron and muon vetoes to it, the result is a sample of tracks dominated by τ_h . The electron and muon selections are as described above, with two modifications for the case of τ_h . To

reduce contamination from $W \rightarrow \ell\nu$ events, the transverse mass $m_T = \sqrt{2p_T^\ell p_T^{\text{miss}}(1 - \cos \Delta\phi)}$ is required to be less than 40 GeV, where p_T^ℓ is the magnitude of the tag lepton's transverse momentum and $\Delta\phi$ is the difference in ϕ between the \vec{p}_T of the tag lepton and the \vec{p}_T^{miss} . In addition, because τ leptons from the Z decay are not fully reconstructed, the invariant mass of the tag-probe pair is required to be in the range $m_Z - 50 < M < m_Z - 15$ GeV.

For each T&P study of P_{veto} (electrons, muons, and τ_h), the number of selected T&P pairs before and after applying the relevant flavor of the reconstructed lepton veto, the $E_{\text{calo}}^{\Delta R < 0.5}$ requirement, and the missing outer hits requirement are labeled $N_{\text{T\&P}}$ and $N_{\text{T\&P}}^{\text{veto}}$, respectively. To subtract non-Z boson contributions from the opposite-sign T&P samples, the selections above are repeated but requiring instead that the tag lepton and probe track have the same electric charge, yielding the quantities $N_{\text{SS T\&P}}$ and $N_{\text{SS T\&P}}^{\text{veto}}$. The probability that a lepton candidate is not explicitly identified as a lepton is then given by:

$$P_{\text{veto}} = \frac{N_{\text{T\&P}}^{\text{veto}} - N_{\text{SS T\&P}}^{\text{veto}}}{N_{\text{T\&P}} - N_{\text{SS T\&P}}}. \quad (1)$$

The results obtained for P_{veto} are summarized in Table 1.

5.1.2. P_{off}

The probability of satisfying the second condition, P_{off} , is defined as the conditional probability of a single-lepton event to pass the offline requirements of $p_T^{\text{miss}, \ell} > 120$ GeV and $|\Delta\phi(\text{leading jet}, \vec{p}_T^{\text{miss}, \ell})| > 0.5$, given that the lepton candidate is not explicitly identified as a lepton. The latter of these criteria requires the existence of a jet having $p_T > 110$ GeV and $|\eta| < 2.4$, as is required in the basic selection. The $\vec{p}_T^{\text{miss}, \ell}$ of events with an unidentified lepton is modeled by assuming the lepton contributes no calorimeter energy to the event, replacing $p_T^{\text{miss}, \ell}$ with the magnitude of $\vec{p}_T^{\text{miss}, \ell} + \vec{p}_T^\ell$. This modification is applied in single-lepton control samples for each flavor, defined as containing data events passing single-lepton triggers and having at least one tag lepton of the appropriate flavor. In the case of muons, no modification of $\vec{p}_T^{\text{miss}, \ell}$ is made as they are already excluded from its calculation. The quantity P_{off} is estimated for each lepton flavor by counting the fraction of single-lepton control sample events with $p_T^{\text{miss}, \ell} > 120$ GeV and $|\Delta\phi(\text{leading jet}, \vec{p}_T^{\text{miss}, \ell})| > 0.5$, after modifying $\vec{p}_T^{\text{miss}, \ell}$ in this way. For electrons and muons, P_{off} is approximately 0.7–0.8, and approximately 0.2 for τ_h .

5.1.3. P_{trig}

The probability of satisfying the third condition, P_{trig} , is defined as the conditional probability that a single-lepton event passes

the trigger requirement, given that the lepton candidate is not identified as a lepton and the event passes the offline requirements of $p_T^{\text{miss},\ell} > 120 \text{ GeV}$ and $|\Delta\phi(\text{leading jet } \vec{p}_T^{\text{miss},\ell})| > 0.5$. In the single-lepton control samples used to measure P_{off} , the efficiency of the trigger requirement is calculated as a function of $p_T^{\text{miss},\ell}$. The trigger efficiency is then multiplied bin-by-bin by the magnitude of $\vec{p}_T^{\text{miss},\ell} + \vec{p}_T^\ell$, described above for P_{off} . The fraction of events in this product that survive the requirement of $p_T^{\text{miss},\ell}$ (modified) $> 120 \text{ GeV}$ is then the estimate of P_{trig} . The value of P_{trig} is approximately 0.3–0.6 for all lepton flavors.

5.1.4. P_{HEM}

The probability of satisfying the fourth condition, P_{HEM} , is defined as the conditional probability that a single-lepton event survives the HEM veto, given that the lepton candidate is not explicitly identified as a lepton and the event passes both the offline and trigger requirements. This probability is calculated in the sample of events forming the numerator of P_{trig} . Because the HEM veto is applied only in the 2018 B data set, P_{HEM} is fixed to unity in the other data-taking periods. The value of P_{HEM} is approximately 0.8 for all lepton flavors.

5.1.5. Charged lepton background estimation

The product of these four conditional probabilities gives the overall probability for an event with a charged lepton to pass the search selection criteria. These probabilities are measured separately for each flavor and within each signal category of n_{lay} . To normalize these probabilities to form the background estimate, the number of events with a charged lepton of each flavor (N_{ctrl}^ℓ) is counted by selecting events passing single-lepton triggers and containing a lepton of the appropriate flavor with $p_T > 55 \text{ GeV}$. No requirement on the presence of $p_T^{\text{miss},\ell}$ or the reconstruction of jets is made in counting N_{ctrl}^ℓ , as P_{off} accounts for the probability to pass those criteria. The value of N_{ctrl}^ℓ is corrected by the efficiency of the relevant single-lepton trigger, $\epsilon_{\text{trigger}}^\ell$, in order to account for any inefficiencies in that trigger. From the T&P samples used to study P_{veto} , $\epsilon_{\text{trigger}}^\ell$ is measured as the fraction of probe tracks satisfying the single-lepton trigger requirement of the N_{ctrl}^ℓ selection. The values are observed to be 84% in the case of electrons, 94% in the case of muons, and 90% in the case of τ_h candidates. The estimated background from charged leptons is calculated using these components as

$$N_{\text{est}}^\ell = \frac{N_{\text{ctrl}}^\ell}{\epsilon_{\text{trigger}}^\ell} P_{\text{veto}} P_{\text{off}} P_{\text{trig}} P_{\text{HEM}}. \quad (2)$$

In the case of the $n_{\text{lay}} = 4$ and $n_{\text{lay}} = 5$ signal categories, insufficient numbers of events are available for muons in the estimation of P_{HEM} , and for muons and τ_h in the estimation of both P_{off} and P_{trig} . Therefore, these quantities are estimated as the average over the inclusive category $n_{\text{lay}} \geq 4$. The dependence of these values on n_{lay} for electrons is applied as a systematic uncertainty in these cases, described below in Section 6.1.

5.2. Spurious tracks

Because spurious tracks do not represent the trajectory of an actual charged particle, the combination of tracker layers with associated hits is largely random. The requirement of zero missing inner and middle hits greatly suppresses the probability of selecting a spurious track.

To measure the probability that an event contains a spurious track, two control samples containing $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ decays,

respectively, are selected as representative samples of SM events. The signal benchmark chosen does not contain Z bosons, so any candidate disappearing tracks observed in these control samples can reliably be labeled as a spurious track. Since spurious tracks generally do not point to the PV, the purity of the spurious tracks samples can be enhanced by replacing the nominal requirement of $|d_0| < 0.02 \text{ cm}$ with a “sideband” selection, defined as $0.05 \leq |d_0| < 0.50 \text{ cm}$.

To normalize the sideband selection to the search region, the shape of the d_0 distribution is described with a fit to a Gaussian function with an added constant, for each control sample in the $n_{\text{lay}} = 4$ category. The fit is made in the slightly restricted range $0.1 \leq |d_0| < 0.5 \text{ cm}$ to remove any overlap with the signal region. A transfer factor ζ is then calculated as the ratio of the integral of the fit function in the signal region to that in the sideband. The value of ζ derived from the $n_{\text{lay}} = 4$ category is applied to the $n_{\text{lay}} = 5$ and $n_{\text{lay}} \geq 6$ categories because the event counts in these categories are not sufficient to observe a different d_0 distribution. Finally, the spurious track background is estimated as the raw probability for a control sample event to contain a sideband disappearing track candidate ($P_{\text{spurious}}^{\text{raw}}$), multiplied by ζ and normalized to the number of events passing the basic selection ($N_{\text{ctrl}}^{\text{basic}}$):

$$N_{\text{spurious}}^{\text{est}} = N_{\text{ctrl}}^{\text{basic}} \zeta P_{\text{spurious}}^{\text{raw}}. \quad (3)$$

This calculation is performed separately for each signal category of n_{lay} for both $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ control samples, using the $Z \rightarrow \mu\mu$ estimate as the central value of the spurious track background estimate.

6. Systematic uncertainties

6.1. Systematic uncertainties in the background estimates

The lepton background estimates make the assumption that no visible energy is deposited in the calorimeters by leptons that are not explicitly identified. This is tested for electrons and τ_h by allowing selected candidates to deposit 10 GeV in the calorimeters, the maximal value allowed by the requirement of $E_{\text{calo}}^{\Delta R < 0.5} < 10 \text{ GeV}$ for candidate signal tracks. The modified $p_T^{\text{miss},\ell}$ is constructed as before, but now the calculation includes 10 GeV in the direction of the lepton momentum. This is applied separately for each n_{lay} category for electrons, and in the inclusive $n_{\text{lay}} \geq 4$ category for τ_h because of small sample sizes. This results in a 13–15% decrease in the electron background estimate and an 11–25% decrease in the τ_h background estimate. These changes are taken as systematic uncertainties.

In the calculation of P_{off} , P_{trig} , and P_{HEM} , the available data in the $n_{\text{lay}} = 4$ and $n_{\text{lay}} = 5$ categories do not separately provide robust measurements for the muon and τ_h background estimates. Therefore we measure the values in the inclusive category $n_{\text{lay}} \geq 4$ instead. The effect of this averaging is estimated by comparing values obtained for these quantities in exclusive and inclusive n_{lay} categories for the single-electron control sample, where there is adequate data to measure each. The differences in these values range between 1 and 11%. These values are applied as one-sided systematic uncertainties in the estimate of the background contribution from muon and τ_h candidates for the $n_{\text{lay}} = 4$ and $n_{\text{lay}} = 5$ categories.

The spurious track background estimate relies on several assumptions. The first assumption is that the spurious track probability is independent of the underlying physics content of the event. This is tested by comparing the estimates obtained from the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ control samples. The differences in the estimates derived from these two control samples range from 0 to 200%, and

Table 2

Summary of the systematic uncertainties in each background estimate. Each value listed represents the average across all data-taking periods. Some uncertainties are single-sided, as indicated, and those given as a dash are negligible.

Background	Source	Uncertainty		
		$n_{\text{lay}} = 4$	$n_{\text{lay}} = 5$	$n_{\text{lay}} \geq 6$
Spurious tracks	Control sample	$\pm 19\%$	$\pm 29\%$	$\pm 116\%$
	ζ	$\pm 47\%$	$\pm 47\%$	$\pm 47\%$
Electrons	Visible calorimeter energy	$\pm 14\%$	$\pm 14\%$	$\pm 13\%$
Muons	P_{off}	+7%	+7%	—
	P_{trig}	+8%	+2%	—
τ_h	Visible calorimeter energy	$\pm 19\%$	$\pm 19\%$	$\pm 19\%$
	P_{off}	+7%	+7%	—
	P_{trig}	+8%	+2%	—

Table 3

Summary of the systematic uncertainties in the signal efficiencies. Each value listed is the average across all data-taking periods, all chargino masses and lifetimes considered, and wino and higgsino cases. The values given as a dash are negligible.

Source	Uncertainty		
	$n_{\text{lay}} = 4$	$n_{\text{lay}} = 5$	$n_{\text{lay}} \geq 6$
Pileup	3.0%	3.3%	2.8%
ISR	13%	13%	13%
Trigger efficiency	1.1%	0.8%	0.4%
Jet energy scale	0.6%	0.7%	1.6%
Jet energy resolution	0.5%	0.5%	1.3%
p_T^{miss}	0.3%	0.3%	0.4%
$E_{\text{calo}}^{\Delta R < 0.5}$	0.7%	0.7%	0.7%
Missing inner hits	2.3%	1.0%	0.3%
Missing middle hits	3.9%	5.1%	4.4%
Missing outer hits	—	—	0.2%
Reconstructed lepton veto efficiency	0.1%	0.1%	—
Track reconstruction efficiency	2.3%	2.3%	2.3%
Total	14%	15%	14%

are taken as systematic uncertainties in the spurious track background estimate. In every case, the statistical uncertainty in the difference is considerably larger than the difference itself.

The second assumption of the spurious track background estimate is that the projection of the d_0 sideband correctly describes the signal d_0 region. This assumption is tested by comparing the number of signal-like tracks ($|d_0| < 0.02 \text{ cm}$) in the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ control samples to the number projected from the sideband. Within the statistical and fit uncertainties, the projected number of tracks agrees well with the observed signal-like counts, so no systematic uncertainty is applied.

The third assumption of the spurious track background estimate is that it is independent of the definition of the d_0 sideband. The validity of this assumption is examined by defining nine alternative, disjoint sidebands of width 0.05 cm instead of the single sideband region of width 0.50 cm. The spurious track estimate is determined for each of these. The observed deviations of these estimates are well within statistical fluctuations of the nominal estimate. Therefore, no systematic uncertainty is introduced to cover these differences.

The uncertainty in ζ due to the fit procedure is evaluated by varying the fit parameters within ± 1 standard deviation of their statistical uncertainties, and comparing the resulting values of ζ . A variation of $\pm(43\text{--}52)\%$ from the nominal value is found, and this variation is taken as an estimate of the contribution from this source to the overall systematic uncertainty in the spurious track background.

The systematic uncertainties in the background estimates are summarized in Table 2.

6.2. Systematic uncertainties in signal selection efficiencies

Theoretical uncertainties in the chargino production cross section arise from the choice of factorization and renormalization scales and from uncertainties in the PDFs used. These effects result in an assigned uncertainty in the expected signal yields of 2–9%, depending on the chargino mass. A 2.3 (2.5)% uncertainty in the total integrated luminosity of the 2017 [22] (2018 [23]) data set is assigned. Uncertainties in the signal yields due to corrections or scale factors are evaluated by varying each correction by ± 1 standard deviation of their measured uncertainties, and comparing the resulting signal yields to their nominal value. The corrections considered include the corrections related to the statistical uncertainty in the ISR corrections (12–15%) and the modeling of pileup (2–5%), jet energy scale and resolution (0.1–1.6%), and $p_T^{\text{miss}, \mu}$ (0.1–2.3%), with the values varying depending on the chargino mass and lifetime. Uncertainties are estimated in the selection criteria of missing inner, middle, and outer hits (0.1–4.6, 2.5–5.2, and $< 0.3\%$, respectively) by comparing the efficiency of each between data and simulation in a control sample of single-muon events. The uncertainty in the efficiency of the $E_{\text{calo}}^{\Delta R < 0.5}$ requirement is taken to be the difference between the efficiencies obtained from data and from simulation in the $Z \rightarrow \mu\mu$ control sample (0.4–1.0%), where the tracks are expected to be predominantly spurious. The uncertainty in the track reconstruction efficiency is evaluated to be 2.1% in 2017 data [45] and 2.5% in 2018 data [46].

The efficiency of the reconstructed lepton veto in simulated events depends on the modeling of detector noise, which may produce calorimeter or muon detector hits that result in a lepton

Table 4

Summary of the estimated backgrounds and the observation. The first and second uncertainties shown are the statistical and systematic contributions, respectively.

Data-taking period	n_{day}	Expected backgrounds			Observation
		Leptons	Spurious tracks	Total	
2017	4	$1.4 \pm 0.9 \pm 0.2$	$10.9 \pm 0.7 \pm 4.7$	$12.2 \pm 1.1 \pm 4.7$	17
	5	$1.1 \pm 0.4 \pm 0.1$	$1.0 \pm 0.2 \pm 0.6$	$2.1 \pm 0.4 \pm 0.6$	4
	≥ 6	$6.7 \pm 1.1 \pm 0.7$	$0.04 \pm 0.04^{+0.08}_{-0.04}$	$6.7 \pm 1.1 \pm 0.7$	6
2018 A	4	$1.1^{+1.0}_{-0.6} \pm 0.1$	$6.2 \pm 0.5 \pm 3.5$	$7.3^{+1.1}_{-0.8} \pm 3.5$	5
	5	$0.2^{+0.6}_{-0.2} \pm 0.0$	$0.5 \pm 0.1 \pm 0.3$	$0.6^{+0.6}_{-0.2} \pm 0.3$	0
	≥ 6	$1.8^{+0.6}_{-0.5} \pm 0.2$	$0.04 \pm 0.04^{+0.06}_{-0.04}$	$1.8^{+0.6}_{-0.5} \pm 0.2$	2
2018 B	4	$0.0^{+0.8}_{-0.0} \pm 0.0$	$10.3 \pm 0.6 \pm 5.4$	$10.3^{+1.0}_{-0.6} \pm 5.4$	11
	5	$0.4^{+0.7}_{-0.3} \pm 0.1$	$0.6 \pm 0.2 \pm 0.3$	$1.0^{+0.7}_{-0.3} \pm 0.3$	2
	≥ 6	$5.7^{+1.2}_{-1.1} \pm 0.6$	$0.00^{+0.04}_{-0.00} \pm 0.00$	$5.7^{+1.2}_{-1.1} \pm 0.6$	1

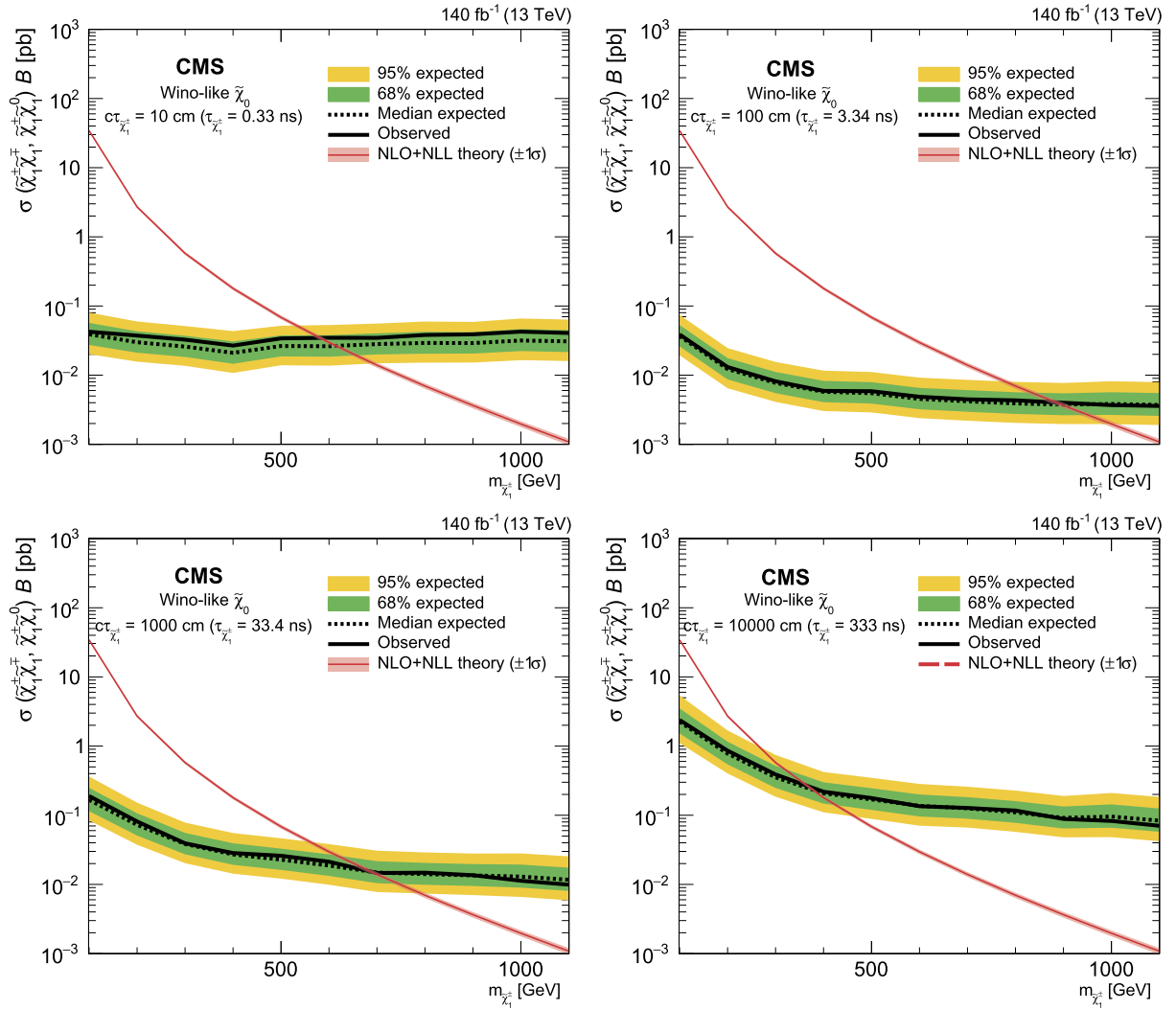


Fig. 1. The expected and observed 95% CL upper limits on the product of cross section and branching fraction for direct production of charginos as a function of chargino mass for chargino lifetimes of 0.33, 3.34, 33.4, and 333 ns, for a purely wino LSP with the branching fraction for $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \pi^\pm$ set to 100%. Shown are the full Run 2 results, derived from the results of the search in the 2017 and 2018 data sets combined with those of Ref. [17], obtained in the 2015 and 2016 data sets. The cross section includes both $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ production in roughly a 2:1 ratio for all chargino masses considered. The red line indicates the theoretical prediction, described in Section 3, with scale and PDF uncertainties displayed in the surrounding band.

candidate and thereby reject the track. The differences in reconstructed lepton veto efficiencies between data and simulation are studied by estimating the efficiencies relative to tighter lepton criteria, for which detailed scale factors are available, in the sample

of events used to measure P_{veto} for the electron and muon backgrounds. Differences between estimates from data and simulation of up to 0.1% are observed, and these are taken into account as systematic uncertainties.

Statistical uncertainties in trigger efficiencies for data and simulation are estimated to be 0.4% for each n_{lay} category, and are applied as systematic uncertainties. In the case of short tracks ($n_{\text{lay}} = 4$ and $n_{\text{lay}} = 5$), no source in data is available outside of the search region to measure the efficiency of the track leg of the trigger requirement, which requires at least five tracker hits associated with the track at HLT. To study this requirement's effect, the trigger efficiency is measured for signal events in each search category as a function of $p_T^{\text{miss}, \ell}$, and the differences between $n_{\text{lay}} \geq 6$ and $n_{\text{lay}} = 4$ (5) efficiencies are used to define weights for the $n_{\text{lay}} = 4$ (5) category. These weights are not applied to the nominal signal yield, but are used to evaluate a conservative systematic uncertainty. The weighted signal yields are compared to the nominal, unweighted values, resulting in an average systematic uncertainty of 1.0% (0.3%) for the $n_{\text{lay}} = 4$ (5) category.

The systematic uncertainties in the signal efficiencies are summarized in Table 3.

7. Results

The expected number of background events and the observed number of events are shown in Table 4 for each event category and each data-taking period. The observations are consistent with the expected total background. Upper limits are set at 95% confidence level (CL) on the product of the cross section and branching fraction for each signal model. These limits are calculated with an asymptotic CL_s criterion [47–49] that uses a test statistic based on a profile likelihood ratio and treats nuisance parameters in a frequentist context. Nuisance parameters for the theoretical uncertainties in the signal cross sections, integrated luminosity, and signal selection efficiencies are constrained with log-normal distributions. The uncertainties in the background estimates are estimated separately for spurious tracks and for reconstruction failures of each flavor of charged leptons, and are treated as independent nuisance parameters. Uncertainties resulting from limited control sample sizes are constrained with gamma distributions, whereas those associated with multiplicative factors or discussed in Section 6.1 are constrained with log-normal distributions. The three n_{lay} categories are treated as independent counting experiments, as are the data-taking periods 2017, 2018 A, and 2018 B.

In the case of electroweak production with a wino LSP, the results of this search are combined with the previous search presented by CMS, based on data collected in 2015 and 2016 [17]. All data-taking periods are treated as completely uncorrelated and are considered as independent counting experiments. Systematic uncertainties are measured independently for each period and treated as uncorrelated nuisance parameters, with the exception of uncertainties in the signal cross section, which are treated as 100% correlated.

The expected and observed upper limits on the product of cross sections of electroweak production and branching fractions in the wino LSP case are shown in Fig. 1 for four chargino lifetimes. Two-dimensional constraints derived from the intersection of the theoretical predictions with the expected and observed upper limits, for each chargino mass and mean proper lifetime considered, are shown in Fig. 2 for a purely wino LSP and in Fig. 3 for a purely higgsino LSP.

Charginos in the wino LSP case with a lifetime of 3 (0.2) ns are excluded up to a mass of 884 (474) GeV at 95% CL, the most stringent constraints to date. In the higgsino LSP case, charginos with a lifetime of 3 (0.05) ns are excluded up to a mass of 750 (175) GeV at 95% CL. This result is the first to constrain chargino masses with a higgsino LSP obtained with the disappearing track signature.

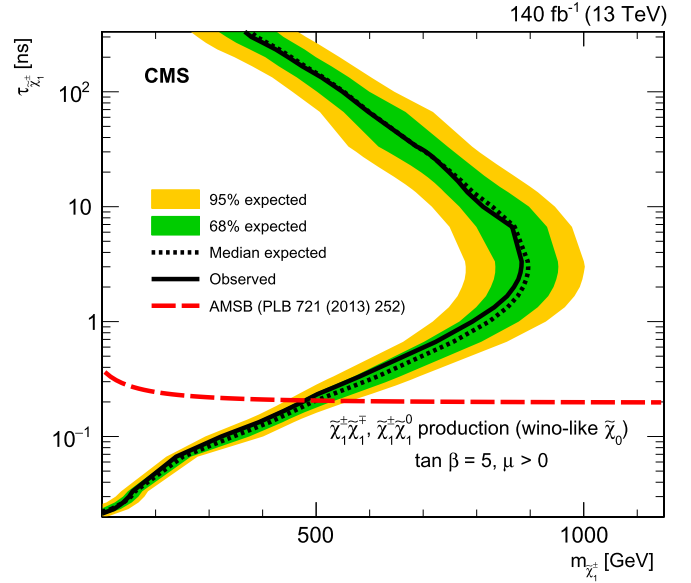


Fig. 2. The expected and observed constraints on chargino lifetime and mass for a purely wino LSP in the context of AMSB, where the chargino lifetime is explicitly varied. The chargino branching fraction is set to 100% for $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \pi^\pm$. Shown are the full Run 2 results, derived from the results of the search in the 2017 and 2018 data sets combined with those of Ref. [17], obtained in the 2015 and 2016 data sets. The region to the left of the curve is excluded at 95% CL. The prediction for the chargino lifetime from Ref. [28] is indicated as the dashed line.

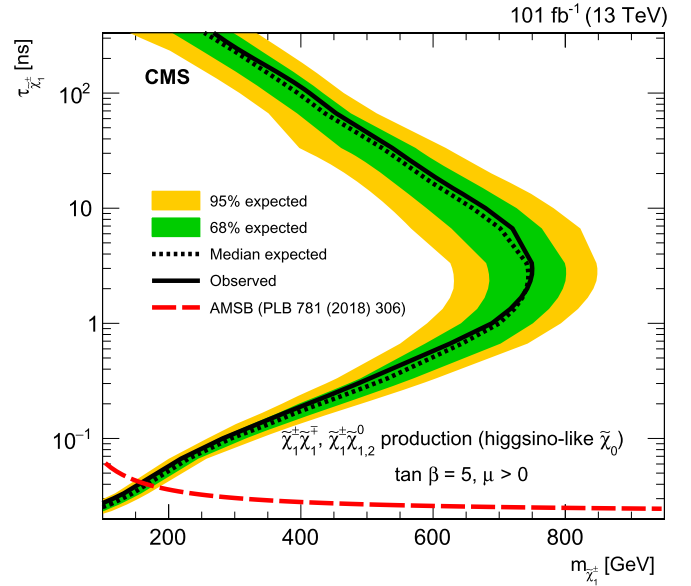


Fig. 3. The expected and observed constraints on chargino lifetime and mass for a purely higgsino LSP in the context of AMSB, where the chargino lifetime is explicitly varied. Following Ref. [29], the branching fractions are taken to be 95.5% for $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_{1,2}^0 \pi^\pm$, 3% for $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_{1,2}^0 e \nu$, and 1.5% for $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_{1,2}^0 \mu \nu$ in the range of chargino masses of interest, with equal branching fractions and production cross sections between $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$. The region to the left of the curve is excluded at 95% CL. The prediction for the chargino lifetime from Ref. [50] is indicated as the dashed line.

8. Summary

A search has been presented for long-lived charged particles that decay within the CMS detector and produce a “disappearing track” signature. In the sample of proton-proton collisions recorded by CMS in 2017 and 2018, corresponding to an integrated luminosity of 101 fb^{-1} , 48 events are observed, which is consistent with

the expected background of $47.8_{-2.3}^{+2.7}(\text{stat}) \pm 8.1(\text{syst})$ events. These results are applicable to any beyond-the-standard-model scenario capable of producing this signature and, in combination with the previous CMS search [17], are the first such results on the complete Run 2 data set, corresponding to a total integrated luminosity of 140 fb^{-1} .

Two interpretations of these results are provided in the context of anomaly-mediated supersymmetry breaking. In the case of a purely higgsino neutralino, charginos are excluded up to a mass of 750 (175) GeV for a mean proper lifetime of 3 (0.05) ns, using the 2017 and 2018 data sets. In the case of a purely wino neutralino, charginos are excluded up to a mass of 884 (474) GeV for a mean proper lifetime of 3 (0.2) ns. These results make use of the upgraded CMS pixel detector to greatly improve sensitivity to shorter particle lifetimes. For chargino lifetimes above approximately 0.1 ns, this search places the most stringent constraints on direct chargino production with a purely wino neutralino obtained with the disappearing track signature. For a purely higgsino neutralino, these constraints are the first obtained with this signature.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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The CMS Collaboration

A.M. Sirunyan[†], A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, F. Ambroggi, T. Bergauer, M. Dragicevic, J. Erö, A. Escalante Del Valle, R. Frühwirth¹, M. Jeitler¹, N. Krammer, L. Lechner, D. Liko, T. Madlener, I. Mikulec, N. Rad, J. Schieck¹, R. Schöfbeck, M. Spanring, S. Templ, W. Waltenberger, C.-E. Wulz¹, M. Zarucki

Institut für Hochenergiephysik, Wien, Austria

V. Chekhovsky, A. Litomin, V. Makarenko, J. Suarez Gonzalez

Institute for Nuclear Problems, Minsk, Belarus

M.R. Darwish, E.A. De Wolf, D. Di Croce, X. Janssen, T. Kello², A. Lelek, M. Pieters, H. Rejeb Sfar, H. Van Haeveer, P. Van Mechelen, S. Van Putte, N. Van Remortel

Universiteit Antwerpen, Antwerpen, Belgium

F. Blekman, E.S. Bols, S.S. Chhibra, J. D'Hondt, J. De Clercq, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, Q. Python, S. Tavernier, W. Van Doninck, P. Van Mulders

Vrije Universiteit Brussel, Brussel, Belgium

D. Beghin, B. Bilin, B. Clerboux, G. De Lentdecker, H. Delannoy, B. Dorney, L. Favart, A. Grebenyuk, A.K. Kalsi, I. Makarenko, L. Moureaux, L. Pétré, A. Popov, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, L. Wezenbeek

Université Libre de Bruxelles, Bruxelles, Belgium

T. Cornelis, D. Dobur, I. Khvastunov³, M. Niedziela, C. Roskas, K. Skovpen, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit

Ghent University, Ghent, Belgium

G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, I.S. Donertas, A. Giammanco, V. Lemaitre, J. Prisciandaro, A. Saggio, A. Taliencio, P. Vischia, S. Wuyckens, J. Zobec

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

G.A. Alves, G. Correia Silva, C. Hensel, A. Moraes

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato⁴, E. Coelho, E.M. Da Costa, G.G. Da Silveira⁵, D. De Jesus Damiao, S. Fonseca De Souza, H. Malbouisson, J. Martins⁶, D. Matos Figueiredo, M. Medina Jaime⁷, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, P. Rebello Teles, L.J. Sanchez Rosas, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, E.J. Tonelli Manganote⁴, F. Torres Da Silva De Araujo, A. Vilela Pereira

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

C.A. Bernardes^a, L. Calligaris^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, D.S. Lemos^a, P.G. Mercadante^b, S.F. Novaes^a, S.S. Padula^a

^a *Universidade Estadual Paulista, São Paulo, Brazil*

^b *Universidade Federal do ABC, São Paulo, Brazil*

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

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

M. Bonchev, A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov

University of Sofia, Sofia, Bulgaria

W. Fang², X. Gao², Q. Guo, H. Wang, L. Yuan

Beihang University, Beijing, China

M. Ahmad, Z. Hu, Y. Wang

Department of Physics, Tsinghua University, Beijing, China

E. Chapon, G.M. Chen⁸, H.S. Chen⁸, M. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, A. Spiezia, J. Tao, J. Wang, E. Yazgan, H. Zhang, S. Zhang⁸, J. Zhao

Institute of High Energy Physics, Beijing, China

A. Agapitos, Y. Ban, C. Chen, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang, Q. Wang

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

Z. You

Sun Yat-Sen University, Guangzhou, China

M. Xiao

Zhejiang University, Hangzhou, China

C. Avila, A. Cabrera, C. Florez, C.F. González Hernández, A. Sarkar, M.A. Segura Delgado

Universidad de Los Andes, Bogota, Colombia

J. Mejia Guisao, J.D. Ruiz Alvarez, C.A. Salazar González, N. Vanegas Arbelaez

Universidad de Antioquia, Medellin, Colombia

D. Giljanović, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

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

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, D. Ferencek, D. Majumder, B. Mesic, M. Roguljic, A. Starodumov⁹, T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

M.W. Ather, A. Attikis, E. Erodotou, A. Ioannou, G. Kole, M. Kolosova, S. Konstantinou, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, D. Tsiakkouri

University of Cyprus, Nicosia, Cyprus

M. Finger¹⁰, M. Finger Jr.¹⁰, A. Kveton, J. Tomsa

Charles University, Prague, Czech Republic

E. Ayala

Escuela Politecnica Nacional, Quito, Ecuador

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

E. Salama^{11,12}

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, L. Forthomme, H. Kirschenmann, K. Osterberg, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

E. Brücken, F. Garcia, J. Havukainen, V. Karimäki, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, H. Siikonen, E. Tuominen, J. Tuominiemi

Helsinki Institute of Physics, Helsinki, Finland

P. Luukka, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, B. Lenzi, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro¹³, M. Titov, G.B. Yu

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

S. Ahuja, C. Amendola, F. Beaudette, M. Bonanomi, P. Busson, C. Charlot, B. Diab, G. Falmagne, R. Granier de Cassagnac, I. Kucher, A. Lobanov, C. Martin Perez, M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A. Zabi, A. Zghiche

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Paris, France

J.-L. Agram¹⁴, J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, J.-C. Fontaine¹⁴, D. Gelé, U. Goerlach, C. Grimault, A.-C. Le Bihan, P. Van Hove

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France

E. Asilar, S. Beauceron, C. Bernet, G. Boudoul, C. Camen, A. Carle, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, Sa. Jain, I.B. Laktineh, H. Lattaud, A. Lesauvage, M. Lethuillier, L. Mirabito, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

T. Toriashvili¹⁵

Georgian Technical University, Tbilisi, Georgia

Z. Tsamalaidze¹⁰

Tbilisi State University, Tbilisi, Georgia

L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M. Preuten, M.P. Rauch, J. Schulz, M. Teroerde

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

D. Eliseev, M. Erdmann, P. Fackeldey, B. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, G. Mocellin, S. Mondal, S. Mukherjee, D. Noll, A. Novak, T. Pook, A. Pozdnyakov, T. Quast, M. Radziej, Y. Rath, H. Reithler, J. Roemer, A. Schmidt, S.C. Schuler, A. Sharma, S. Wiedenbeck, S. Zaleski

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

C. Dziwok, G. Flügge, W. Haj Ahmad¹⁶, O. Hlushchenko, T. Kress, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl¹⁷, T. Ziemons

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

H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, I. Babounikau, S. Baxter, K. Beernaert, O. Behnke, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borrás¹⁸, V. Botta, D. Brunner, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodríguez, C. Contreras-Campana, V. Danilov, A. De Wit, M.M. Defranchis, L. Didukh, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, T. Eichhorn, A. Elwood, E. Eren, L.I. Estevez Banos, E. Gallo¹⁹, A. Geiser, A. Giralardi, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, A. Jafari, N.Z. Jomhari, H. Jung, A. Kasem¹⁸, M. Kasemann, H. Kaveh, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Lidrych, K. Lipka, W. Lohmann²⁰, R. Mankel, I.-A. Melzer-Pellmann, J. Metwally, A.B. Meyer, M. Meyer, M. Missiroli, J. Mnich, A. Mussgiller, V. Myronenko, Y. Otarid, D. Pérez Adán, S.K. Pflitsch, D. Pitzl, A. Raspereza, A. Saibel, M. Savitskyi, V. Scheurer, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, R.E. Sosa Ricardo, H. Tholen,

N. Tonon, O. Turkot, A. Vagnerini, M. Van De Klundert, R. Walsh, D. Walter, Y. Wen, K. Wichmann, C. Wissing, S. Wuchterl, O. Zenaiev, R. Zlebick

Deutsches Elektronen-Synchrotron, Hamburg, Germany

R. Aggleton, S. Bein, L. Benato, A. Benecke, K. De Leo, T. Dreyer, A. Ebrahimi, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, D. Gonzalez, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, S. Kurz, V. Kutzner, J. Lange, T. Lange, A. Malara, J. Multhaup, C.E.N. Niemeyer, A. Nigamova, K.J. Pena Rodriguez, A. Reimers, O. Rieger, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, B. Vormwald, I. Zoi

University of Hamburg, Hamburg, Germany

M. Akbiyik, M. Baselga, S. Baur, J. Bechtel, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, K. Flöh, M. Giffels, A. Gottmann, F. Hartmann¹⁷, C. Heidecker, U. Husemann, M.A. Iqbal, I. Katkov²¹, S. Kudella, S. Maier, M. Metzler, S. Mitra, M.U. Mozer, D. Müller, Th. Müller, M. Musich, G. Quast, K. Rabbertz, J. Rauser, D. Savoie, D. Schäfer, M. Schnepf, M. Schröder, I. Shvetsov, H.J. Simonis, R. Ulrich, M. Wassmer, M. Weber, C. Wöhrmann, R. Wolf, S. Wozniewski

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

G. Anagnostou, P. Asenov, G. Daskalakis, T. Gerasis, A. Kyriakis, D. Loukas, G. Paspalaki, A. Stakia

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

M. Diamantopoulou, G. Karathanasis, P. Kontaxakis, A. Manousakis-katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, K. Vellidis, E. Vourliotis

National and Kapodistrian University of Athens, Athens, Greece

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

National Technical University of Athens, Athens, Greece

I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, K. Manitaras, N. Manthos, I. Papadopoulos, J. Stroligas, F.A. Triantis, D. Tsitsonis

University of Ioánnina, Ioánnina, Greece

M. Bartók²², R. Chudasama, M. Csanad, M.M.A. Gadallah, P. Major, K. Mandal, A. Mehta, G. Pasztor, O. Surányi, G.I. Veres

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

G. Bencze, C. Hajdu, D. Horvath²³, F. Sikler, V. Veszpremi, G. Vesztergombi[†]

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karacsi²², J. Molnar, Z. Szillasi, D. Teyssier

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

P. Raics, Z.L. Trocsanyi, B. Ujvari

Institute of Physics, University of Debrecen, Debrecen, Hungary

T. Csorgo, S. Lökös, F. Nemes, T. Novak

Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary

S. Choudhury, J.R. Komaragiri, D. Kumar, L. Panwar, P.C. Tiwari

Indian Institute of Science (IISc), Bangalore, India

S. Bahinipati²⁴, C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu, A. Nayak²⁵, D.K. Sahoo²⁴, N. Sur, S.K. Swain

National Institute of Science Education and Research, HBNI, Bhubaneswar, India

S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, N. Dhingra²⁶, R. Gupta, A. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, K. Sandeep, S. Sharma, J.B. Singh, A.K. Viridi

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India

M. Bharti²⁷, R. Bhattacharya, S. Bhattacharya, D. Bhowmik, S. Dutta, S. Ghosh, B. Gomber²⁸, M. Maity²⁹, K. Mondal, S. Nandan, P. Palit, A. Purohit, P.K. Rout, G. Saha, S. Sarkar, M. Sharan, B. Singh²⁷, S. Thakur²⁷

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

P.K. Behera, S.C. Behera, P. Kalbhor, A. Muhammad, R. Pradhan, P.R. Pujahari, A. Sharma, A.K. Sikdar

Indian Institute of Technology Madras, Madras, India

D. Dutta, V. Jha, D.K. Mishra, K. Naskar³⁰, P.K. Netrakanti, L.M. Pant, P. Shukla

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, M.A. Bhat, S. Dugad, R. Kumar Verma, U. Sarkar

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee, N. Sahoo

Tata Institute of Fundamental Research-B, Mumbai, India

S. Dube, B. Kansal, A. Kapoor, K. Kotheekar, S. Pandey, A. Rane, A. Rastogi, S. Sharma

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

H. Bakhshiansohi³¹

Isfahan University of Technology, Isfahan, Iran

S. Chenarani³², S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia^{a,b}, R. Aly^{a,b,33}, C. Calabria^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, N. De Filippis^{a,c}, M. De Palma^{a,b}, A. Di Florio^{a,b}, A. Di Pilato^{a,b}, W. Elmetenawee^{a,b}, L. Fiore^a, A. Gelmi^{a,b}, G. Iaselli^{a,c}, M. Ince^{a,b}, S. Lezki^{a,b}, G. Maggi^{a,c}, M. Maggi^a, I. Margjeka^{a,b}, J.A. Merlin^a, G. Miniello^{a,b}, S. My^{a,b}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, A. Ranieri^a, G. Selvaggi^{a,b}, L. Silvestris^a, F.M. Simone^{a,b}, R. Venditti^a, P. Verwilligen^a

^a INFN Sezione di Bari, Bari, Italy

^b Università di Bari, Bari, Italy

^c Politecnico di Bari, Bari, Italy

G. Abbiendi^a, C. Battilana^{a,b}, D. Bonacorsi^{a,b}, L. Borgonovi^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, C. Ciocca^a, M. Cuffiani^{a,b}, G.M. Dallavalle^a, T. Diotallevi^{a,b}, F. Fabbri^a, A. Fanfani^{a,b}, E. Fontanesi^{a,b}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, F. Iemmi^{a,b}, S. Lo Meo^{a,34}, S. Marcellini^a, G. Masetti^a, F.L. Navarria^{a,b}, A. Perrotta^a, F. Primavera^a, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, N. Tosi^a

^a INFN Sezione di Bologna, Bologna, Italy

^b Università di Bologna, Bologna, Italy

S. Albergo^{a,b,35}, S. Costa^{a,b}, A. Di Mattia^a, R. Potenza^{a,b}, A. Tricomi^{a,b,35}, C. Tuve^{a,b}

^a INFN Sezione di Catania, Catania, Italy

^b Università di Catania, Catania, Italy

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

^a INFN Sezione di Firenze, Firenze, Italy

^b Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

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

^a INFN Sezione di Genova, Genova, Italy

^b Università di Genova, Genova, Italy

A. Benaglia^a, A. Beschi^{a,b}, F. Brivio^{a,b}, F. Cetorelli^{a,b}, V. Ciriolo^{a,b,17}, F. De Guio^{a,b}, M.E. Dinardo^{a,b}, P. Dini^a, S. Gennai^a, A. Ghezzi^{a,b}, P. Govoni^{a,b}, L. Guzzi^{a,b}, M. Malberti^a, S. Malvezzi^a, D. Menasce^a, F. Monti^{a,b}, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, T. Tabarelli de Fatis^{a,b}, D. Valsecchi^{a,b,17}, D. Zuolo^{a,b}

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

^b Università di Milano-Bicocca, Milano, Italy

S. Buontempo^a, N. Cavallo^{a,c}, A. De Iorio^{a,b}, F. Fabozzi^{a,c}, F. Fienga^a, G. Galati^a, A.O.M. Iorio^{a,b}, L. Layer^{a,b}, L. Lista^{a,b}, S. Meola^{a,d,17}, P. Paolucci^{a,17}, B. Rossi^a, C. Sciacca^{a,b}, E. Voevodina^{a,b}

^a INFN Sezione di Napoli, Napoli, Italy

^b Università di Napoli "Federico II", Napoli, Italy

^c Università della Basilicata, Potenza, Italy

^d Università G. Marconi, Roma, Italy

P. Azzi^a, N. Bacchetta^a, D. Bisello^{a,b}, A. Boletti^{a,b}, A. Bragagnolo^{a,b}, R. Carlin^{a,b}, P. Checchia^a, P. De Castro Manzano^a, T. Dorigo^a, U. Dosselli^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, S.Y. Hoh^{a,b}, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, M. Presilla^b, P. Ronchese^{a,b}, R. Rossin^{a,b}, F. Simonetto^{a,b}, G. Strong^a, A. Tiko^a, M. Tosi^{a,b}, M. Zanetti^{a,b}, P. Zotto^{a,b}, A. Zucchetta^{a,b}, G. Zumerle^{a,b}

^a INFN Sezione di Padova, Padova, Italy

^b Università di Padova, Padova, Italy

^c Università di Trento, Trento, Italy

A. Braghieri^a, S. Calzaferri^{a,b}, D. Fiorina^{a,b}, P. Montagna^{a,b}, S.P. Ratti^{a,b}, V. Re^a, M. Ressegotti^{a,b}, C. Riccardi^{a,b}, P. Salvini^a, I. Vai^a, P. Vitulo^{a,b}

^a INFN Sezione di Pavia, Pavia, Italy

^b Università di Pavia, Pavia, Italy

M. Biasini^{a,b}, G.M. Bilei^a, D. Ciangottini^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b}, G. Mantovani^{a,b}, V. Mariani^{a,b}, M. Menichelli^a, A. Rossi^{a,b}, A. Santocchia^{a,b}, D. Spiga^a, T. Tedeschi^{a,b}

^a INFN Sezione di Perugia, Perugia, Italy

^b Università di Perugia, Perugia, Italy

K. Androsov^a, P. Azzurri^a, G. Bagliesi^a, V. Bertacchi^{a,c}, L. Bianchini^a, T. Boccali^a, R. Castaldi^a, M.A. Ciocci^{a,b}, R. Dell'Orso^a, M.R. Di Domenico^{a,b}, S. Donato^a, L. Giannini^{a,c}, A. Giassi^a, M.T. Grippo^a, F. Ligabue^{a,c}, E. Manca^{a,c}, G. Mandorli^{a,c}, A. Messineo^{a,b}, N. Shafiei^{a,b}, F. Palla^a, A. Rizzi^{a,b}, G. Rolandi^{a,c}, S. Roy Chowdhury^{a,c}, A. Scribano^a, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b}, N. Turini^a, A. Venturi^a, P.G. Verdini^a

^a INFN Sezione di Pisa, Pisa, Italy

^b Università di Pisa, Pisa, Italy

^c Scuola Normale Superiore di Pisa, Pisa, Italy

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

^a INFN Sezione di Roma, Rome, Italy

^b Sapienza Università di Roma, Rome, Italy

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, N. Bartosik^a, R. Bellan^{a,b}, A. Bellora^{a,b}, C. Biino^a, A. Cappati^{a,b}, N. Cartiglia^a, S. Cometti^a, M. Costa^{a,b}, R. Covarelli^{a,b}, N. Demaria^a, B. Kiani^{a,b}, F. Legger^a, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, E. Monteil^{a,b}, M. Monteno^a, M.M. Obertino^{a,b}, G. Ortona^a, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G.L. Pinna Angioni^{a,b}, M. Ruspa^{a,c}, R. Salvatico^{a,b}, F. Siviero^{a,b}, V. Sola^a, A. Solano^{a,b}, D. Soldi^{a,b}, A. Staiano^a, D. Trocino^{a,b}

^a INFN Sezione di Torino, Torino, Italy

^b Università di Torino, Torino, Italy

^c Università del Piemonte Orientale, Novara, Italy

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

^a INFN Sezione di Trieste, Trieste, Italy

^b Università di Trieste, Trieste, Italy

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

Kyungpook National University, Daegu, Republic of Korea

H. Kim, D.H. Moon

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

B. Francois, T.J. Kim, J. Park

Hanyang University, Seoul, Republic of Korea

S. Cho, S. Choi, Y. Go, S. Ha, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, Y. Roh, J. Yoo

Korea University, Seoul, Republic of Korea

J. Goh, A. Gurtu

Kyung Hee University, Department of Physics, Seoul, Republic of Korea

H.S. Kim, Y. Kim

Sejong University, Seoul, Republic of Korea

J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, S. Ko, H. Kwon, H. Lee, K. Lee, S. Lee, K. Nam, B.H. Oh, M. Oh, S.B. Oh, B.C. Radburn-Smith, H. Seo, U.K. Yang, I. Yoon

Seoul National University, Seoul, Republic of Korea

D. Jeon, J.H. Kim, B. Ko, J.S.H. Lee, I.C. Park, I.J. Watson

University of Seoul, Seoul, Republic of Korea

H.D. Yoo

Yonsei University, Department of Physics, Seoul, Republic of Korea

Y. Choi, C. Hwang, Y. Jeong, H. Lee, J. Lee, Y. Lee, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

T. Torims, V. Veckalns³⁶

Riga Technical University, Riga, Latvia

A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

Vilnius University, Vilnius, Lithuania

W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

Universidad de Sonora (UNISON), Hermosillo, Mexico

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz³⁷, R. Lopez-Fernandez, A. Sanchez-Hernandez

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

S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

J. Eysermans, I. Pedraza, H.A. Salazar Ibarquen, C. Uribe Estrada

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

J. Mijuskovic³, N. Raicevic

University of Montenegro, Podgorica, Montenegro

D. Krofcheck

University of Auckland, Auckland, New Zealand

S. Bheesette, P.H. Butler

University of Canterbury, Christchurch, New Zealand

A. Ahmad, M. Ahmad, M.I. Asghar, M.I.M. Awan, Q. Hassan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

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

V. Avati, L. Grzanka, M. Malawski

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

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, M. Szleper, P. Traczyk, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland

K. Bunkowski, A. Byszuk³⁸, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Olszewski, M. Walczak

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

M. Araujo, P. Bargassa, D. Bastos, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, J. Seixas, K. Shchelina, O. Toldaiev, J. Varela

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

P. Bunin, Y. Ershov, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev^{39,40}, P. Moisezenz, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, B.S. Yuldashev⁴¹, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

G. Gavrilov, V. Golovtsov, Y. Ivanov, V. Kim⁴², E. Kuznetsova⁴³, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Volkov, A. Vorobyev

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, G. Pivovarov, D. Tlisov, A. Toropin

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko⁴⁴, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepenov, M. Toms, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia

T. Aushev

Moscow Institute of Physics and Technology, Moscow, Russia

R. Chistov⁴⁵, M. Danilov⁴⁵, A. Oskin, P. Parygin, D. Philippov, S. Polikarpov⁴⁵

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin⁴⁶, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, V. Savrin

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

V. Blinov⁴⁷, T. Dimova⁴⁷, L. Kardapoltsev⁴⁷, I. Ovtin⁴⁷, Y. Skovpen⁴⁷

Novosibirsk State University (NSU), Novosibirsk, Russia

I. Azhgirey, I. Bayshev, S. Bitiukov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia

A. Babaev, A. Iuzhakov, V. Okhotnikov

National Research Tomsk Polytechnic University, Tomsk, Russia

V. Borchsh, V. Ivanchenko, E. Tcherniaev

Tomsk State University, Tomsk, Russia

P. Adzic⁴⁸, P. Cirkovic, M. Dordevic, P. Milenovic, J. Milosevic, M. Stojanovic

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Belgrade, Serbia

M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, C. Fernandez Bedoya, J.A. Brochero Cifuentes, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, Á. Navarro Tobar, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M.S. Soares, A. Triossi, C. Willmott

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

C. Albajar, J.F. de Trocóniz, R. Reyes-Almanza

Universidad Autónoma de Madrid, Madrid, Spain

B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, C. Ramón Álvarez, V. Rodríguez Bouza, S. Sanchez Cruz

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

I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, F. Ricci-Tam, T. Rodrigo, A. Ruiz-Jimeno, L. Russo⁴⁹, L. Scodellaro, I. Vila, J.M. Vizan Garcia

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

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

University of Colombo, Colombo, Sri Lanka

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

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

T.K. Aarrestad, D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, J. Baechler, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, P. Bortignon, E. Bossini, E. Brondolin, T. Camporesi, G. Cerminara, L. Cristella, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, O. Davignon, A. De Roeck, M. Deile, R. Di Maria, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, N. Emrskova, F. Fallavollita⁵⁰, D. Fasanella, S. Fiorendi, G. Franzoni, J. Fulcher, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Gruchala, M. Guilbaud, D. Gulhan, J. Hegeman, C. Heidegger, Y. Iiyama, V. Innocente, T. James, P. Janot, J. Kaspar, J. Kieseler, M. Komm, N. Kratochwil, C. Lange, P. Lecoq, K. Long, C. Lourenço, L. Malgeri, M. Mannelli, A. Massironi, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, J. Ngadiuba, J. Niedziela, S. Orfanelli, L. Orsini, F. Pantaleo¹⁷, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabady, A. Racz, M. Rieger, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas⁵¹, J. Steggemann, S. Summers, V.R. Tavolaro, D. Treille, A. Tsirou, G.P. Van Onsem, A. Vartak, M. Verzetti, K.A. Wozniak, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

L. Caminada⁵², K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe

Paul Scherrer Institut, Villigen, Switzerland

M. Backhaus, P. Berger, A. Calandri, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T. Gadek, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni,

M.T. Meinhard, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pauss, V. Perovic, G. Perrin, L. Perrozzi, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, V. Stampf, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

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

C. Amsler⁵³, C. Botta, D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, J.K. Heikkilä, M. Huwiler, B. Kilminster, S. Leontsinis, A. Macchiolo, V.M. Mikuni, I. Neutelings, G. Rauco, P. Robmann, K. Schweiger, Y. Takahashi, S. Wertz

Universität Zürich, Zurich, Switzerland

C.M. Kuo, W. Lin, A. Roy, T. Sarkar²⁹, S.S. Yu

National Central University, Chung-Li, Taiwan

L. Ceard, P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas

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

A. Bat, F. Boran, S. Damarseckin⁵⁴, Z.S. Demiroglu, F. Dolek, C. Dozen⁵⁵, I. Dumanoglu⁵⁶, E. Eskut, G. Gokbulut, Y. Guler, E. Gurpinar Guler⁵⁷, I. Hos⁵⁸, C. Isik, E.E. Kangal⁵⁹, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir⁶⁰, A. Polatoz, A.E. Simsek, B. Tali⁶¹, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

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

B. Isildak⁶², G. Karapinar⁶³, K. Ocalan⁶⁴, M. Yalvac⁶⁵

Middle East Technical University, Physics Department, Ankara, Turkey

I.O. Atakisi, E. Gülmez, M. Kaya⁶⁶, O. Kaya⁶⁷, Ö. Özçelik, S. Tekten⁶⁸, E.A. Yetkin⁶⁹

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak⁵⁶, Y. Komurcu, S. Sen⁷⁰

Istanbul Technical University, Istanbul, Turkey

F. Aydogmus Sen, S. Cerci⁶¹, B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci⁶¹

Istanbul University, Istanbul, Turkey

B. Grynyov

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

L. Levchuk

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

E. Bhal, S. Bologna, J.J. Brooke, D. Burns⁷¹, E. Clement, D. Cussans, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, T. Sakuma, S. Seif El Nasr-Storey, V.J. Smith, J. Taylor, A. Titterton

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev⁷², C. Brew, R.M. Brown, D.J.A. Cockerill, K.V. Ellis, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, V. Cepaitis, G.S. Chahal⁷³, D. Colling, P. Dauncey, G. Davies, M. Della Negra, P. Everaerts, G. Hall, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, V. Milosevic, A. Morton, J. Nash⁷⁴, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, M. Stoye, A. Tapper, K. Uchida, T. Virdee¹⁷, N. Wardle, S.N. Webb, D. Winterbottom, A.G. Zecchinelli, S.C. Zenz

Imperial College, London, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, I.D. Reid, L. Teodorescu, S. Zahid

Brunel University, Uxbridge, United Kingdom

A. Brinkerhoff, K. Call, B. Caraway, J. Dittmann, K. Hatakeyama, C. Madrid, B. McMaster, N. Pastika, C. Smith

Baylor University, Waco, USA

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

Catholic University of America, Washington, DC, USA

A. Buccilli, O. Charaf, S.I. Cooper, S.V. Gleyzer, C. Henderson, P. Rumerio, C. West

The University of Alabama, Tuscaloosa, USA

A. Albert, D. Arcaro, Z. Demiragli, D. Gastler, C. Richardson, J. Rohlf, D. Sperka, D. Spitzbart, I. Suarez, D. Zou

Boston University, Boston, USA

G. Benelli, B. Burkle, X. Coubez¹⁸, D. Cutts, Y.t. Duh, M. Hadley, U. Heintz, J.M. Hogan⁷⁵, K.H.M. Kwok, E. Laird, G. Landsberg, K.T. Lau, J. Lee, M. Narain, S. Sagir⁷⁶, R. Syarif, E. Usai, W.Y. Wong, D. Yu, W. Zhang

Brown University, Providence, USA

R. Band, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, F. Jensen, W. Ko[†], O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, M. Shi, D. Taylor, K. Tos, M. Tripathi, Z. Wang, Y. Yao, F. Zhang

University of California, Davis, Davis, USA

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, D. Hamilton, J. Hauser, M. Ignatenko, T. Lam, N. Mccoll, W.A. Nash, S. Regnard, D. Saltzberg, C. Schnaible, B. Stone, V. Valuev

University of California, Los Angeles, USA

K. Burt, Y. Chen, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, O.R. Long, N. Manganelli, M. Olmedo Negrete, M.I. Paneva, W. Si, S. Wimpenny, Y. Zhang

University of California, Riverside, Riverside, USA

J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, N. Deelen, M. Derdzinski, J. Duarte, R. Gerosa, D. Gilbert, B. Hashemi, D. Klein, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, S. Padhi, M. Pieri, V. Sharma, M. Tadel, F. Würthwein, A. Yagil

University of California, San Diego, La Jolla, USA

N. Amin, R. Bhandari, C. Campagnari, M. Citron, A. Dorsett, V. Dutta, J. Incandela, B. Marsh, H. Mei, A. Ovcharova, H. Qu, J. Richman, U. Sarica, D. Stuart, S. Wang

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

D. Anderson, A. Bornheim, O. Cerri, I. Dutta, J.M. Lawhorn, N. Lu, J. Mao, H.B. Newman, T.Q. Nguyen, J. Pata, M. Spiropulu, J.R. Vlimant, S. Xie, Z. Zhang, R.Y. Zhu

California Institute of Technology, Pasadena, USA

J. Alison, M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, W.T. Ford, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

University of Colorado Boulder, Boulder, USA

J. Alexander, Y. Cheng, J. Chu, A. Datta, A. Frankenthal, K. Mcdermott, J. Monroy, J.R. Patterson, D. Quach, A. Ryd, W. Sun, S.M. Tan, Z. Tao, J. Thom, P. Wittich, M. Zientek

Cornell University, Ithaca, USA

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, S. Hasegawa, R. Heller, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, M.J. Kortelainen, S. Lammel, J. Lewis, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, V. Papadimitriou, K. Pedro, C. Pena⁴⁶, O. Prokofyev, F. Ravera, A. Reinsvold Hall, L. Ristori, B. Schneider, E. Sexton-Kennedy, N. Smith, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, M. Wang, H.A. Weber, A. Woodard

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, F. Errico, R.D. Field, D. Guerrero, B.M. Joshi, M. Kim, J. Konigsberg, A. Korytov, K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, D. Rosenzweig, K. Shi, J. Wang, S. Wang, X. Zuo

University of Florida, Gainesville, USA

Y.R. Joshi

Florida International University, Miami, USA

T. Adams, A. Askew, D. Diaz, R. Habibullah, S. Hagopian, V. Hagopian, K.F. Johnson, R. Khurana, T. Kolberg, G. Martinez, H. Prosper, C. Schiber, R. Yohay, J. Zhang

Florida State University, Tallahassee, USA

M.M. Baarmand, S. Butalla, T. Elkafrawy¹², M. Hohlmann, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

M.R. Adams, L. Apanasevich, H. Becerril Gonzalez, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, V. Kumar, C. Mills, G. Oh, T. Roy, M.B. Tonjes, N. Varelas, J. Viinikainen, H. Wang, X. Wang, Z. Wu

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

M. Alhousseini, B. Bilki⁵⁷, K. Dilsiz⁷⁷, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili⁷⁸, A. Moeller, J. Nachtman, H. Ogul⁷⁹, Y. Onel, F. Ozok⁸⁰, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi⁸¹

The University of Iowa, Iowa City, USA

O. Amram, B. Blumenfeld, L. Corcodilos, M. Eminizer, A.V. Gritsan, S. Kyriacou, P. Maksimovic, C. Mantilla, J. Roskes, M. Swartz, T.Á. Vámi

Johns Hopkins University, Baltimore, USA

C. Baldenegro Barrera, P. Baringer, A. Bean, S. Boren, A. Bylinkin, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, C. Lindsey, W. Mcbrayer, N. Minafra, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang, J. Williams, G. Wilson

The University of Kansas, Lawrence, USA

S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi

Kansas State University, Manhattan, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

E. Adams, A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, T. Koeth, A.C. Mignerey, S. Nabili, M. Seidel, A. Skuja, S.C. Tonwar, L. Wang, K. Wong

University of Maryland, College Park, USA

D. Abercrombie, B. Allen, R. Bi, S. Brandt, W. Busza, I.A. Cali, Y. Chen, M. D'Alfonso, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, M. Klute, D. Kovalskyi, J. Krupa, Y.-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

Massachusetts Institute of Technology, Cambridge, USA

R.M. Chatterjee, A. Evans, S. Guts[†], P. Hansen, J. Hiltbrand, Sh. Jain, M. Krohn, Y. Kubota, Z. Lesko, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

K. Bloom, S. Chauhan, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, J.R. González Fernández, I. Kravchenko, J.E. Siado, G.R. Snow[†], B. Stieger, W. Tabb

University of Nebraska-Lincoln, Lincoln, USA

G. Agarwal, C. Harrington, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, A. Parker, J. Pekkanen, S. Rappoccio, B. Roozbahani

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, G. Madigan, B. Marzocchi, D.M. Morse, V. Nguyen, T. Orimoto, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northeastern University, Boston, USA

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

Northwestern University, Evanston, USA

R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, K. Lannon, W. Li, N. Loukas, N. Marinelli, I. Mcalister, F. Meng, Y. Musienko³⁹, R. Ruchti, P. Siddireddy, S. Taroni, M. Wayne, A. Wightman, M. Wolf

University of Notre Dame, Notre Dame, USA

J. Alimena, B. Bylsma, B. Cardwell, L.S. Durkin, B. Francis, C. Hill, W. Ji, A. Lefeld, K. Wei, B.L. Winer, B.R. Yates

The Ohio State University, Columbus, USA

G. Dezoort, P. Elmer, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, G. Kopp, S. Kwan, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully

Princeton University, Princeton, USA

S. Malik, S. Norberg

University of Puerto Rico, Mayaguez, USA

V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, B. Mahakud, G. Negro, N. Neumeister, C.C. Peng, S. Piperov, H. Qiu, J.F. Schulte, N. Trevisani, F. Wang, R. Xiao, W. Xie

Purdue University, West Lafayette, USA

T. Cheng, J. Dolen, N. Parashar

Purdue University Northwest, Hammond, USA

A. Baty, S. Dildick, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, A. Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts[†], J. Rorie, W. Shi, A.G. Stahl Leiton, Z. Tu, A. Zhang

Rice University, Houston, USA

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

University of Rochester, Rochester, USA

B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, O. Karacheban²⁰, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S. Thomas

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

H. Acharya, A.G. Delannoy, S. Spanier

University of Tennessee, Knoxville, USA

O. Bouhali⁸², M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁸³, H. Kim, S. Luo, S. Malhotra, D. Marley, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

Texas A&M University, College Station, USA

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

Texas Tech University, Lubbock, USA

E. Appelt, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij

Vanderbilt University, Nashville, USA

L. Ang, M.W. Arenton, B. Cox, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, C. Neu, B. Tannenwald, Y. Wang, E. Wolfe, F. Xia

University of Virginia, Charlottesville, USA

P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa

Wayne State University, Detroit, USA

K. Black, T. Bose, J. Buchanan, C. Caillol, S. Dasu, I. De Bruyn, L. Dodd, C. Galloni, H. He, M. Herndon, A. Hervé, U. Hussain, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, D. Pinna, T. Ruggles, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, S. Trembath-reichert, W. Vetens

University of Wisconsin – Madison, Madison, WI, USA

[†] Deceased.

¹ Also at Vienna University of Technology, Vienna, Austria.

² Also at Université Libre de Bruxelles, Bruxelles, Belgium.

³ Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.

⁴ Also at Universidade Estadual de Campinas, Campinas, Brazil.

⁵ Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.

⁶ Also at UFMS, Nova Andradina, Brazil.

⁷ Also at Universidade Federal de Pelotas, Pelotas, Brazil.

⁸ Also at University of Chinese Academy of Sciences, Beijing, China.

⁹ Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia.

¹⁰ Also at Joint Institute for Nuclear Research, Dubna, Russia.

¹¹ Also at British University in Egypt, Cairo, Egypt.

¹² Now at Ain Shams University, Cairo, Egypt.

¹³ Also at Purdue University, West Lafayette, USA.

¹⁴ Also at Université de Haute Alsace, Mulhouse, France.

¹⁵ Also at Tbilisi State University, Tbilisi, Georgia.

¹⁶ Also at Erzincan Binali Yildirim University, Erzincan, Turkey.

¹⁷ Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

¹⁸ Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.

¹⁹ Also at University of Hamburg, Hamburg, Germany.

²⁰ Also at Brandenburg University of Technology, Cottbus, Germany.

²¹ Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

²² Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.

²³ Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

²⁴ Also at IIT Bhubaneswar, Bhubaneswar, India.

²⁵ Also at Institute of Physics, Bhubaneswar, India.

²⁶ Also at G.H.G. Khalsa College, Punjab, India.

²⁷ Also at Shoolini University, Solan, India.

²⁸ Also at University of Hyderabad, Hyderabad, India.

²⁹ Also at University of Visva-Bharati, Santiniketan, India.

³⁰ Also at Indian Institute of Technology (IIT), Mumbai, India.

³¹ Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.

³² Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.

³³ Now at INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy.

³⁴ Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.

³⁵ Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.

³⁶ Also at Riga Technical University, Riga, Latvia.

³⁷ Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.

³⁸ Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.

³⁹ Also at Institute for Nuclear Research, Moscow, Russia.

⁴⁰ Now at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia.

⁴¹ Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.

⁴² Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.

⁴³ Also at University of Florida, Gainesville, USA.

⁴⁴ Also at Imperial College, London, United Kingdom.

⁴⁵ Also at P.N. Lebedev Physical Institute, Moscow, Russia.

⁴⁶ Also at California Institute of Technology, Pasadena, USA.

- ⁴⁷ Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
- ⁴⁸ Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- ⁴⁹ Also at Università degli Studi di Siena, Siena, Italy.
- ⁵⁰ Also at INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy.
- ⁵¹ Also at National and Kapodistrian University of Athens, Athens, Greece.
- ⁵² Also at Universität Zürich, Zurich, Switzerland.
- ⁵³ Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
- ⁵⁴ Also at Şırnak University, Şırnak, Turkey.
- ⁵⁵ Also at Department of Physics, Tsinghua University, Beijing, China.
- ⁵⁶ Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey.
- ⁵⁷ Also at Beykent University, Istanbul, Turkey.
- ⁵⁸ Also at Istanbul Aydın University, Application and Research Center for Advanced Studies (App. & Res. Cent. for Advanced Studies), Istanbul, Turkey.
- ⁵⁹ Also at Mersin University, Mersin, Turkey.
- ⁶⁰ Also at Piri Reis University, Istanbul, Turkey.
- ⁶¹ Also at Adiyaman University, Adiyaman, Turkey.
- ⁶² Also at Ozyegin University, Istanbul, Turkey.
- ⁶³ Also at Izmir Institute of Technology, Izmir, Turkey.
- ⁶⁴ Also at Necmettin Erbakan University, Konya, Turkey.
- ⁶⁵ Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey.
- ⁶⁶ Also at Marmara University, Istanbul, Turkey.
- ⁶⁷ Also at Milli Savunma University, Istanbul, Turkey.
- ⁶⁸ Also at Kafkas University, Kars, Turkey.
- ⁶⁹ Also at Istanbul Bilgi University, Istanbul, Turkey.
- ⁷⁰ Also at Hacettepe University, Ankara, Turkey.
- ⁷¹ Also at Vrije Universiteit Brussel, Brussel, Belgium.
- ⁷² Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- ⁷³ Also at IPPP Durham University, Durham, United Kingdom.
- ⁷⁴ Also at Monash University, Faculty of Science, Clayton, Australia.
- ⁷⁵ Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA.
- ⁷⁶ Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
- ⁷⁷ Also at Bingol University, Bingol, Turkey.
- ⁷⁸ Also at Georgian Technical University, Tbilisi, Georgia.
- ⁷⁹ Also at Sinop University, Sinop, Turkey.
- ⁸⁰ Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
- ⁸¹ Also at Nanjing Normal University Department of Physics, Nanjing, China.
- ⁸² Also at Texas A&M University at Qatar, Doha, Qatar.
- ⁸³ Also at Kyungpook National University, Daegu, Republic of Korea.