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Search for electroweakinos in compressed-spectrum scenarios with low-momentum isolated tracks in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

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Abstract

A search for supersymmetric electroweakinos is performed using events with a low-momentum (soft) isolated track and large missing transverse momentum, targeting nearly mass-degenerate higgsino-like charginos and neutralinos. For mass splittings of 0.3–1 GeV, the chargino decays to the lightest neutralino and a low-momentum pion, which can produce a soft, potentially displaced track. A parameterized neural network separates signal from background using kinematic and impact parameter information. The analysis uses 138 fb^{-1} of proton–proton collision data at a center-of-mass energy of 13 TeV recorded with the CMS detector. No significant excess above the standard model expectation is observed. At 95% confidence level, the considered higgsino model is excluded for mass splittings in the range 0.28–1.15 GeV and for chargino masses up to 185 GeV, setting stringent constraints on natural supersymmetry scenarios.

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*See Appendix A for the list of collaboration members

Weak-scale R-parity conserving supersymmetry (SUSY) [1–9] is a well-motivated framework for physics beyond the standard model (SM). It provides a candidate for dark matter [10, 11], resolves the large hierarchy problem [12], and enables the unification of gauge couplings. Models with 100 GeV-scale superpartners of the Higgs boson, known as higgsinos, are considered natural [13] because they reduce the need for fine-tuning among SUSY parameters.

Minimal SUSY models contain two Higgs doublets, the ratio of whose vacuum expectation values is given by $\tan\beta$. Electroweakino mass eigenstates consist of four neutralinos ($\widetilde{\chi}_i^0$, $i = 1$–4) and four charginos ($\widetilde{\chi}_j^{\pm}$, $j = 1, 2$). These arise from the mixing of the fermionic superpartners of the Higgs and electroweak gauge fields: the higgsinos, bino (superpartner of the B field), and winos (superpartners of the W fields), each associated with the mass parameters μ, M_1, and M_2, which govern the electroweakino properties and mass spectrum. In the regime $\mu \ll M_1, M_2$, the lightest mass eigenstate $\widetilde{\chi}_1^0$ is a dominantly higgsino-like and stable neutralino, making it a viable dark matter candidate. It is accompanied by a nearly mass-degenerate second neutralino $\widetilde{\chi}_2^0$ and the lightest chargino $\widetilde{\chi}_1^{\pm}$. The mass splittings $\Delta m^{\pm} \equiv m(\widetilde{\chi}_1^{\pm}) - m(\widetilde{\chi}_1^0)$ and $\Delta m^0 \equiv m(\widetilde{\chi}_2^0) - m(\widetilde{\chi}_1^0)$ arise from electroweak radiative corrections and small mixing of the higgsinos with the wino and bino states, and typically range from 0.25 to 10 GeV [14]. The dominant production processes and decays are illustrated in Fig. 1. For $\Delta m^0 \gtrsim 1$ GeV, low-momentum (soft) leptons from electroweakino decays can be observed [15, 16]. For $\Delta m^{\pm} \lesssim 0.3$ GeV, the chargino lifetime is sufficiently long to yield a disappearing track signature [17–19]. The intermediate range, 0.3–1 GeV, is particularly difficult to probe, as the chargino decays primarily to a single soft pion with a displacement of up to about 1 cm from the primary vertex (PV) [20].

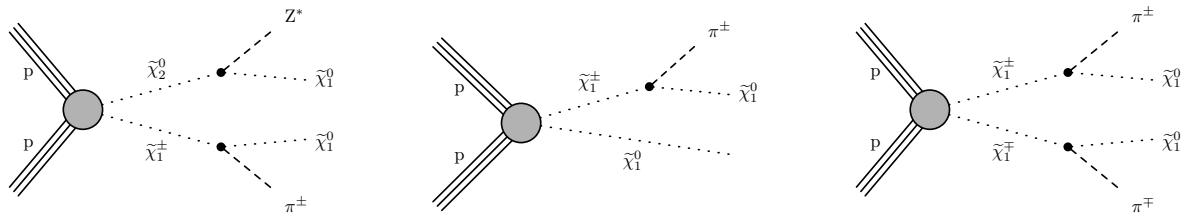

Figure 1: Representative diagrams for the production of signal events. The signature considered in the analysis also involves one or more jets from initial state radiation with significant p_{T} in the final state, which are not shown in the figure. All processes are included in the interpretation of the search.

The analysis presented in this Letter is based on 138 fb^{-1} of proton-proton collision data collected with the CMS detector at the CERN LHC during 2016–2018, targeting signal scenarios with $0.3 < \Delta m^{\pm} < 1$ GeV. Sensitivity in this regime is achieved by exploiting the transverse momentum p_{T} and displacement of the pion track relative to the PV, as well as each event's missing transverse momentum vector $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ and magnitude $p_{\mathrm{T}}^{\mathrm{miss}}$. The considered signal model corresponds to the large $\tan\beta$ regime [14], in which the neutralino mass splitting satisfies $\Delta m^0 = 2\Delta m^{\pm}$. In the scenario following Ref. [21], smaller $\Delta m^{\pm}$ values yield longer $\widetilde{\chi}_1^{\pm}$ lifetimes and more pronounced displacement. Events are selected with $p_{\mathrm{T}}^{\mathrm{miss}}$ exceeding 120 GeV at the trigger level and 300 GeV offline, along with at least one isolated track and no isolated electrons, muons, or photons. Rare decays of the $\widetilde{\chi}_2^0$ to soft electrons or muons are allowed, but the leptons have sufficiently small p_{T} to not invoke the lepton-based event vetoes. A parameterized neural network (NN) is trained to distinguish signal tracks from the dominant background. The background mainly consists of events with significant $p_{\mathrm{T}}^{\mathrm{miss}}$ due to the presence of neutrinos, where soft tracks from sources unrelated to the hard process mimic the signal signature. A cut-based search targeting a similar phase space was previously reported by ATLAS [22], and recently a study with increased sensitivity based on an NN has been presented [23].

The CMS apparatus [24, 25] is a nearly hermetic detector, designed to trigger [26–28] on and identify electrons, muons, photons, and hadrons [29–31]. The particle-flow (PF) algorithm [32] aims to reconstruct all detectable particles in an event, combining information provided by the silicon inner tracker and by the crystal electromagnetic and brass-scintillator hadron calorimeters, operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. The reconstructed particles are used to build τ leptons, jets, and the vector $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ [33–35]. Jets are clustered using the anti-k_{T} algorithm [36, 37] with a distance parameter of 0.4.

Monte Carlo (MC) samples of SM background processes, including top quark pair production, W+jets, and Z+jets, are simulated at leading order (LO) in perturbative quantum chromodynamics using MADGRAPH5_aMC@NLO 2.2.2 [38, 39], with up to four additional partons in the matrix element. The PYTHIA 8.240 [40] generator is used for parton showering, fragmentation, and hadronization, with matching between jets from the matrix element and those from the parton shower. The CUETP8M1 [41] (CP5 [42]) underlying event tunes are used for background samples, along with NNPDF3.0 LO [43] (NNPDF3.1 next-to-next-to-leading-order [44]) parton distribution functions for the 2016 (2017–2018) data-taking periods. Additional interactions in the same or adjacent bunch crossings (pileup) are generated with PYTHIA and added to the hard-scatter event in all simulated samples, with the multiplicity distribution matching that observed in data. Signal events are simulated at LO using PYTHIA 8.240 and normalized to next-to-LO plus next-to-leading-logarithmic (NLO+NLL) precision.

Decays of the $\widetilde{\chi}_2^0$ to electrons or muons are set with a branching fraction of 5% for each lepton flavor as a benchmark choice. The analysis sensitivity is only weakly affected by this assumption because no particle identification requirement is applied to the selected isolated track. For background events, the CMS detector response is modeled with the GEANT4 [45]-based application FULLSIM; to save computing resources, signal events are emulated with the CMS fast simulation engine FASTSIM [46, 47].

Signal candidate tracks are reconstructed using the algorithm described in Ref. [31] and selected with $p_{\mathrm{T}} < 20\,\mathrm{GeV}$ and pseudorapidity $|\eta| < 2.4$. No requirement is imposed that the track be compatible with the PV, and no additional lower-p_{T} threshold is applied at the analysis level. The reconstruction retains an efficiency of about 10% for p_{T} as low as 100 MeV, increasing to 80% by 500 MeV and plateauing around 90% by 1 GeV [31, 48]. Criteria are applied to the track fit quality and the number of associated hits to ensure high purity of charged-particle reconstruction. Tracks must lie outside the reconstruction cone of all jets. No dedicated pion identification is used. The separation of signal-like charged-particle tracks from PV-associated, pileup, and spurious tracks is performed by the classifier described below.

Jets are required to have $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 5.0$, while hadronic τ-lepton candidates are identified from an alternate set of jets with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and $|\eta| < 2.3$, using track, vertex, and calorimetric information and satisfying the tight working point (WP) of the DEEPTAU algorithm [49]. Electrons (photons) are selected with $|\eta| < 2.5$ and $p_{\mathrm{T}} > 10$ (15) GeV based on the medium WP [29]. Muons are selected with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ and $|\eta| < 2.4$, with the loose identification WP [30]. Electrons, photons, and muons are further required to satisfy a relative isolation requirement, in which the p_{T} sum of reconstructed particles within a cone of radius $\Delta R \equiv [(\Delta\eta)^2 + (\Delta\phi)^2]^{1/2} = 0.3$ around the object is less than 20% of the object's p_{T}. The corresponding efficiencies are approximately 80% for electrons and photons, and above 95% for muons. Jets originating from the hadronization of b quarks are identified using the DEEPJET algorithm, with the medium WP corresponding to an efficiency in the 70–80% range for b jets, depending on jet kinematics [50, 51].

The $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ is computed as the negative vector p_{T} sum of all reconstructed PF candidates. A related quantity $H_{\mathrm{T}}^{\mathrm{miss}}$, defined as the magnitude of the vector p_{T} sum of all jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 5.0$, is also used to render the offline selection more consistent with the trigger requirement. Both measures are corrected to mitigate the effects of pileup and geometric dependencies of the jet energy response.

Events passing filters to reject anomalous $p_{\mathrm{T}}^{\mathrm{miss}}$ arising from calorimeter noise, misreconstructed particles or vertices, or beam halo interactions are selected [35]. The baseline selection requires $p_{\mathrm{T}}^{\mathrm{miss}} > 300\,\mathrm{GeV}$, $H_{\mathrm{T}}^{\mathrm{miss}} > 300\,\mathrm{GeV}$, and at least one jet with $p_{\mathrm{T}} > 100\,\mathrm{GeV}$, targeting signal events with significant initial state radiation. These requirements ensure the effective rejection of SM multijet events and a high trigger efficiency of 99% or greater. Events must contain fewer than five jets, no b-tagged jets, and a minimum $\Delta\phi$ of 0.4 radians between the vector $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ and each of the four jets. Events containing photons, electrons, muons, or hadronically decaying τ leptons are rejected.

Background events remaining after these selection criteria include mainly $\mathrm{Z} \to \nu\nu$, and $\mathrm{W} \to \ell\nu$ in which the lepton is out of acceptance or fails the identification criteria, yielding large $p_{\mathrm{T}}^{\mathrm{miss}}$ from the neutrino(s). A large number of low-p_{T} tracks arise in each event from the underlying event, pileup interactions, and reconstruction failures, and are largely uncorrelated with the hard process. A rare population of tracks arises from the decay chain $\mathrm{W} \to \tau\nu$.

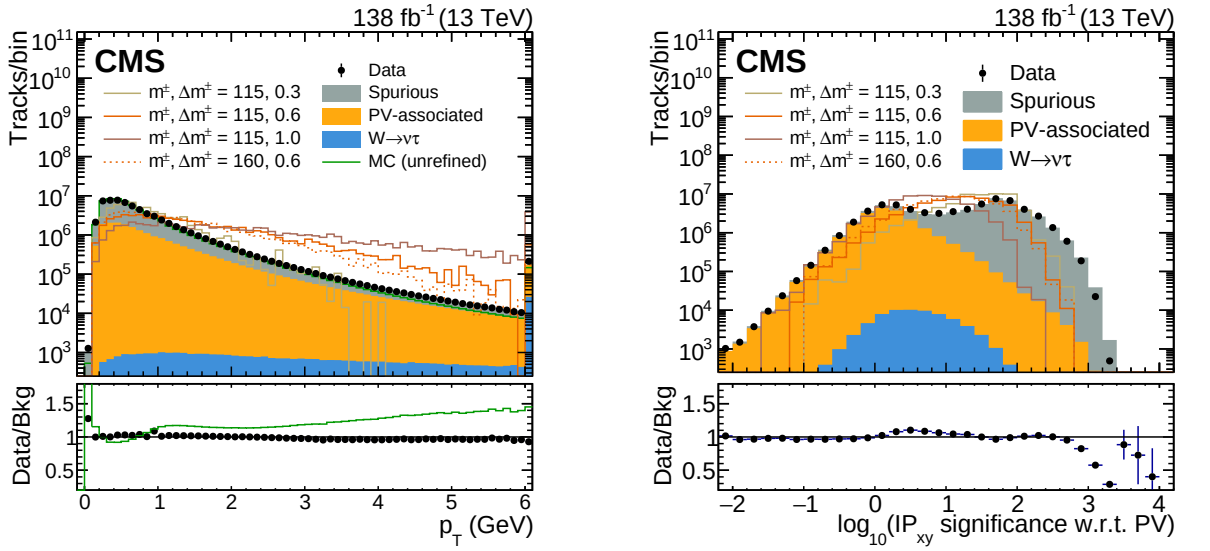

Figure 2: Distributions of example kinematic track observables for data and simulation. The filled histograms show tracks in background events, with negligible statistical uncertainty. Simulated tracks matched to charginos from selected benchmark models, indicated by the chargino mass labels $m^{\pm}$ and $\Delta m^{\pm}$ in GeV, are shown as colored open histograms normalized to the total background yield. The green line in the lower panel of the left plot indicates the ratio of the data to the background simulation before the refinement procedure is applied.

Tracks arising from signal processes are typically isolated from jets and more closely aligned in direction with $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ than tracks in background events. The characteristic track p_{T} increases with larger $\Delta m^{\pm}$, while the transverse displacement, measured by the impact parameter, IP_{xy}, decreases, as shown by the colored open histograms in the main panels of Fig. 2. To suppress the overwhelming rate of background tracks, a deep parameterized NN is trained on approximately 4 million simulated reconstructed tracks, with training labels assigned using generator-level information. The NN has a three-layer architecture with 256 hidden units per layer, LeakyReLU activations [52], and preprocessing layers for input normalization. There

are five output nodes corresponding to five track classes: signal tracks; secondary tracks from hadronic τ lepton decays in $W \to \tau_h \nu$ events; other secondary tracks from particles created at the PV; prompt tracks from the PV (together with the previous class referred to as "PV-associated"); and spurious tracks. Spurious tracks lack generator-level matches and include contributions from pileup and misreconstructed tracks. The input features comprise 37 observables related to track kinematic properties, helix fit quality, impact parameter (IP) significance relative to each pileup vertex and the PV (where significance is defined as the measurement value divided by its uncertainty), and the event p_T^{miss}. The data-taking year is encoded as a parameter to account for varying detector conditions. The network is parameterized by $\Delta m^{\pm}$ to capture correlations that evolve across the signal model phase space. Training is performed using the categorical cross-entropy loss. Track p_T provides comparatively larger discriminating power at large $\Delta m^{\pm}$, while displacement observables are more discriminating at low $\Delta m^{\pm}$ due to longer $\widetilde{\chi}^{\pm}$ lifetime. Background tracks are assigned random values of $\Delta m^{\pm}$ drawn from the inclusive signal distribution to avoid bias. The network is calibrated to produce per-track likelihood estimates. A logit transformation,

$$\widetilde{P} \equiv \mathrm{logit}(P) = \ln\left(\frac{P+\epsilon}{1-P+\epsilon}\right), \tag{1}$$

is applied to the NN output score P to enhance separation in the signal-like region for visualization and for use in the final statistical interpretation, where ϵ is a constant equal to 1×10^{-6}.

Signal regions (SRs) are defined by evaluating the signal-class output node of the NN for tracks in each event at three values of input mass difference $\Delta m_{in}^{\pm}$: 0.3, 0.6, and 1.0 GeV. For each event, the track and $\Delta m_{in}^{\pm}$ with the highest score, denoted $\widetilde{P}_{max}(\mathrm{Signal} \,|\, \Delta m_{in}^{\pm})$, are identified and the event is assigned to the corresponding $\Delta m_{in}^{\pm}$ category. This procedure defines three non-overlapping event categories, each further divided into bins of $\widetilde{P}_{max}$ as follows: (9.5–10, 10–11, 11–11.5, and >11.5) for $\Delta m_{in}^{\pm} = 0.3$ GeV; (8.75–9, 9–9.5, 9.5–10.5, and >10.5) for $\Delta m_{in}^{\pm} = 0.6$ GeV; and (7–7.5, 7.5–8, 8–8.75, and >8.75) for $\Delta m_{in}^{\pm} = 1.0$ GeV, for a total of 12 SRs.

Expected background yields are estimated using templates for each NN-defined background track class, derived from simulation and corrected using data. The modeling of the dominant PV-associated and spurious-track components is corrected and constrained with data in a cleaned Drell–Yan control region (DY CR), which is orthogonal to the SRs because of the requirement of two high-p_T muons. The cleaned DY CR is defined by selecting $Z \to \mu^+\mu^-$ events and removing the muons from the event record. Events are selected with two oppositely charged, isolated muons, each with $p_T > 30$ GeV and relative isolation <0.2. The dimuon invariant mass is required to be in the range 75–105 GeV and p_T exceeding 200 GeV. The p_T of the selected muons are vectorially added to $\vec{p}_T^{miss}$, and the muons, as well as matching tracks, PF candidates, photons, and jets, are removed from the event record. The matching requires $\Delta R < 0.4$ for jets and $\Delta R < 0.05$ for all other objects.

The overall background rates of the PV-associated and spurious tracks in simulation are corrected using normalization factors derived in inclusive regions of the longitudinal IP, d_z, of candidate tracks in the cleaned DY CR. Tracks with $d_z < 0.001$ cm with respect to the PV are used to extract the scale factor for PV-associated tracks, while tracks with $d_z > 0.63$ cm define the region for spurious tracks. The resulting normalization factors are 0.92 for PV-associated tracks and 1.18 for spurious tracks. Simulated background samples are also corrected to improve agreement with the p_T^{miss} distribution observed in data. A weight is applied to simulated events, calculated by a linear fit to the data-to-simulation ratio as a function of p_T^{miss} in the range 300–1000 GeV, and events with $p_T^{miss} > 1000$ GeV are weighted using the value of the fit at $p_T^{miss} = 1000$ GeV.

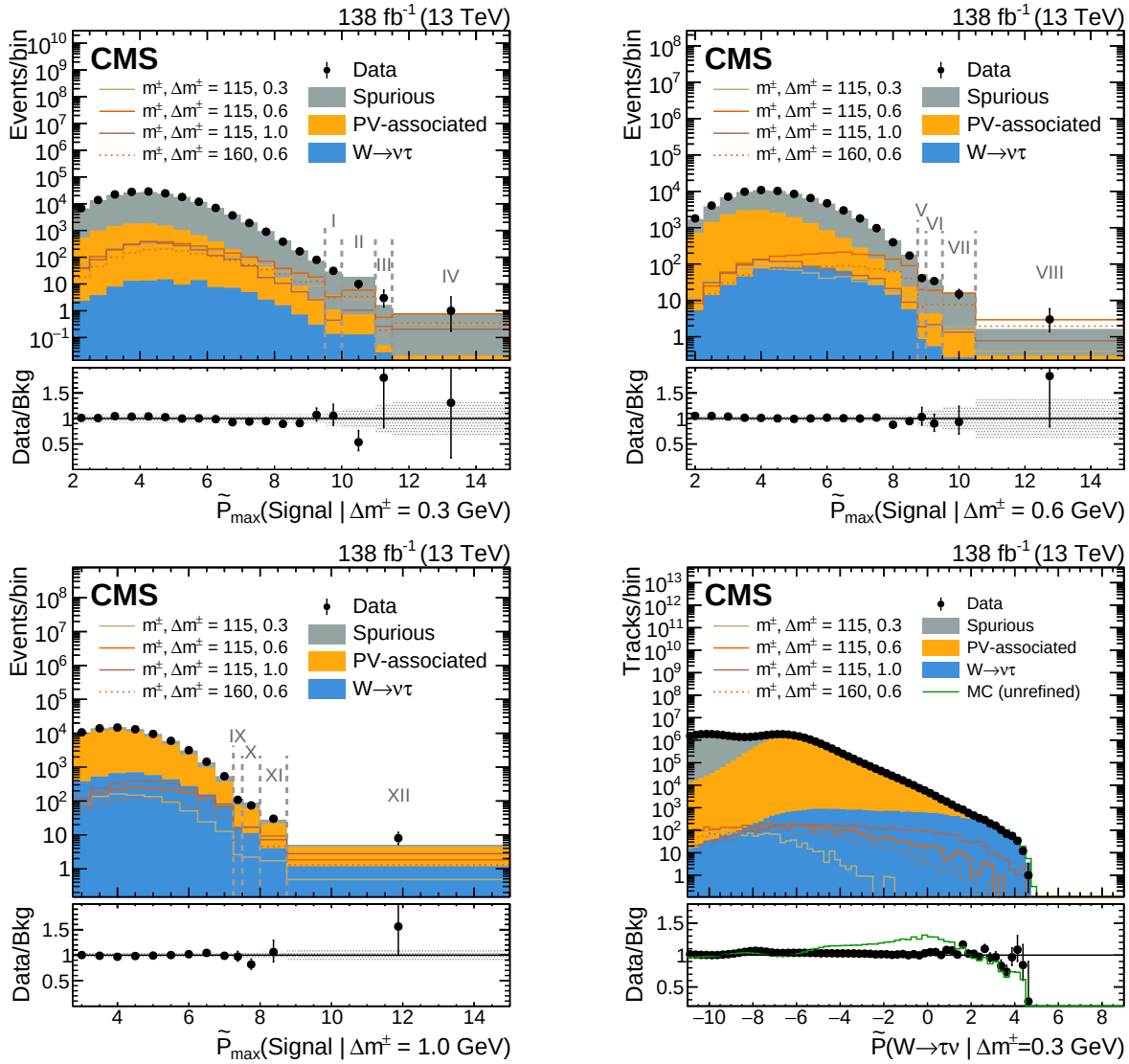

Figure 3: The expected and observed yields as a function of the 0.3 GeV (upper left), 0.6 GeV (upper right), and 1.0 GeV (lower left) NN signal node, where the Roman numerals indicate the SR bin. In the upper panels, uncertainties shown are statistical only, while in the lower panels, shaded regions indicate the relative systematic uncertainty in the background yields and black vertical bars show the total statistical uncertainty in the ratio. The lower-right plot shows the distributions in the τ-lepton node of tracks after a selection of $\widetilde{P}(\text{Signal} \,|\, \Delta m_{\text{in}}^{\pm} = 0.3\,\text{GeV}) > -2$, where the green line in the lower panel shows the ratio of the data to background simulation before the refinement procedure. The colored open histograms are as in Fig. 2, except normalized to the integrated luminosity.

Inaccuracies in the simulation of $\widetilde{P}_{\text{max}}(\text{Signal} \,|\, \Delta m_{\text{in}}^{\pm} = 0.3, 0.6, 1.0\,\text{GeV})$, arising from mismodeling of the track IPs and the p_{T} of soft tracks are corrected by a refinement procedure using a multivariate regression based on the Fast Perfekt methodology [53]. An NN is trained and applied to morph simulated observables to better match those in data. For training, inclusive sets of tracks passing the baseline selection are taken from the cleaned DY CR in both data and simulation. The regression network outputs refined values of the observables by minimizing the maximum mean discrepancy loss [54] between the training data and the corrected simulation. The resulting corrections are applied to the track p_{T} and the uncertainties in the transverse and

longitudinal IP, which serve as inputs to the classifier. The procedure improves the modeling of simulated tracks, particularly for PV-associated background and for τ-lepton-based signal proxy tracks, as shown in Figs. 2 (left) and 3 (lower right). Differences between FASTSIM and FULLSIM in event- and track-level kinematics and displacement related variables are corrected using per-SR correction factors.

The uncertainty in the scale factors for the PV-associated and spurious backgrounds, accounting for potential mismodeling of the NN score shape in simulation, as well as potential bias stemming from the maximum-score criterion, is assessed to be 10%. The uncertainty in the simulation shape, corrected through the refinement procedure, is evaluated by fitting polynomials to the ratio of data to the refined simulation in the signal-sensitive regions $\widetilde{P}_{\max}(\text{Signal} \,|\, \Delta m^{\pm}_{\text{in}} = 0.3, 0.6, 1.0\,\text{GeV}) > 5$ of the cleaned DY CR and varies up to 10%, depending on the SR. Additional uncertainties are applied to simulated events to account for potential mismodeling of the jet energy scale, pileup, trigger efficiency, and integrated luminosity [55–58]. An overall uncertainty of 10% is assessed for the modeling of signal and τ-lepton events, based on the agreement between data and simulation in the τ-lepton-enriched CR, shown in Fig. 3 in the lower-right panel. Uncertainties in the range 17–83% in the signal yields are included to cover potential mismodeling in the FASTSIM and statistical uncertainties in FULLSIM-based signal samples used for calibrating the FASTSIM.

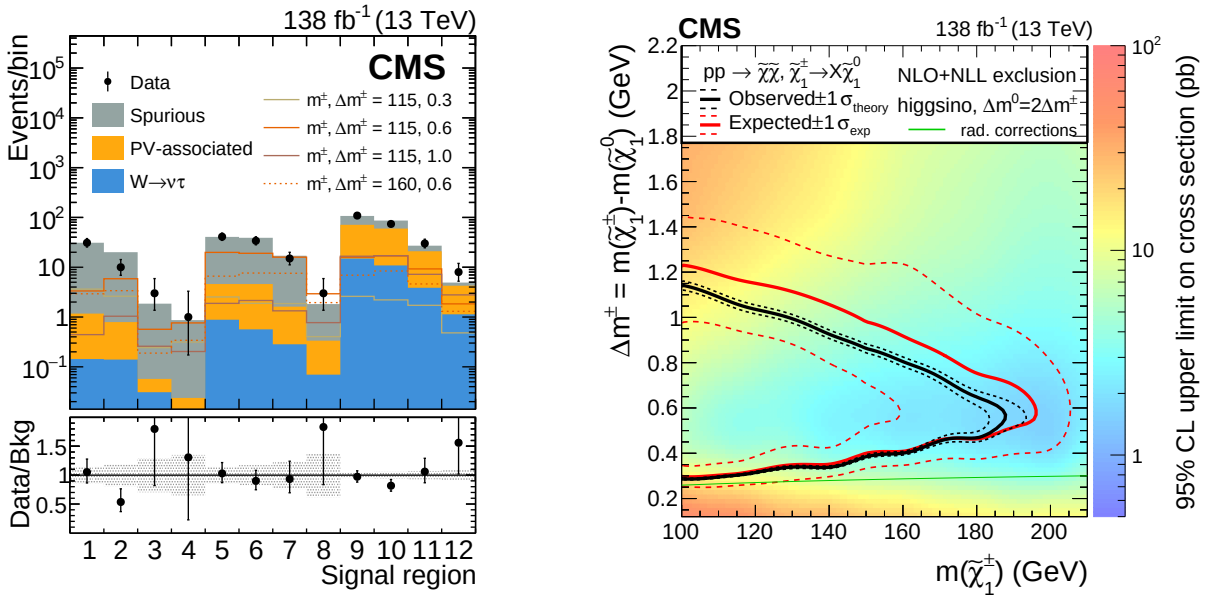

Figure 4: The expected and observed data yields in the 12 SRs (left), where the uncertainties in the upper panel are statistical only, while in the lower panel the shaded region indicates the relative systematic uncertainty in the background yields and the black vertical bars show the total statistical uncertainty in the ratio. The colored open histograms are as in Fig. 3. The right plot shows the observed 95% CL upper limit on the cross section, accounting for all production modes of the higgsino model. The expected (red) and observed (black) solid contours indicate the region excluded to the left of the curves, assuming NLO+NLL cross sections [59, 60]. Dashed lines show the variation in the expected (observed) limits arising from experimental (theoretical) uncertainties. The chargino branching fractions and the minimum $\Delta m^{\pm}$ allowed by radiative corrections (green line) are taken from Ref. [61].

The results are shown in Fig. 3, which displays the observed event counts compared to the stacked background expectations, along with superimposed yields of selected signal benchmark models. The SRs correspond to the four highest bins in each signal-class NN output

distribution, which are shown in aggregate in Fig. 4 (left). The results are consistent with the SM-only expectation. The data are interpreted using a maximum likelihood fit. The likelihood is written

$$\mathcal{L}(\mu_s, \boldsymbol{\theta}) = \prod_{i \in \mathrm{SR}} \mathrm{Pois}\big(n_i \,|\, \mu_s s_i(\boldsymbol{\theta}) + b_i(\boldsymbol{\theta})\big) \prod_k \pi_k(\theta_k), \tag{2}$$

where n_i is the observed number of events in SR bin i, s_i and b_i are the expected signal and background yields, μ_s is the signal strength parameter, and $\boldsymbol{\theta}$ denotes the vector of nuisance parameters with index k running over the sources of systematic uncertainty. The constraint terms $\pi_k(\theta_k)$ account for these uncertainties, with log-normal functions used for normalization uncertainties and Gaussian functions used for shape uncertainties. Correlations across bins are taken into account through the shared dependence of s_i and b_i on the nuisance parameters. The fit is performed simultaneously in the 12 SR bins. Upper limits at the 95% confidence level (CL) are derived on the inclusive electroweakino production cross section using a profile likelihood ratio test statistic based on the modified frequentist $\mathrm{CL_s}$ criterion with the asymptotic approximation [62, 63].

The expected and observed limits are shown in Fig. 4 (right) in the mass plane of the electroweakinos. The excluded region spans $\Delta m^{\pm}$ values of 0.28–1.15 GeV for a $\widetilde{\chi}_1^{\pm}$ mass of 100 GeV and extends to 185 GeV for $\Delta m^{\pm} = 0.55$ GeV.

In summary, a search for electroweakinos in compressed-spectrum scenarios has been performed using events containing a soft, isolated track and large missing transverse momentum. The results of the analysis are tabulated in Ref. [64]. A parameterized neural network was employed to optimize sensitivity across a range of models not previously probed. No significant excess above the standard model prediction was observed. The resulting 95% confidence level limits exclude chargino masses up to 185 GeV for a mass splitting between the chargino and lightest neutralino of 0.55 GeV, and mass splittings between 0.28 and 1.15 GeV for a chargino mass of 100 GeV, placing stringent constraints on natural supersymmetry scenarios.

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A The CMS Collaboration

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
Y. Li, Y. Zhou[16]

Zhejiang University, Hangzhou, Zhejiang, China
Z. Lin, C. Lu, M. Xiao[17]

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

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

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

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

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

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

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

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

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

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
H. Abdalla[18], Y. Assran[19,20]

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

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

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

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

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

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, P. Devouge, J.L. Faure, F. Ferri, P. Gaigne, S. Ganjour, P. Gras, G. Hamel de Monchenault, M. Kumar, V. Lohezic, Y. Maidannyk, J. Malcles, F. Orlandi, L. Portales, S. Ronchi, M.Ö. Sahin, A. Savoy-Navarro[21], P. Simkina, M. Titov, M. Tornago

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

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[22], J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, G. Coulon, S. Falke, U. Goerlach, R. Haeberle, A.-C. Le Bihan, M. Meena, O. Poncet, G. Saha, P. Vaucelle

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

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

Georgian Technical University, Tbilisi, Georgia
G. Adamov, I. Lomidze, Z. Tsamalaidze[23]

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

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

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

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

University of Hamburg, Hamburg, Germany
A.R. Alves Andrade, M. Antonello, S. Bollweg, M. Bonanomi, K. El Morabit, Y. Fischer, M. Frahm, E. Garutti, A. Grohsjean, A.A. Guvenli, J. Haller, D. Hundhausen, G. Kasieczka, P. Keicher, R. Klanner, W. Korcari, T. Kramer, C.c. Kuo, F. Labe, J. Lange, A. Lobanov, L. Moureaux, K. Nikolopoulos, A. Paasch, K.J. Pena Rodriguez, N. Prouvost, B. Raciti, M. Rieger, D. Savoiu, P. Schleper, M. Schröder, J. Schwandt, M. Sommerhalder, H. Stadie, G. Steinbrück, R. Ward, B. Wiederspan, M. Wolf, C. Yede

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

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

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

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

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

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

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

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

Faculty of Informatics, University of Debrecen, Debrecen, Hungary
L. Olah, B. Ujvari

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

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

IIT Bhubaneswar, Bhubaneswar, India
S. Bahinipati, S. Nayak, R. Raturi

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

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

Indian Institute of Technology Mandi (IIT-Mandi), Himachal Pradesh, India

P. Palni

University of Hyderabad, Hyderabad, India
S. Acharya[37], B. Gomber

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

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

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

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

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

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

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

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

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

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

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

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

INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy
M. Abbrescia[a,b], M. Barbieri[a,b], M. Buonsante[a,b], A. Colaleo[a,b], D. Creanza[a,c], N. De Filippis[a,c], M. De Palma[a,b], W. Elmetenawee[a,b,46], N. Ferrara[a,c], L. Fiore[a], L. Generoso[a,b], L. Longo[a], M. Louka[a,b], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a], V. Mastrapasqua[a,b], S. My[a,b], F. Nenna[a,b], S. Nuzzo[a,b], A. Pellecchia[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a,b], D. Ramos[a], A. Ranieri[a], L. Silvestris[a], F.M. Simone[a,c], Ü. Sözbilir[a], A. Stamerra[a,b], D. Troiano[a,b], R. Venditti[a,b], P. Verwilligen[a], A. Zaza[a,b]

INFN Sezione di Bologna[a], Università di Bologna[b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], P. Capiluppi[a,b], F.R. Cavallo[a], M. Cuffiani[a,b], G.M. Dallavalle[a], T. Diotalevi[a,b], F. Fabbri[a], A. Fanfani[a,b], R. Farinelli[a], D. Fasanella[a], C. Grandi[a], S. Lo Meo[a,47], M. Lorusso[a,b], L. Lunerti[a], S. Marcellini[a], G. Masetti[a], F.L. Navarria[a,b], G. Paggi[a,b], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], S. Rossi Tisbeni[a,b], T. Rovelli[a,b], G.P. Siroli[a,b]

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

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

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

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

INFN Sezione di Milano-Bicocca[a], Università di Milano-Bicocca[b], Milano, Italy
A. Benaglia[a], F. Brivio[a], V. Camagni[a,b], F. Cetorelli[a,b], F. De Guio[a,b], M.E. Dinardo[a,b], P. Dini[a], S. Gennai[a], R. Gerosa[a,b], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a], M.R. Kim[a], G. Lavizzari[a,b], M.T. Lucchini[a,b], M. Malberti[a], S. Malvezzi[a], A. Massironi[a], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], S. Palluotto[a,b], D. Pedrini[a], A. Perego[a,b], G. Pizzati[a,b], T. Tabarelli de Fatis[a,b]

INFN Sezione di Napoli[a], Università di Napoli 'Federico II'[b], Napoli, Italy; Università della Basilicata[c], Potenza, Italy; Scuola Superiore Meridionale (SSM)[d], Napoli, Italy
S. Buontempo[a], C. Di Fraia[a,b], F. Fabozzi[a,c], L. Favilla[a,d], A.O.M. Iorio[a,b], L. Lista[a,b,50], P. Paolucci[a,29], B. Rossi[a]

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

INFN Sezione di Pavia[a], Università di Pavia[b], Pavia, Italy
S. Abu Zeid[a,53], A. Braghieri[a], S. Calzaferri[a,b], P. Montagna[a,b], M. Pelliccioni[a,b], V. Re[a], C. Riccardi[a,b], P. Salvini[a], P. Vitulo[a,b]

INFN Sezione di Perugia[a], Università di Perugia[b], Perugia, Italy
S. Ajmal[a,b], M.E. Ascioti[a,b], G.M. Bilei[†a], C. Carrivale[a,b], D. Ciangottini[a,b], L. Della Penna[a,b], L. Fanò[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,54], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a], T. Tedeschi[a,b]

INFN Sezione di Pisa[a], Università di Pisa[b], Scuola Normale Superiore di Pisa[c], Pisa, Italy;

Università di Siena[d], Siena, Italy
C. Aimè[a,b], C.A. Alexe[a,c], P. Asenov[a,b], P. Azzurri[a], G. Bagliesi[a], L. Bianchini[a,b], T. Boccali[a], E. Bossini[a], D. Bruschini[a,c], R. Castaldi[a], F. Cattafesta[a,c], M.A. Ciocci[a,d], M. Cipriani[a,b], R. Dell'Orso[a], S. Donato[a,b], R. Forti[a,b], A. Giassi[a], F. Ligabue[a,c], A.C. Marini[a,b], D. Matos Figueiredo[a], A. Messineo[a,b], S. Mishra[a], V.K. Muraleedharan Nair Bindhu[a,b], S. Nandan[a], F. Palla[a], M. Riggirello[a,c], A. Rizzi[a,b], G. Rolandi[a,c], S. Roy Chowdhury[a,55], T. Sarkar[a], A. Scribano[a], P. Solanki[a,b], P. Spagnolo[a], F. Tenchini[a,b], R. Tenchini[a], G. Tonelli[a,b], N. Turini[a,d], F. Vaselli[a,c], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma[a], Sapienza Università di Roma[b], Roma, Italy
P. Akrap[a,b], C. Basile[a,b], S.C. Behera[a], F. Cavallari[a], L. Cunqueiro Mendez[a,b], F. De Riggi[a,b], D. Del Re[a,b], E. Di Marco[a], M. Diemoz[a], F. Errico[a], L. Frosina[a,b], R. Gargiulo[a,b], B. Harikrishnan[a,b], F. Lombardi[a,b], E. Longo[a,b], L. Martikainen[a,b], J. Mijuskovic[a,b], G. Organtini[a,b], N. Palmeri[a,b], R. Paramatti[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], L. Soffi[a], V. Vladimirov[a,b]

INFN Sezione di Torino[a], Università di Torino[b], Torino, Italy; Università del Piemonte Orientale[c], Novara, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[†a,c], N. Bartosik[a,c], R. Bellan[a,b], A. Bellora[a,b], C. Biino[a], C. Borca[a,b], N. Cartiglia[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], L. Finco[a], M. Grippo[a,b], B. Kiani[a,b], L. Lanteri[a,b], F. Legger[a], F. Luongo[a,b], C. Mariotti[a], S. Maselli[a], A. Mecca[a,b], L. Menzio[a,b], P. Meridiani[a], E. Migliore[a,b], M. Monteno[a], M.M. Obertino[a,b], G. Ortona[a], L. Pacher[a,b], N. Pastrone[a], M. Ruspa[a,c], F. Siviero[a,b], V. Sola[a,b], A. Solano[a,b], A. Staiano[a], C. Tarricone[a,b], D. Trocino[a], G. Umoret[a,b], E. Vlasov[a,b], R. White[a,b]

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

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

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

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

Hanyang University, Seoul, Korea
E. Asilar, F. Carnevali, J. Choi[56], T.J. Kim, Y. Ryou

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

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

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

Seoul National University, Seoul, Korea

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

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

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

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

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

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

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

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

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

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Yusuff[57], Z. Zolkapli

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

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

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

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

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

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

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

AGH University of Krakow, Krakow, Poland

V. Avati, L. Forthomme, L. Grzanka, M. Malawski, K. Piotrzkowski

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

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

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

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

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

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

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

Universidad Autónoma de Madrid, Madrid, Spain
J.F. de Trocóniz

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
B. Alvarez Gonzalez, J. Ayllon Torresano, A. Cardini, J. Cuevas, J. Del Riego Badas, D. Estrada Acevedo, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, P. Leguina, M. Obeso Menendez, E. Palencia Cortezon, J. Prado Pico, A. Soto Rodríguez, P. Vischia

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

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

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

W.G.D. Dharmaratna[59], K. Liyanage, N. Perera

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, C. Amendola, R. Ardino, E. Auffray, J. Baechler, D. Barney, J. Bendavid, M. Bianco, A. Bocci, L. Borgonovi, C. Botta, A. Bragagnolo, C.E. Brown, C. Caillol, G. Cerminara, P. Connor, K. Cormier, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, P.J. Fernández Manteca, B.A. Fontana Santos Alves, E. Fontanesi, W. Funk, A. Gaddi, S. Giani, D. Gigi, K. Gill, F. Glege, M. Glowacki, A. Gruber, J. Hegeman, J.K. Heikkilä, R. Hofsaess, B. Huber, T. James, P. Janot, O. Kaluzinska, O. Karacheban[27], G. Karathanasis, S. Laurila, P. Lecoq, E. Leutgeb, C. Lourenço, A.-M. Lyon, M. Magherini, L. Malgeri, M. Mannelli, A. Mehta, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, M. Migliorini, F. Monti, F. Moortgat, M. Mulders, M. Musich, I. Neutelings, S. Orfanelli, F. Pantaleo, M. Pari, G. Petrucciani, A. Pfeiffer, M. Pierini, M. Pitt, H. Qu, D. Rabady, A. Reimers, B. Ribeiro Lopes, F. Riti, P. Rosado, M. Rovere, H. Sakulin, R. Salvatico, S. Sanchez Cruz, S. Scarfi, M. Selvaggi, K. Shchelina, P. Silva, P. Sphicas[60], A.G. Stahl Leiton, A. Steen, S. Summers, D. Treille, P. Tropea, E. Vernazza, J. Wanczyk[61], S. Wuchterl, M. Zarucki, P. Zehetner, P. Zejdl, G. Zevi Della Porta

PSI Center for Neutron and Muon Sciences, Villigen, Switzerland
T. Bevilacqua[62], L. Caminada[62], W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, U. Langenegger, A. Nigamova, L. Noehte[62], T. Rohe, A. Samalan

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
T.K. Aarrestad, M. Backhaus, G. Bonomelli, C. Cazzaniga, K. Datta, P. De Bryas Dexmiers D'Archiacchiac[61], A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, K. Gedia, F. Glessgen, C. Grab, N. Härringer, T.G. Harte, W. Lustermann, M. Malucchi, R.A. Manzoni, L. Marchese, A. Mascellani[61], F. Nessi-Tedaldi, F. Pauss, V. Perovic, B. Ristic, R. Seidita, J. Steggemann[61], A. Tarabini, D. Valsecchi, R. Wallny

Universität Zürich, Zurich, Switzerland
C. Amsler[63], P. Bärtschi, F. Bilandzija, M.F. Canelli, G. Celotto, A. Jofrehei, B. Kilminster, T.H. Kwok, S. Leontsinis, V. Lukashenko, A. Macchiolo, F. Meng, M. Missiroli, J. Motta, P. Robmann, E. Shokr, F. Stäger, R. Tramontano, P. Viscone

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

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

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

Tunis El Manar University, Tunis, Tunisia
Y. Maghrbi

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

D. Agyel, F. Dolek, I. Dumanoglu[64], Y. Guler[65], E. Gurpinar Guler[65], C. Isik, O. Kara, A. Kayis Topaksu, Y. Komurcu, G. Onengut, K. Ozdemir[66], B. Tali[67], U.G. Tok, E. Uslan, I.S. Zorbakir

Hacettepe University, Ankara, Turkey
S. Sen

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

Bogazici University, Istanbul, Turkey
B. Akgun, I.O. Atakisi[69], E. Gülmez, M. Kaya[70], O. Kaya[71], M.A. Sarkisla[72], S. Tekten[73]

Istanbul Technical University, Istanbul, Turkey
D. Boncukcu, A. Cakir, K. Cankocak[64,74]

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

Yildiz Technical University, Istanbul, Turkey
S. Cerci, C. Dozen[76], B. Isildak[77], E. Simsek, D. Sunar Cerci, T. Yetkin[76]

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

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

University of Bristol, Bristol, United Kingdom
J.J. Brooke, A. Bundock, F. Bury, E. Clement, D. Cussans, D. Dharmender, H. Flacher, J. Goldstein, H.F. Heath, M.-L. Holmberg, L. Kreczko, S. Paramesvaran, L. Robertshaw, M.S. Sanjrani[41], J. Segal, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom
A.H. Ball, K.W. Bell, A. Belyaev[78], C. Brew, R.M. Brown, D.J.A. Cockerill, A. Elliot, K.V. Ellis, J. Gajownik, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, M. Moallemi, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, A.R. Sahasransu, G. Salvi, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, K.C. Whalen, T. Williams

Imperial College, London, United Kingdom
I. Andreou, R. Bainbridge, P. Bloch, O. Buchmuller, C.A. Carrillo Montoya, D. Colling, I. Das, P. Dauncey, G. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, H.R. Hoorani, A. Howard, G. Iles, C.R. Knight, P. Krueper, J. Langford, K.H. Law, J. León Holgado, L. Lyons, A.-M. Magnan, B. Maier, S. Mallios, A. Mastronikolis, M. Mieskolainen, J. Nash[79], M. Pesaresi, P.B. Pradeep, B.C. Radburn-Smith, A. Richards, A. Rose, L. Russell, K. Savva, C. Seez, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, T. Virdee[29], M. Vojinovic, N. Wardle, D. Winterbottom

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

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

Bethel University, St. Paul, Minnesota, USA
J.M. Hogan

Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez, S. Raj, B. Sahu[37], A.E. Simsek, S.S. Yu

The University of Alabama, Tuscaloosa, Alabama, USA
B. Bam, A. Buchot Perraguin, S. Campbell, R. Chudasama, S.I. Cooper, C. Crovella, G. Fidalgo, S.V. Gleyzer, A. Khukhunaishvili, K. Matchev, E. Pearson, C.U. Perez, P. Rumerio[80], E. Usai, R. Yi

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

Brown University, Providence, Rhode Island, USA
G. Barone, G. Benelli, D. Cutts, S. Ellis, L. Gouskos, M. Hadley, U. Heintz, K.W. Ho, T. Kwon, L. Lambrecht, G. Landsberg, K.T. Lau, J. Luo, S. Mondal, J. Roloff, T. Russell, S. Sagir[81], X. Shen, M. Stamenkovic, N. Venkatasubramanian

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

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

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

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

University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA
A. Barzdukas, L. Brennan, C. Campagnari, S. Carron Montero[82], K. Downham, C. Grieco, M.M. Hussain, J. Incandela, M.W.K. Lai, A.J. Li, P. Masterson, J. Richman, S.N. Santpur, U. Sarica, R. Schmitz, D. Stuart, T.Á. Vámi, X. Yan, D. Zhang

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

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

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

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

Fermi National Accelerator Laboratory, Batavia, Illinois, USA
M. Albrow, M. Alyari, O. Amram, G. Apollinari, A. Apresyan, L.A.T. Bauerdick, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, C. Cosby, G. Cummings, I. Dutta, V.D. Elvira, J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, A. Grummer, S. Grünendahl, D. Guerrero, O. Gutsche, R.M. Harris, T.C. Herwig, J. Hirschauer, V. Innocente, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, S. Lammel, C. Lee, D. Lincoln, R. Lipton, T. Liu, K. Maeshima, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, D. Noonan, S. Norberg, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[83], C.E. Perez Lara, F. Ravera, A. Reinsvold Hall[84], L. Ristori, M. Safdari, E. Sexton-Kennedy, N. Smith, A. Soha, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Wang, I. Zoi

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

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

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

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

The University of Iowa, Iowa City, Iowa, USA

M. Alhusseini, D. Blend, K. Dilsiz[85], O.K. Köseyan, A. Mestvirishvili[86], O. Neogi, H. Ogul[87], Y. Onel, A. Penzo, C. Snyder, E. Tiras[88]

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

The University of Kansas, Lawrence, Kansas, USA
A. Abreu, L.F. Alcerro Alcerro, J. Anguiano, S. Arteaga Escatel, P. Baringer, A. Bean, R. Bhattacharya, Z. Flowers, D. Grove, J. King, G. Krintiras, M. Lazarovits, C. Le Mahieu, J. Marquez, M. Murray, M. Nickel, S. Popescu[89], C. Rogan, C. Royon, S. Rudrabhatla, S. Sanders, C. Smith, G. Wilson

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

University of Maryland, College Park, Maryland, USA
A. Baden, A. Belloni, J. Bistany-riebman, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, B. Kronheim, S. Lascio, P. Major, A.C. Mignerey, C. Palmer, C. Papageorgakis, M.M. Paranjpe, E. Popova[90], A. Shevelev, L. Zhang

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

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

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

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

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

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

University of Notre Dame, Notre Dame, Indiana, USA
G. Agarwal, R. Band, R. Bucci, S. Castells, A. Das, A. Datta, A. Ehnis,

R. Goldouzian, M. Hildreth, K. Hurtado Anampa, T. Ivanov, C. Jessop, A. Karneyeu, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, J. Mariano, N. Marinelli, T. McCauley, C. Mcgrady, C. Moore, Y. Musienko[23], H. Nelson, M. Osherson, A. Piccinelli, R. Ruchti, A. Townsend, Y. Wan, M. Wayne, H. Yockey

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

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

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

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

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

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

University of Rochester, Rochester, New York, USA
O. Bessidskaia Bylund, A. Bodek, P. de Barbaro[†], R. Demina, A. Garcia-Bellido, H.S. Hare, O. Hindrichs, N. Parmar, P. Parygin[90], H. Seo, R. Taus

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

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

Texas A&M University, College Station, Texas, USA
D. Aebi, M. Ahmad, T. Akhter, K. Androsov, A. Bolshov, O. Bouhali[91], A. Cagnotta, V. D'Amante, R. Eusebi, P. Flanagan, J. Gilmore, Y. Guo, T. Kamon, S. Luo, R. Mueller, A. Safonov

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

Vanderbilt University, Nashville, Tennessee, USA

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

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

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

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

Authors affiliated with an international laboratory covered by a cooperation agreement with CERN
S. Afanasiev, V. Alexakhin, Yu. Andreev, T. Aushev, D. Budkouski, R. Chistov, M. Danilov, T. Dimova, A. Ershov, S. Gninenko, I. Gorbunov, A. Gribushin, A. Kamenev, V. Karjavine, M. Kirsanov, V. Klyukhin, O. Kodolova[92], V. Korenkov, I. Korsakov, A. Kozyrev, N. Krasnikov, A. Lanev, A. Malakhov, V. Matveev, A. Nikitenko[93,92], V. Palichik, V. Perelygin, S. Petrushanko, S. Polikarpov, O. Radchenko, M. Savina, V. Shalaev, S. Shmatov, S. Shulha, Y. Skovpen, K. Slizhevskiy, V. Smirnov, O. Teryaev, I. Tlisova, A. Toropin, N. Voytishin, A. Zarubin, I. Zhizhin

Authors affiliated with an institute formerly covered by a cooperation agreement with CERN
L. Dudko, V. Kim[23], V. Murzin, V. Oreshkin, D. Sosnov, E. Boos, V. Bunichev, M. Dubinin[83], V. Savrin, A. Snigirev

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

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

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