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Search for fractionally charged particles in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

Abstract

A search is presented for fractionally charged particles with charge below $1e$, using their small energy loss in the tracking detector as a key variable to observe a signal. The analyzed data set corresponds to an integrated luminosity of $138\,\text{fb}^{-1}$ of proton-proton collisions collected at $\sqrt{s} = 13\,\text{TeV}$ in 2016–2018 at the CERN LHC. This is the first search at the LHC for new particles with charges between $e/3$ and e. Masses up to 640 GeV and charges as low as $e/3$ are excluded at 95% confidence level. These are the most stringent limits to date for the considered Drell-Yan-like production mode.

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*See Appendix B for the list of collaboration members

Colorless freely-propagating particles with a fractional electric charge, or fractionally charged particles (FCPs), have never been observed. In particular, such particles with a charge lower than the electron charge e remain unseen, although nothing from first principle prevents their existence. The theoretical motivations for the existence of FCPs are closely related to possible hidden symmetries and fields weakly or not connected to the standard model (SM) fields. For example, these particles are predicted in the hypercharge portal scenario, where a new U(1) symmetry is added to the SM Lagrangian, and the corresponding new boson, called a dark photon, kinetically mixes with the SM hypercharge field [1]. New U(1) symmetries are introduced, e.g., in string theory phenomenology [2] and Grand Unified Theories, as remnants of large symmetries that break down to the SM symmetry group and extra U(1) groups [3]. Breaking supersymmetry in a hidden sector is another way to generate such new Abelian groups [4].

When adding to the SM Lagrangian such a U(1) gauge field A' that couples to a new Dirac fermion ψ with mass M through a coupling constant e', the kinetic mixing between the new gauge field and the SM hypercharge field B leads (after a field redefinition $A'_\mu \to A'_\mu - \kappa B_\mu$) to the ψ field acquiring an effective nonzero weak hypercharge $e'\kappa$ and thus a coupling to the SM photon and Z boson after electroweak symmetry breaking:

$$\mathcal{L} \supset -\frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}(\partial\!\!\!/ + ie'A\!\!\!/' - ie'\kappa B\!\!\!/ + iM)\psi.$$

The electric charge $Q = e'\kappa\cos\theta_\mathrm{W} \equiv \epsilon e$ of the new fermion ψ, where θ_W denotes the weak mixing angle, can take any value. For the purpose of this search, the sign of the charge is irrelevant and we will always use Q as a positive value. In the SM, fermions couple to electroweak vector bosons through vector and axial-vector couplings $g_\mathrm{V} = I_3 - 2Q\sin^2\theta_\mathrm{W}$ and $g_\mathrm{A} = I_3$. Since ψ only carries U(1) charge, it has no SU(2) weak isospin I_3, and we take the same value for θ_W as in the SM. The matter field ψ is what we refer to as the FCP. We consider FCPs to be pair-produced in a Drell–Yan (DY)-like process with an associated DY cross section where the charge and mass of the final state fermion are taken to be that of the FCP.

In this Letter, we present a search for FCPs in proton-proton (pp) collisions at a center-of-mass energy of 13 TeV with the CMS detector at the CERN LHC. The data analyzed correspond to an integrated luminosity of $138\,\mathrm{fb}^{-1}$ collected in 2016–2018. As we probe FCP charges lower than e, the FCP-matter interaction cross section is smaller than that of unit charge particles such as muons. Consequently, the FCP interaction length is larger, resulting in a smaller energy loss per unit length $\mathrm{d}E/\mathrm{d}x$. The strategy adopted in this search is to measure the ionization of particles passing through the tracking detector to discriminate signal from background events. A similar search was pursued previously by CMS using pp collision data corresponding to an integrated luminosity of $5.0\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 7\,\mathrm{TeV}$ [5]. Another CMS analysis, also based on ionization measurements but using a different approach [6], combined data sets of $5.0\,\mathrm{fb}^{-1}$ at 7 TeV and $18.8\,\mathrm{fb}^{-1}$ at 8 TeV. These results exclude at 95% confidence level (CL) the existence of FCPs with a charge of $2e/3$ in the mass range 100–460 GeV. Exclusions for a charge of $e/3$ have been recently understood to be affected by an issue with the muon trigger simulation at low charge, and have been retracted (see Errata of Refs. [5, 6]). In this work, we improve the simulation of the FCP signal in terms of $\mathrm{d}E/\mathrm{d}x$ in the CMS muon detectors. This allows us to produce an exclusion result for a charge of $e/3$ and to extend the reach of the search for other probed FCP charge and mass scenarios.

At higher masses, the most stringent constraints are derived indirectly from the anisotropy of the cosmic microwave background, which can be affected by FCPs in the hot primordial plasma [7]. In models with a massless dark photon with coupling $e' = 0.1$, such constraints exclude the existence of FCPs with a mass larger than about 250 GeV [8], for all charges considered in this paper. These results are model-dependent and are complementary to those of the model-independent direct-detection search we pursue in this work. At lower masses, FCPs have been searched for at colliders. In particular, LEP constraints exclude the existence of particles with a charge larger than $2e/3$ and a mass below 95 GeV [9, 10]. Future proposed dedicated experiments at the LHC intend to probe down to $10^{-3}e$ for masses below half the Z boson mass [11–14]. Finally, through the reinterpretation of cosmic ray measurements, other bounds have been derived [15] that depend on the nature of dark matter and on FCP cosmic acceleration. The range of these bounds overlap with the phase space accessible at the LHC, and go as low as $10^{-4}e$.

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. The silicon tracker consists of pixel and strip modules that measure ionization clusters (hits) and the associated $\mathrm{d}E/\mathrm{d}x$ arising from tracks in the pseudorapidity range $|\eta| < 2.5$. Between the 2016 and 2017 data-taking periods, the pixel tracker was fully replaced, adding an extra detection layer both in the central and forward sections of the detector [16]. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. They are measured in the range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers. A 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. [17].

Isolated particles with transverse momentum $p_{\mathrm{T}} = 100$ GeV emitted with $|\eta| < 1.4$ have track p_{T} resolution of 2.8%. In this η range, the distribution of the number of tracker layers a particle sees is narrowly centered around 13 (14) with the old (new) pixel detector. The efficiency to reconstruct and identify muons is greater than 96% for muons with p_{T} above 20 GeV [18]. Matching muons to tracks measured in the silicon tracker results, for muons with p_{T} up to 100 GeV, in a relative p_{T} resolution of 1% in the barrel and 3% in the endcaps. For higher-p_{T} muons, up to a p_{T} of 1 TeV, the resolution in the barrel remains better than 7%.

The experimental signature of an FCP in CMS is very similar to that of a muon, i.e., a minimum-ionizing long-lived particle. It is expected to leave a track both in the silicon tracker and in the muon chambers. In order to assign a p_{T} to charged particles with curved trajectories in the CMS magnetic field, the track reconstruction algorithm assumes that particles carry an electric charge of $1e$. Because their charge Q is lower than $1e$, the measured p_{T} of FCPs is overestimated by a factor of $1/Q$. This leads to an improved efficiency for the selection of high-p_{T} signal tracks. On the other hand, FCPs ionize in the detector with a $\mathrm{d}E/\mathrm{d}x$ proportional to Q^2. As a consequence, FCPs produce a softer $\mathrm{d}E/\mathrm{d}x$ spectrum than SM charged particles. For smaller FCP charges ($Q < 0.5e$), energy deposits in the tracker and in the muon chambers have an increased probability to fall below the readout threshold, which may lead to a loss of signal efficiency because of tracks not being reconstructed.

Signal events are simulated using PYTHIA 8.215 [19] at leading order (LO). Background events from $\mathrm{W} \to \mu\nu$, $\mathrm{Z} \to \mu^+\mu^-$, and $\mathrm{t\bar{t}}$ production are generated with MADGRAPH5_aMC@NLO [20] (v5_2.2.2) with at LO or next-to-LO (NLO), depending on the process. Diboson events are generated with PYTHIA at LO. All samples are generated with the corresponding 2016, 2017, and 2018 detector conditions. The LO NNPDF3.0 PDF set [21] is used for 2016 samples, while the next-to-NLO NNPDF3.1 PDF set [21] is used for 2017 and 2018 samples. Parton showering and fragmentation is performed for the 2016 event samples using the CUETP8M1 tune [22], except for $\mathrm{t\bar{t}}$ events, for which the CUETP8M2T4 tune is used [23]. For all 2017–2018 samples, the CP5 tune is used [24]. All generated events are passed through a simulation of the CMS detector, using GEANT4 [25], and its readout electronics and electronic signals from additional pp interactions within the same or adjacent bunch crossings are overlaid. In the muon chambers, FCP-matter interactions are generated using a combination of GEANT4 and a parametrized framework to simulate the creation of individual electrons through ionization and their drift to the collecting electrodes.

Events of interest are selected using a two-tiered trigger system [26]. In this search, we employ a single-muon trigger with a p_{T} threshold of 50 GeV [18]. The muon reconstructed offline is required to have p_{T} above 55 GeV, i.e. above the peak in the p_{T} spectrum of muons from W and Z boson decays. Events are further selected if they contain at least one central, isolated, high-p_{T} track geometrically matched to a muon. The track must have $|\eta| < 1.5$, and come from the primary vertex of the event. To ensure a sufficient track quality, at least 5 hits are required overall in the tracker, among which at least one should be in the pixel detector. For each track, the muon system is used to estimate the time at which the particle traveling at nearly the speed of light would have emerged from the primary vertex. By convention, this time is redefined to have its mean centered around zero. For ultrarelativistic particles, the resolution is of the order of 5 nanoseconds. As FCPs are massive and thus travel slower and arrive later in the muon chambers, tracks are selected if this time is positive. This rejects about half of the muon background from SM processes. Furthermore, the maximum angle between the track and any other track or muon with $p_{\mathrm{T}} > 35$ GeV is required to be smaller than 2.8 radians to reject back-to-back tracks from traversing cosmic ray muons. These selection criteria define candidate tracks, to which the signal selection is then applied. Events are retained for analysis if they contain 1 or 2 candidate tracks.

Because of their smaller ionization, FCP tracks have a larger number of tracker hits with low $\mathrm{d}E/\mathrm{d}x$ than expected for particles with charge e. To discriminate FCPs (signal) from muons (background), we count the number of track hits with a low value of $\mathrm{d}E/\mathrm{d}x$ ($N_{\text{hits}}^{\text{low d}E/\text{d}x}$). The choice of the $\mathrm{d}E/\mathrm{d}x$ threshold below which a hit is considered low is detailed later together with the background estimation.

Some instrumental effects that reduce the $\mathrm{d}E/\mathrm{d}x$ values are not well simulated. Radiation damage affects the ability for the tracker sensors to collect the ionization charge, leading to an increased probability for tracks to have a high number of low-$\mathrm{d}E/\mathrm{d}x$ hits. In particular, we observe the pixel detector layer closest to the beam to be strongly affected by radiation. For this reason, and because the readout of this layer was defective in some data-taking periods [27], we choose not to count hits on this layer. Furthermore, we observe the number of low-$\mathrm{d}E/\mathrm{d}x$ hits to be underestimated in simulations, even for tracker layers further away from the collision point. Therefore, the signal $\mathrm{d}E/\mathrm{d}x$ spectrum in each of the tracker layers is corrected independently, using correction factors derived from comparisons of candidate tracks between data and simulations. The effect of these corrections is to reduce the $\mathrm{d}E/\mathrm{d}x$ value of a fraction of the hits. These corrections are particularly important for data collected in the first half of 2016, when an electronic saturation problem in the strip tracker led to an increase in hits with low-$\mathrm{d}E/\mathrm{d}x$ values [28, 29]. Another experimental effect not well simulated is related to the edges of the tracker modules. When a particle deposits energy close to the edge of a module, part of the charge is not collected, leading to a low-charge hit. Because of the way the modules are physically arranged, this increases the probability of such tracks having a high multiplicity of low-$\mathrm{d}E/\mathrm{d}x$ hits. Consequently, we ignore tracks containing at least one hit close to the edge of a tracker module. Finally, we observe an anomalous accumulation of hits with $\mathrm{d}E/\mathrm{d}x < 0.25$ MeV/ cm for a few modules in the strip tracker with poor gain calibration, which we ignore.

We divide the total data set into four periods: early 2016 (19.9 fb^{-1}), late 2016 (16.4 fb^{-1}), 2017 (41.5 fb^{-1}), and 2018 (59.7 fb^{-1}). Each period includes different instrumental effects. Thus, the expected number of tracks from background and signal events is estimated separately in each of these four periods. In the following, we demonstrate some features of the search using the 2018 data set, which is the largest and contributes most to the overall sensitivity. The final results derive from a combination of all four data-taking periods.

We split our selected events into a search region (SR) and a control region (CR). The SR consists of events with only one track and events with two tracks with an invariant mass smaller than 80 or larger than 100 GeV. The CR consists of events with two tracks that have an invariant mass in the range 80–100 GeV, and is dominated by Z boson production. The CR has fewer tracks than the SR and is normalized to the number of tracks in the SR. As shown in Fig. 1, the shape of the $\mathrm{d}E/\mathrm{d}x$ distributions in the CR and the SR agree well.

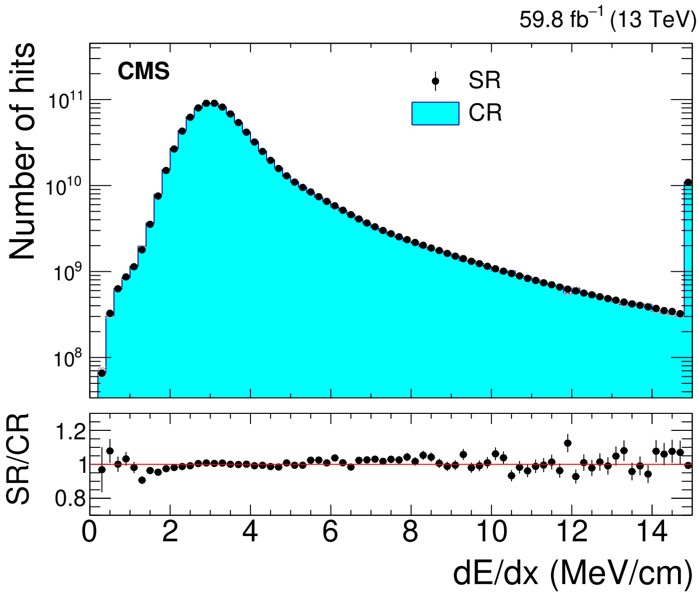

Figure 1: The $\mathrm{d}E/\mathrm{d}x$ distribution for hits on candidate tracks in the CR and SR in 2018 data. The last bin is an overflow bin. The vertical bars and the shaded area correspond to the statistical uncertainty in the SR and the CR, respectively.

To estimate the background directly from data, we extrapolate the number of tracks in the CR from low $N_{\mathrm{hits}}^{\mathrm{low}\ \mathrm{d}E/\mathrm{d}x}$ to high $N_{\mathrm{hits}}^{\mathrm{low}\ \mathrm{d}E/\mathrm{d}x}$ values, where we expect few events. The distribution of this variable is shown in Fig. 2 for 2018 data in the CR and the SR, as well as for signal events. Corresponding figures for the other data periods can be found in Appendix A. Tabulated results are provided in the HEPData record for this analysis [31]. The extrapolation is done by fitting the $N_{\mathrm{hits}}^{\mathrm{low}\ \mathrm{d}E/\mathrm{d}x}$ distribution in the CR with a binomial function. This background evaluation method is valid for FCPs with masses larger than 50 GeV, which would give a negligible contribution to the CR. The use of the binomial function to describe the $N_{\mathrm{hits}}^{\mathrm{low}\ \mathrm{d}E/\mathrm{d}x}$ distribution is justified by the track hits being a priori uncorrelated binary measurements by identical detector modules. The number of binomial measurements is given by the mean number of hits per track and the probability for a measurement to have a positive outcome is given by the mean fraction of low-$\mathrm{d}E/\mathrm{d}x$ hits per track. However, instrumental effects, in particular radiation damage, affect the tracker modules in a way that the assumption that measurements come from identical detectors is not strictly met. As a consequence, the choice of a single $\mathrm{d}E/\mathrm{d}x$

threshold yields a $N_{\text{hits}}^{\text{low } dE/dx}$ distribution that deviates from a binomial distribution. To restore a quasi-binomial behavior, layer-dependent upper dE/dx thresholds are chosen to enforce an equal average binomial probability for each tracker layer. These upper thresholds typically vary around 2 MeV/cm, below the peak of the dE/dx distribution for unit charge particles (see Fig. 1). Together with the lower threshold at 0.25 MeV/cm, they define low-dE/dx windows in which $N_{\text{hits}}^{\text{low } dE/dx}$ is counted. A χ^2 test and the associated p-value [32] are used to evaluate the hypothesis of the binomial distribution. The validity of the background estimation in the SR from a fit to the CR is supported by the good agreement between the SR and the CR in the distributions of dE/dx.

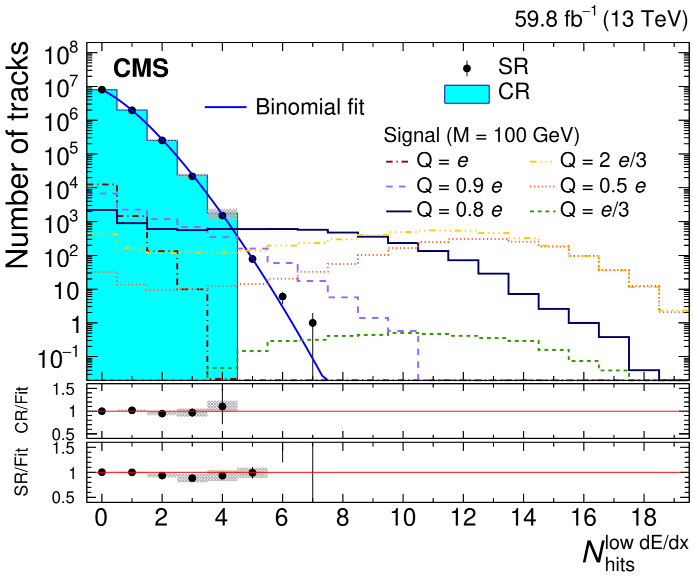

Figure 2: Distribution of $N_{\text{hits}}^{\text{low } dE/dx}$ in the SR and the CR for the 2018 data set, as well as for an FCP signal at a mass of 100 GeV and different charge scenarios. The vertical bars and the shaded area correspond to the statistical uncertainty in the SR and the CR, respectively. The p-value of the fit is 9%. The two lower panels show the ratio of the number of tracks observed in the CR (upper) and SR (lower), and the fit function. The vertical bars correspond to the uncertainty from statistical sources, while the shaded area shows the systematic uncertainty in the binomial fit (see text).

In order to extract signal, we count the number of observed and expected tracks in the bins of the $N_{\text{hits}}^{\text{low } dE/dx}$ spectrum with the highest expected signal significance, separately for each data period. These bins correspond to $N_{\text{hits}}^{\text{low } dE/dx} = 5, 6, 7, 8$, and ≥ 9 for the early 2016 data set, and $N_{\text{hits}}^{\text{low } dE/dx} = 4, 5, 6$, and ≥ 7, for the late 2016, 2017, and 2018 data sets. In each data period, both the shape and the normalization information are used in the signal extraction.

We consider three distinct systematic uncertainties for the background prediction. The first uncertainty arises from the fit function. Although binomial from first principles and corrected for instrumental effects, residual correlations make the $N_{\text{hits}}^{\text{low } dE/dx}$ distribution slightly nonbinomial. To account for this, we fit the distribution with an alternative function, $N_{\text{tracks}}(n) = p_0 n^{p_1 + p_2 n}$, where $n = N_{\text{hits}}^{\text{low } dE/dx}$ and p_0, p_1, and p_2 are free parameters. We then take the uncertainty as the relative difference between the predictions of this fit and those of the binomial function. The second uncertainty relates to the choice of the fit range. It is taken as the relative difference between the predictions with the binomial fit starting at $N_{\text{hits}}^{\text{low } dE/dx} = 0$ and $N_{\text{hits}}^{\text{low } dE/dx} = 1$, except for early 2016 data where the $N_{\text{hits}}^{\text{low } dE/dx}$ distribution is wider and we compare the fits starting at $N_{\text{hits}}^{\text{low d}E/\text{d}x} = 0$ and $N_{\text{hits}}^{\text{low d}E/\text{d}x} = 2$. Finally, the uncertainty for the background prediction arising from the limited number of tracks in the fitted CR is negligible.

The main systematic uncertainties in the signal expectation come from the estimation of the Level-1 (L1) trigger inefficiency resulting from the large FCP mass (hence small velocity) and from the simulation of the loss of hits in the muon detector at low charge, estimated by varying dedicated muon simulation parameters. The low FCP $\text{d}E/\text{d}x$ causes a reconstruction inefficiency in the muon detector, for which we evaluate the uncertainty as well. Other contributions arise from the knowledge of the integrated luminosity in the considered data sets [33–35] and the understanding in simulation of other event and candidate track selection requirements, in particular the track isolation and cosmic rejection. To evaluate the uncertainty related to the correction of the underestimated fraction of low-$\text{d}E/\text{d}x$ hits in simulation, we define $N_{\text{hits},Q^2}^{\text{low dE/dx}}$ as $N_{\text{hits}}^{\text{low d}E/\text{d}x}$ with the low-$\text{d}E/\text{d}x$ window boundaries divided by Q^2. As $Q < e$ for FCPs, this means that we include higher $\text{d}E/\text{d}x$ values in the window from which the hits contributing to $N_{\text{hits}}^{\text{low d}E/\text{d}x}$ are counted. This reflects the fact that for a signal with low charge, the hits selected to count $N_{\text{hits}}^{\text{low d}E/\text{d}x}$ originate from a higher part of the $\text{d}E/\text{d}x$ spectrum than for an equivalent unity charge particle. The uncertainty in the signal is then obtained from the relative difference of $N_{\text{hits},Q^2}^{\text{low dE/dx}}$ between data and DY simulation in the CR.

Table 1 shows the number of tracks expected from background and observed in 2018 data, for the upper inclusive $N_{\text{hits}}^{\text{low d}E/\text{d}x}$ bin, which drives the sensitivity over most of the explored parameter space. Corresponding tables for the other data periods can be found in Appendix A. The expected signal rate is shown for an FCP with a mass of 100 GeV in two different charge scenarios, along with the associated systematic uncertainties. These uncertainties are considered to follow a log-normal distribution.

Table 1: Number of tracks observed and expected for background and signal events, in the $N_{\text{hits}}^{\text{low d}E/\text{d}x}$ bin with highest signal significance ($\geq$7), for 2018 data. The corresponding systematic uncertainties are also listed. The results are shown for FCP scenarios at a mass of 100 GeV with a charge of $2e/3$ (the most sensitive scenario) and $e/3$ (the lowest considered charge).

N^{observed}	1	
$N_{\text{BG}}^{\text{expected}}$	0.09	
Fit function	±19%	
Fit range	±28%	
	$Q = 2e/3$	$Q = e/3$
$N_{\text{signal}}^{\text{expected}}$	3622	3.51
L1 trigger inefficiency	5%	5%
Muon system energy loss simul.	+4%/−3%	75%
Muon detector inefficiency	3%	15%
Integrated luminosity	2.5%	2.5%
Selection	2.0%	2.0%
$\text{d}E/\text{d}x$ corrections	1.7%	2.3%
Limited signal sample	<1%	1.8%

No significant deviation is observed when comparing data with the background prediction in all search region bins across all considered data sets. Using the CL_s method [36, 37], 95% CL upper limits are computed for the FCP production cross section for a given charge and mass scenario. The excluded parameter space for the considered signal is shown in Fig. 3, using the full 2016–2018 data set. The exclusion shown is valid for masses above 50 GeV. The limit for a charge of $2e/3$ is improved with respect to prior analyses, and we extend the exclusion to other charge points, from $0.9e$ down to $e/3$. For an FCP of charge $2e/3$ ($e/3$), we exclude cross sections above 0.28 fb (0.39 pb) at the maximal excluded mass of 640 (60) GeV.

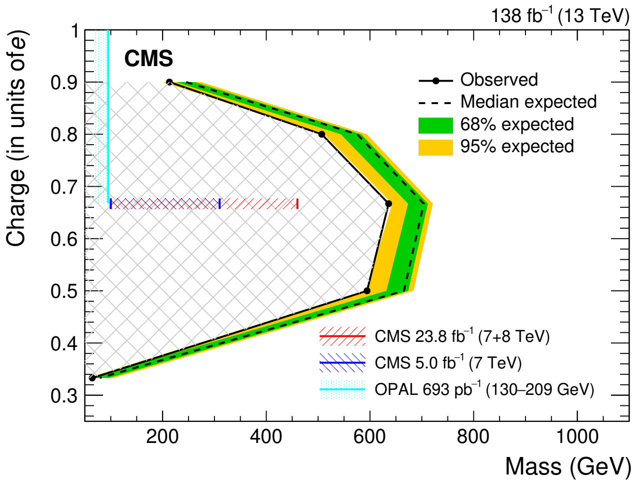

Figure 3: Exclusion region (hatched) at 95% CL in the FCP charge-mass plane for the considered signal. The expected exclusion is shown with the associated 1 (green) and 2 (orange) standard deviations bands. Signal points at charges 0.9, 0.8, 2/3, 0.5, and $1/3e$ are connected by straight lines to guide the eye. This is a conservative interpolation. Previous exclusions from CMS [5, 6] as well as OPAL [10] are given for comparison.

In summary, we presented a search for fractionally charged particles using proton-proton collisions corresponding to an integrated luminosity of $138\,\text{fb}^{-1}$, collected at $\sqrt{s} = 13$ TeV with the CMS detector. The key feature of low ionization energy in the CMS tracker detector is used to discriminate a potential signal from the background. No significant deviation is observed in data with respect to the expected background. The search presents for the first time a scan of the new particle charge between $e/3$ and e. The existence of fractionally charged particles arising from the considered DY-like pair production is excluded in the mass range between 50 and 640 (60) GeV for a signal of charge $Q = 2e/3$ ($e/3$). These are the most stringent limits to date for this production mode.

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A Additional figures and tables

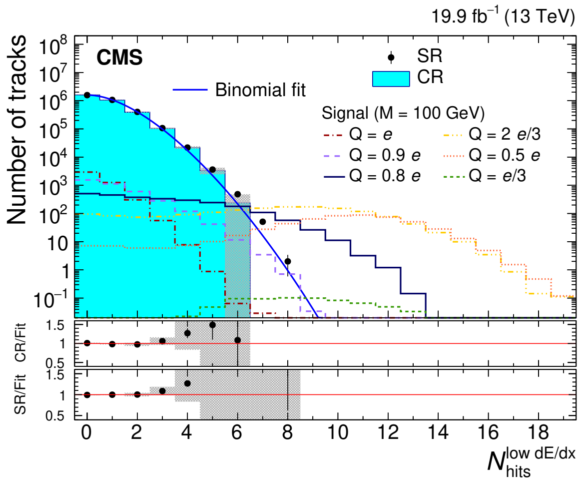

Figure A.1: Distribution of $N_{\mathrm{hits}}^{\mathrm{low}\ \mathrm{d}E/\mathrm{d}x}$ in the SR and the CR for the early 2016 data set, as well as for an FCP signal at a mass of 100 GeV and different charge scenarios. The vertical bars and the shaded area correspond to the statistical uncertainty in the SR and the CR, respectively. The p-value of the fit is 6%. The two lower panels show the ratio of the number of tracks observed in the CR (upper) and SR (lower), and the fit function. The vertical bars correspond to the uncertainty from statistical sources, while the shaded area shows the systematic uncertainty in the fit due to the choice of the fitting function and the binomial fit range as explained in the main text. Comparing with respect to the binomial fit starting at $N_{\mathrm{hits}}^{\mathrm{low}\ \mathrm{d}E/\mathrm{d}x} = 2$, and not $N_{\mathrm{hits}}^{\mathrm{low}\ \mathrm{d}E/\mathrm{d}x} = 1$, is needed to account for the fact that early 2016 data is more strongly affected by instrumental effects that widen the $N_{\mathrm{hits}}^{\mathrm{low}\ \mathrm{d}E/\mathrm{d}x}$ distribution.

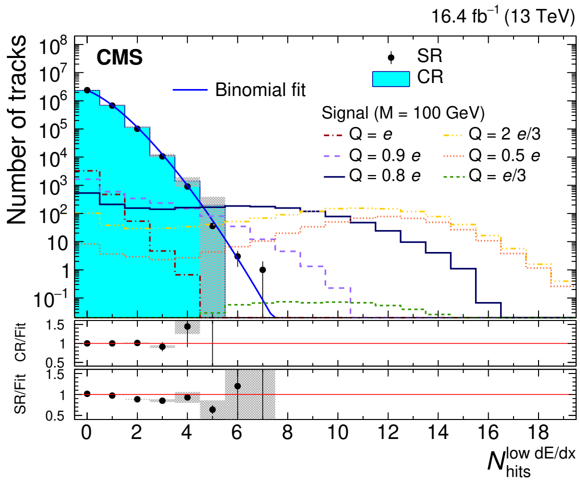

Figure A.2: Distribution of $N_{\mathrm{hits}}^{\mathrm{low}\ \mathrm{d}E/\mathrm{d}x}$ in the SR and the CR for the late 2016 data set, as well as for an FCP signal at a mass of 100 GeV and different charge scenarios. The vertical bars and the shaded area correspond to the statistical uncertainty in the SR and the CR, respectively. The p-value of the fit is 78%. The two lower panels show the ratio of the number of tracks observed in the CR (upper) and SR (lower), and the fit function. The vertical bars correspond to the uncertainty from statistical sources, while the shaded area shows the systematic uncertainty in the fit due to the choice of the fitting function and the binomial fit range as explained in the main text.

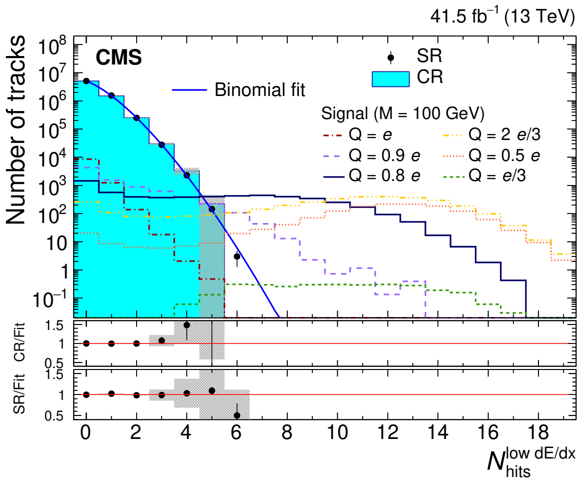

Figure A.3: Distribution of $N_{\mathrm{hits}}^{\mathrm{low}\ \mathrm{d}E/\mathrm{d}x}$ in the SR and the CR for the 2017 data set, as well as for an FCP signal at a mass of 100 GeV and different charge scenarios. The vertical bars and the shaded area correspond to the statistical uncertainty on the SR and the CR, respectively. The p-value of the fit is 65%. The two lower panels show the ratio of the number of tracks observed in the CR (upper) and SR (lower), and the fit function. The vertical bars correspond to the uncertainty from statistical sources, while the shaded area shows the systematic uncertainty in the fit due to the choice of the fitting function and the binomial fit range as explained in the main text.

Table A.1: Number of tracks observed and expected for background and signal events, in the $N_{\mathrm{hits}}^{\mathrm{low}\ \mathrm{d}E/\mathrm{d}x}$ bin with highest signal significance ($\geq$9), for early 2016 data. The corresponding systematic uncertainties are also listed. The results are shown for FCP scenarios at a mass of 100 GeV with a charge of $2e/3$ (the most sensitive scenario) and $e/3$ (the lowest considered charge).

N^{observed}	0	
$N_{\mathrm{BG}}^{\mathrm{expected}}$	0.04	
Fit function	$\pm$287%	
Fit range	$\pm$109%	
	$Q = 2e/3$	$Q = e/3$
$N_{\mathrm{signal}}^{\mathrm{expected}}$	602	0.328
L1 trigger inefficiency	5%	5%
Muon system energy loss simul.	+4%/−3%	75%
Muon detector inefficiency	3%	15%
Integrated luminosity	1.2%	1.2%
Selection	2.0%	2.0%
dE/dx corrections	3.8%	12.2%
Limited signal sample	<1%	2.4%

Table A.2: Number of tracks observed and expected for background and signal events, in the $N_{\text{hits}}^{\text{low}\,\mathrm{d}E/\mathrm{d}x}$ bin with highest signal significance (≥7), for late 2016 data. The corresponding systematic uncertainties are also listed. The results are shown for FCP scenarios at a mass of 100 GeV with a charge of $2e/3$ (the most sensitive scenario) and $e/3$ (the lowest considered charge).

N^{observed}	1	
$N_{\text{BG}}^{\text{expected}}$	0.09	
Fit function	±159%	
Fit range	±0.3%	
	$Q = 2e/3$	$Q = e/3$
$N_{\text{signal}}^{\text{expected}}$	988	0.454
L1 trigger inefficiency	5%	5%
Muon system energy loss simul.	+4%/−3%	75%
Muon detector inefficiency	3%	15%
Integrated luminosity	1.2%	1.2%
Selection	2.0%	2.0%
$\mathrm{d}E/\mathrm{d}x$ corrections	1.1%	1.4%
Limited signal sample	<1%	2.6%

Table A.3: Number of tracks observed and expected for background and signal events, in the $N_{\text{hits}}^{\text{low}\,\mathrm{d}E/\mathrm{d}x}$ bin with highest signal significance (≥7), for 2017 data. The corresponding systematic uncertainties are also listed. The results are shown for FCP scenarios at a mass of 100 GeV with a charge of $2e/3$ (the most sensitive scenario) and $e/3$ (the lowest considered charge).

N^{observed}	0	
$N_{\text{BG}}^{\text{expected}}$	0.2	
Fit function	±231%	
Fit range	±13.7%	
	$Q = 2e/3$	$Q = e/3$
$N_{\text{signal}}^{\text{expected}}$	2720	2.25
L1 trigger inefficiency	5%	5%
Muon system energy loss simul.	+4%/−3%	75%
Muon detector inefficiency	3%	15%
Integrated luminosity	2.3%	2.3%
Selection	2.0%	2.0%
$\mathrm{d}E/\mathrm{d}x$ corrections	2.3%	3.3%
Limited signal sample	<1%	1.5%

B The CMS Collaboration

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

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

Universiteit Antwerpen, Antwerpen, Belgium
M.R. Darwish[3], T. Janssen, P. Van Mechelen

Vrije Universiteit Brussel, Brussel, Belgium
E.S. Bols, J. D'Hondt, S. Dansana, A. De Moor, M. Delcourt, H. El Faham, S. Lowette, I. Makarenko, A. Morton, D. Müller, A.R. Sahasransu, S. Tavernier, M. Tytgat[4], S. Van Putte, D. Vannerom

Université Libre de Bruxelles, Bruxelles, Belgium
B. Clerbaux, G. De Lentdecker, L. Favart, D. Hohov, J. Jaramillo, A. Khalilzadeh, K. Lee, M. Mahdavikhorrami, A. Malara, S. Paredes, L. Pétré, N. Postiau, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer

Ghent University, Ghent, Belgium
M. De Coen, D. Dobur, J. Knolle, L. Lambrecht, G. Mestdach, C. Rendón, A. Samalan, K. Skovpen, N. Van Den Bossche, B. Vermassen, L. Wezenbeek

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
A. Benecke, G. Bruno, C. Caputo, C. Delaere, I.S. Donertas, A. Giammanco, K. Jaffel, Sa. Jain, V. Lemaitre, J. Lidrych, P. Mastrapasqua, K. Mondal, T.T. Tran, S. Wertz

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, E. Coelho, C. Hensel, T. Menezes De Oliveira, A. Moraes, P. Rebello Teles, M. Soeiro

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, M. Alves Gallo Pereira, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[5], E.M. Da Costa, G.G. Da Silveira[6], D. De Jesus Damiao, S. Fonseca De Souza, J. Martins[7], C. Mora Herrera, K. Mota Amarilo, L. Mundim, H. Nogima, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, A. Vilela Pereira

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

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

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

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

Beihang University, Beijing, China
T. Cheng, Q. Guo, T. Javaid, M. Mittal, L. Yuan

Department of Physics, Tsinghua University, Beijing, China
G. Bauer[8], Z. Hu, K. Yi[8,9]

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

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. Ban, A. Levin, C. Li, Q. Li, X. Lyu, Y. Mao, S.J. Qian, X. Sun, D. Wang, H. Yang, C. Zhou

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

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

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
X. Gao[12], D. Leggat, H. Okawa, Y. Zhang

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

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

Universidad de Antioquia, Medellin, Colombia
J. Mejia Guisao, F. Ramirez, M. Rodriguez, J.D. Ruiz Alvarez

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

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

Institute Rudjer Boskovic, Zagreb, Croatia
P. Bargassa, V. Brigljevic, B.K. Chitroda, D. Ferencek, S. Mishra, A. Starodumov[13], T. Susa

University of Cyprus, Nicosia, Cyprus
A. Attikis, K. Christoforou, S. Konstantinou, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, A. Stepennov

Charles University, Prague, Czech Republic
M. Finger[13], M. Finger Jr.[13], A. Kveton

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador

E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran[14,15], S. Elgammal[15]

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

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
R.K. Dewanjee[16], K. Ehataht, M. Kadastik, T. Lange, S. Nandan, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

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

Helsinki Institute of Physics, Helsinki, Finland
S. Bharthuar, E. Brücken, F. Garcia, J. Havukainen, K.T.S. Kallonen, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, M. Lotti, L. Martikainen, M. Myllymäki, M.m. Rantanen, H. Siikonen, E. Tuominen, J. Tuominiemi

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

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, V. Lohezic, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[17], P. Simkina, M. Titov

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
C. Baldenegro Barrera, F. Beaudette, A. Buchot Perraguin, P. Busson, A. Cappati, C. Charlot, F. Damas, O. Davignon, B. Diab, G. Falmagne, B.A. Fontana Santos Alves, S. Ghosh, A. Gilbert, R. Granier de Cassagnac, A. Hakimi, B. Harikrishnan, L. Kalipoliti, G. Liu, J. Motta, M. Nguyen, C. Ochando, L. Portales, R. Salerno, U. Sarkar, J.B. Sauvan, Y. Sirois, A. Tarabini, E. Vernazza, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[18], J. Andrea, D. Apparu, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, S. Falke, U. Goerlach, C. Grimault, R. Haeberle, A.-C. Le Bihan, M.A. Sessini, P. Van Hove

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
S. Beauceron, B. Blancon, G. Boudoul, N. Chanon, J. Choi, D. Contardo, P. Depasse, C. Dozen[19], H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, C. Greenberg, G. Grenier, B. Ille, I.B. Laktineh, M. Lethuillier, L. Mirabito, S. Perries, M. Vander Donckt, P. Verdier, J. Xiao

Georgian Technical University, Tbilisi, Georgia
D. Chokheli, I. Lomidze, Z. Tsamalaidze[13]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
V. Botta, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, N. Röwert,

M. Teroerde

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
S. Diekmann, A. Dodonova, N. Eich, D. Eliseev, F. Engelke, M. Erdmann, P. Fackeldey, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, M.y. Lee, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, S. Mondal, S. Mukherjee, D. Noll, A. Novak, F. Nowotny, A. Pozdnyakov, Y. Rath, W. Redjeb, F. Rehm, H. Reithler, V. Sarkisovi, A. Schmidt, S.C. Schuler, A. Sharma, A. Stein, F. Torres Da Silva De Araujo[20], L. Vigilante, S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
C. Dziwok, G. Flügge, W. Haj Ahmad[21], T. Kress, A. Nowack, O. Pooth, A. Stahl, T. Ziemons, A. Zotz

Deutsches Elektronen-Synchrotron, Hamburg, Germany
H. Aarup Petersen, M. Aldaya Martin, J. Alimena, S. Amoroso, Y. An, S. Baxter, M. Bayatmakou, H. Becerril Gonzalez, O. Behnke, A. Belvedere, S. Bhattacharya, F. Blekman[22], K. Borras[23], D. Brunner, A. Campbell, A. Cardini, C. Cheng, F. Colombina, S. Consuegra Rodríguez, G. Correia Silva, M. De Silva, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, O. Filatov, E. Gallo[22], A. Geiser, A. Giraldi, G. Greau, V. Guglielmi, M. Guthoff, A. Hinzmann, A. Jafari[24], L. Jeppe, N.Z. Jomhari, H. Jung, B. Kaech, M. Kasemann, H. Kaveh, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, W. Lange, D. Leyva Pernia, K. Lipka[25], W. Lohmann[26], R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, J. Metwally, A.B. Meyer, G. Milella, M. Mormile, A. Mussgiller, A. Nürnberg, Y. Otarid, D. Pérez Adán, E. Ranken, A. Raspereza, B. Ribeiro Lopes, J. Rübenach, A. Saggio, M. Scham[27,23], V. Scheurer, S. Schnake[23], P. Schütze, C. Schwanenberger[22], M. Shchedrolosiev, R.E. Sosa Ricardo, L.P. Sreelatha Pramod, D. Stafford, F. Vazzoler, A. Ventura Barroso, R. Walsh, Q. Wang, Y. Wen, K. Wichmann, L. Wiens[23], C. Wissing, S. Wuchterl, Y. Yang, A. Zimermmane Castro Santos

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

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
S. Brommer, M. Burkart, E. Butz, T. Chwalek, A. Dierlamm, A. Droll, N. Faltermann, M. Giffels, A. Gottmann, F. Hartmann[28], M. Horzela, U. Husemann, M. Klute, R. Koppenhöfer, M. Link, A. Lintuluoto, S. Maier, S. Mitra, Th. Müller, M. Neukum, M. Oh, G. Quast, K. Rabbertz, I. Shvetsov, H.J. Simonis, N. Trevisani, R. Ulrich, J. van der Linden, R.F. Von Cube, M. Wassmer, S. Wieland, F. Wittig, R. Wolf, S. Wunsch, X. Zuo

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, P. Assiouras, G. Daskalakis, A. Kyriakis, A. Papadopoulos[28], A. Stakia

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

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

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

HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
M. Bartók[29], C. Hajdu, D. Horvath[30,31], F. Sikler, V. Veszpremi

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

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
G. Bencze, S. Czellar, J. Karancsi[29], J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, B. Ujvari[34], G. Zilizi

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

Panjab University, Chandigarh, India
J. Babbar, S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra[35], R. Gupta, A. Kaur, A. Kaur, H. Kaur, M. Kaur, S. Kumar, P. Kumari, M. Meena, K. Sandeep, T. Sheokand, J.B. Singh[36], A. Singla

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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
S. Baradia, S. Barman[37], S. Bhattacharya, D. Bhowmik, S. Dutta, S. Dutta, B. Gomber[38], P. Palit, G. Saha, B. Sahu[38], S. Sarkar

Indian Institute of Technology Madras, Madras, India
P.K. Behera, S.C. Behera, S. Chatterjee, P. Jana, P. Kalbhor, J.R. Komaragiri[39], D. Kumar[39], M. Mohammad Mobassir Ameen, A. Muhammad, L. Panwar[39], R. Pradhan, P.R. Pujahari, N.R. Saha, A. Sharma, A.K. Sikdar, S. Verma

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, I. Das, S. Dugad, M. Kumar, G.B. Mohanty, P. Suryadevara

Tata Institute of Fundamental Research-B, Mumbai, India
A. Bala, S. Banerjee, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee, A. Thachayath

National Institute of Science Education and Research, An OCC of Homi Bhabha National

Institute, Bhubaneswar, Odisha, India
S. Bahinipati[40], A.K. Das, C. Kar, D. Maity[41], P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu[41], K. Naskar[41], A. Nayak[41], P. Sadangi, P. Saha, S.K. Swain, S. Varghese[41], D. Vats[41]

Indian Institute of Science Education and Research (IISER), Pune, India
A. Alpana, S. Dube, B. Kansal, A. Laha, S. Pandey, A. Rastogi, S. Sharma

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[42,43], E. Khazaie[43], M. Zeinali[44]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani[45], S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi

University College Dublin, Dublin, Ireland
M. Grunewald

INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy
M. Abbrescia[a,b], R. Aly[a,c,46], A. Colaleo[a], D. Creanza[a,c], B. D'Anzi[a,b], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,c], W. Elmetenawee[a,b], L. Fiore[a], G. Iaselli[a,c], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a,b], V. Mastrapasqua[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pellecchia[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a], G. Ramirez-Sanchez[a,c], D. Ramos[a], A. Ranieri[a], L. Silvestris[a], F.M. Simone[a,b], Ü. Sözbilir[a], A. Stamerra[a], R. Venditti[a], 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], L. Borgonovi[a], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], M. Cuffiani[a,b], G.M. Dallavalle[a], T. Diotalevi[a,b], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a,b], P. Giacomelli[a], L. Giommi[a,b], C. Grandi[a], L. Guiducci[a,b], S. Lo Meo[a,47], L. Lunerti[a,b], G. Masetti[a], F.L. Navarria[a,b], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[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], R. Potenza[a,b], A. Tricomi[a,b,48], C. Tuve[a,b]

INFN Sezione di Firenze[a], Università di Firenze[b], Firenze, Italy
G. Barbagli[a], G. Bardelli[a,b], B. Camaiani[a,b], A. Cassese[a], R. Ceccarelli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], G. Latino[a,b], P. Lenzi[a,b], M. Lizzo[a,b], 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
P. Chatagnon[a], F. Ferro[a], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca[a], Università di Milano-Bicocca[b], Milano, Italy
A. Benaglia[a], G. Boldrini[a], F. Brivio[a,b], F. Cetorelli[a,b], 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.T. Lucchini[a,b], M. Malberti[a], S. Malvezzi[a], A. Massironi[a], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], B.S. Pinolini[a], S. Ragazzi[a,b], N. Redaelli[a], T. Tabarelli de Fatis[a,b], D. Zuolo[a,b]

INFN Sezione di Napoli[a], Università di Napoli 'Federico II'[b], Napoli, Italy; Università della Basilicata[c], Potenza, Italy; Scuola Superiore Meridionale (SSM)[d], Napoli, Italy
S. Buontempo[a], A. Cagnotta[a,b], F. Carnevali[a,b], N. Cavallo[a,c], A. De Iorio[a,b], F. Fabozzi[a,c], A.O.M. Iorio[a,b], L. Lista[a,b,50], P. Paolucci[a,28], B. Rossi[a], C. Sciacca[a,b]

INFN Sezione di Padova[a], Università di Padova[b], Padova, Italy; Università di Trento[c], Trento, Italy
R. Ardino[a], P. Azzi[a], N. Bacchetta[a,51], M. Bellato[a], M. Benettoni[a], D. Bisello[a,b], P. Bortignon[a], A. Bragagnolo[a,b], R. Carlin[a,b], T. Dorigo[a], F. Gasparini[a,b], U. Gasparini[a,b], G. Grosso[a], L. Layer[a,52], E. Lusiani[a], M. Margoni[a,b], A.T. Meneguzzo[a,b], M. Migliorini[a,b], J. Pazzini[a,b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], G. Strong[a], M. Tosi[a,b], A. Triossi[a,b], S. Ventura[a], H. Yarar[a,b], M. Zanetti[a,b], P. Zotto[a,b], A. Zucchetta[a,b]

INFN Sezione di Pavia[a], Università di Pavia[b], Pavia, Italy
S. Abu Zeid[a,53], C. Aimè[a,b], A. Braghieri[a], S. Calzaferri[a,b], D. Fiorina[a,b], P. Montagna[a,b], V. Re[a], C. Riccardi[a,b], P. Salvini[a], I. Vai[a,b], P. Vitulo[a,b]

INFN Sezione di Perugia[a], Università di Perugia[b], Perugia, Italy
S. Ajmal[a,b], P. Asenov[a,54], G.M. Bilei[a], D. Ciangottini[a,b], L. Fanò[a,b], M. Magherini[a,b], G. Mantovani[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,54], A. Piccinelli[a,b], M. Presilla[a,b], 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
P. Azzurri[a], G. Bagliesi[a], R. Bhattacharya[a], L. Bianchini[a,b], T. Boccali[a], E. Bossini[a], D. Bruschini[a,c], R. Castaldi[a], M.A. Ciocci[a,b], M. Cipriani[a,b], V. D'Amante[a,d], R. Dell'Orso[a], S. Donato[a], A. Giassi[a], F. Ligabue[a,c], D. Matos Figueiredo[a], A. Messineo[a,b], M. Musich[a,b], F. Palla[a], S. Parolia[a], A. Rizzi[a,b], G. Rolandi[a,c], S. Roy Chowdhury[a], T. Sarkar[a], A. Scribano[a], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], N. Turini[a,d], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma[a], Sapienza Università di Roma[b], Roma, Italy
P. Barria[a], M. Campana[a,b], F. Cavallari[a], L. Cunqueiro Mendez[a,b], D. Del Re[a,b], E. Di Marco[a], M. Diemoz[a], F. Errico[a,b], E. Longo[a,b], P. Meridiani[a], J. Mijuskovic[a,b], G. Organtini[a,b], F. Pandolfi[a], R. Paramatti[a,b], C. Quaranta[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], L. Soffi[a], R. Tramontano[a,b]

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

INFN Sezione di Trieste[a], Università di Trieste[b], Trieste, Italy
S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], K. De Leo[a,b],

G. Della Ricca[a,b], G. Sorrentino[a,b]

Kyungpook National University, Daegu, Korea
S. Dogra, C. Huh, B. Kim, D.H. Kim, J. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, M.S. Ryu, S. Sekmen, Y.C. Yang

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

Hanyang University, Seoul, Korea
E. Asilar, D. Kim, T.J. Kim, J.A. Merlin, J. Park

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

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

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

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

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

Yonsei University, Department of Physics, Seoul, Korea
S. Ha, H.D. Yoo

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

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

Riga Technical University, Riga, Latvia
K. Dreimanis, A. Gaile, G. Pikurs, A. Potrebko, M. Seidel, V. Veckalns[55]

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

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

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

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

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
G. Ayala, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz[57],

R. Lopez-Fernandez, C.A. Mondragon Herrera, D.A. Perez Navarro, A. Sánchez Hernández

Universidad Iberoamericana, Mexico City, Mexico
C. Oropeza Barrera, M. Ramírez García

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

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

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

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

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

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, 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

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

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, D. Bastos, C. Beirão Da Cruz E Silva, A. Boletti, M. Bozzo, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, M. Pisano, J. Seixas, J. Varela

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

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
M. Dordevic, J. Milosevic, V. Rekovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, M. Barrio Luna, Cristina F. Bedoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, D. Fernández Del Val, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. León Holgado, D. Moran, C. M. Morcillo Perez, Á. Navarro Tobar, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, D.D. Redondo Ferrero, L. Romero, S. Sánchez Navas, L. Urda Gómez, J. Vazquez Escobar, C. Willmott

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

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

B. Alvarez Gonzalez, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, C. Ramón Álvarez, V. Rodríguez Bouza, A. Soto Rodríguez, A. Trapote, C. Vico Villalba, P. Vischia

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

University of Colombo, Colombo, Sri Lanka
M.K. Jayananda, B. Kailasapathy[58], D.U.J. Sonnadara, D.D.C. Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G.D. Dharmaratna[59], K. Liyanage, N. Perera, N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, C. Amendola, E. Auffray, G. Auzinger, J. Baechler, D. Barney, A. Bermúdez Martínez, M. Bianco, B. Bilin, A.A. Bin Anuar, A. Bocci, E. Brondolin, C. Caillol, T. Camporesi, G. Cerminara, N. Chernyavskaya, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, F. Fallavollita[60], L. Forthomme, G. Franzoni, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Haranko, J. Hegeman, V. Innocente, T. James, P. Janot, J. Kieseler, N. Kratochwil, S. Laurila, P. Lecoq, E. Leutgeb, C. Lourenço, B. Maier, L. Malgeri, M. Mannelli, A.C. Marini, F. Meijers, S. Mersi, E. Meschi, V. Milosevic, F. Moortgat, M. Mulders, S. Orfanelli, F. Pantaleo, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Piparo, H. Qu, D. Rabady, G. Reales Gutiérrez, M. Rovere, H. Sakulin, S. Scarfi, C. Schwick, M. Selvaggi, A. Sharma, K. Shchelina, P. Silva, P. Sphicas[61], A.G. Stahl Leiton, A. Steen, S. Summers, D. Treille, P. Tropea, A. Tsirou, D. Walter, J. Wanczyk[62], K.A. Wozniak, P. Zehetner, P. Zejdl, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
T. Bevilacqua[63], L. Caminada[63], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli[63], L. Noehte[63], T. Rohe

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
T.K. Aarrestad, K. Androsov[62], M. Backhaus, A. Calandri, K. Datta, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, M. Galli, K. Gedia, F. Glessgen, C. Grab, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, L. Marchese, C. Martin Perez, A. Mascellani[62], F. Nessi-Tedaldi, F. Pauss, V. Perovic, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, F. Riti, D. Ruini, D.A. Sanz Becerra, R. Seidita, J. Steggemann[62], D. Valsecchi, R. Wallny

Universität Zürich, Zurich, Switzerland
C. Amsler[64], P. Bärtschi, C. Botta, D. Brzhechko, M.F. Canelli, K. Cormier, A. De Wit, R. Del Burgo, J.K. Heikkilä, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, V.M. Mikuni, U. Molinatti, I. Neutelings, A. Reimers, P. Robmann, S. Sanchez Cruz, K. Schweiger, M. Senger, Y. Takahashi

National Central University, Chung-Li, Taiwan
C. Adloff[65], C.M. Kuo, W. Lin, P.K. Rout, P.C. Tiwari[39], S.S. Yu

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

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

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
D. Agyel, F. Boran, Z.S. Demiroglu, F. Dolek, I. Dumanoglu[66], E. Eskut, Y. Guler[67], E. Gurpinar Guler[67], C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir[68], A. Polatoz, B. Tali[69], U.G. Tok, S. Turkcapar, E. Uslan, I.S. Zorbakir

Middle East Technical University, Physics Department, Ankara, Turkey
K. Ocalan[70], M. Yalvac[71]

Bogazici University, Istanbul, Turkey
B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya[72], O. Kaya[73], S. Tekten[74]

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak[66], Y. Komurcu, S. Sen[75]

Istanbul University, Istanbul, Turkey
O. Aydilek, S. Cerci[69], V. Epshteyn, B. Hacisahinoglu, I. Hos[76], B. Isildak[77], B. Kaynak, S. Ozkorucuklu, H. Sert, C. Simsek, D. Sunar Cerci[69], C. Zorbilmez

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

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

University of Bristol, Bristol, United Kingdom
D. Anthony, J.J. Brooke, A. Bundock, F. Bury, E. Clement, D. Cussans, H. Flacher, M. Glowacki, J. Goldstein, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou[78], K. Walkingshaw Pass, R. White

Rutherford Appleton Laboratory, Didcot, United Kingdom
A.H. Ball, K.W. Bell, A. Belyaev[79], C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, K.V. Ellis, K. Harder, S. Harper, M.-L. Holmberg[80], Sh. Jain, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, G. Salvi, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom
R. Bainbridge, P. Bloch, C.E. Brown, O. Buchmuller, V. Cacchio, C.A. Carrillo Montoya, V. Cepaitis, G.S. Chahal[81], D. Colling, J.S. Dancu, P. Dauncey, G. Davies, J. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, A. Howard, G. Iles, M. Knight, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli,

M. Mieskolainen, J. Nash[82], M. Pesaresi, B.C. Radburn-Smith, A. Richards, A. Rose, C. Seez, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, L.H. Vage, T. Virdee[28], M. Vojinovic, N. Wardle, D. Winterbottom

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

Baylor University, Waco, Texas, USA
S. Abdullin, A. Brinkerhoff, B. Caraway, J. Dittmann, K. Hatakeyama, J. Hiltbrand, A.R. Kanuganti, B. McMaster, M. Saunders, S. Sawant, C. Sutantawibul, M. Toms, J. Wilson

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

The University of Alabama, Tuscaloosa, Alabama, USA
R. Chudasama, S.I. Cooper, S.V. Gleyzer, C.U. Perez, P. Rumerio[83], E. Usai, C. West

Boston University, Boston, Massachusetts, USA
A. Akpinar, A. Albert, D. Arcaro, C. Cosby, Z. Demiragli, C. Erice, E. Fontanesi, D. Gastler, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, S. Yuan

Brown University, Providence, Rhode Island, USA
G. Benelli, X. Coubez[23], D. Cutts, M. Hadley, U. Heintz, J.M. Hogan[84], T. Kwon, G. Landsberg, K.T. Lau, D. Li, J. Luo, M. Narain[†], N. Pervan, S. Sagir[85], F. Simpson, W.Y. Wong, X. Yan, D. Yu, W. Zhang

University of California, Davis, Davis, California, USA
S. Abbott, J. Bonilla, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, M. Citron, J. Conway, P.T. Cox, R. Erbacher, G. Haza, F. Jensen, O. Kukral, G. Mocellin, M. Mulhearn, D. Pellett, B. Regnery, W. Wei, Y. Yao, F. Zhang

University of California, Los Angeles, California, USA
M. Bachtis, R. Cousins, A. Datta, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, E. Manca, W.A. Nash, D. Saltzberg, B. Stone, V. Valuev

University of California, Riverside, Riverside, California, USA
R. Clare, M. Gordon, G. Hanson, W. Si, S. Wimpenny[†]

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

University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA
L. Brennan, C. Campagnari, G. Collura, A. Dorsett, J. Incandela, M. Kilpatrick, J. Kim, A.J. Li, P. Masterson, H. Mei, M. Oshiro, J. Richman, U. Sarica, R. Schmitz, F. Setti, J. Sheplock, D. Stuart, S. Wang

California Institute of Technology, Pasadena, California, USA
A. Bornheim, O. Cerri, A. Latorre, J.M. Lawhorn, J. Mao, H.B. Newman, T. Q. Nguyen, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
J. Alison, S. An, M.B. Andrews, P. Bryant, V. Dutta, T. Ferguson, A. Harilal, C. Liu, T. Mudholkar, S. Murthy, M. Paulini, A. Roberts, A. Sanchez, W. Terrill

University of Colorado Boulder, Boulder, Colorado, USA
J.P. Cumalat, W.T. Ford, A. Hassani, G. Karathanasis, E. MacDonald, N. Manganelli, F. Marini, A. Perloff, C. Savard, N. Schonbeck, K. Stenson, K.A. Ulmer, S.R. Wagner, N. Zipper

Cornell University, Ithaca, New York, USA
J. Alexander, S. Bright-Thonney, X. Chen, D.J. Cranshaw, J. Fan, X. Fan, D. Gadkari, S. Hogan, J. Monroy, J.R. Patterson, J. Reichert, M. Reid, A. Ryd, J. Thom, P. Wittich, R. Zou

Fermi National Accelerator Laboratory, Batavia, Illinois, USA
M. Albrow, M. Alyari, O. Amram, G. Apollinari, A. Apresyan, L.A.T. Bauerdick, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, G. Cummings, J. Dickinson, I. Dutta, V.D. Elvira, Y. Feng, J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, S. Grünendahl, D. Guerrero, O. Gutsche, R.M. Harris, R. Heller, T.C. Herwig, J. Hirschauer, L. Horyn, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, D. Lincoln, R. Lipton, T. Liu, C. Madrid, K. Maeshima, C. Mantilla, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, D. Noonan, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[86], F. Ravera, A. Reinsvold Hall[87], L. Ristori, E. Sexton-Kennedy, N. Smith, A. Soha, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, I. Zoi

University of Florida, Gainesville, Florida, USA
C. Aruta, P. Avery, D. Bourilkov, L. Cadamuro, P. Chang, V. Cherepanov, R.D. Field, E. Koenig, M. Kolosova, J. Konigsberg, A. Korytov, K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, A. Muthirakalayil Madhu, N. Rawal, D. Rosenzweig, S. Rosenzweig, K. Shi, J. Wang

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

Florida Institute of Technology, Melbourne, Florida, USA
B. Alsufyani, M.M. Baarmand, S. Butalla, T. Elkafrawy[53], M. Hohlmann, R. Kumar Verma, M. Rahmani, F. Yumiceva

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

The University of Iowa, Iowa City, Iowa, USA

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

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

The University of Kansas, Lawrence, Kansas, USA
A. Abreu, L.F. Alcerro Alcerro, J. Anguiano, P. Baringer, A. Bean, Z. Flowers, D. Grove, J. King, G. Krintiras, M. Lazarovits, C. Le Mahieu, C. Lindsey, J. Marquez, N. Minafra, M. Murray, M. Nickel, M. Pitt, S. Popescu[92], C. Rogan, C. Royon, R. Salvatico, S. Sanders, C. Smith, Q. Wang, G. Wilson

Kansas State University, Manhattan, Kansas, USA
B. Allmond, A. Ivanov, K. Kaadze, A. Kalogeropoulos, D. Kim, Y. Maravin, K. Nam, J. Natoli, D. Roy

Lawrence Livermore National Laboratory, Livermore, California, USA
F. Rebassoo, D. Wright

University of Maryland, College Park, Maryland, USA
E. Adams, A. Baden, O. Baron, A. Belloni, A. Bethani, Y.m. Chen, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, Y. Lai, S. Lascio, A.C. Mignerey, S. Nabili, C. Palmer, C. Papageorgakis, L. Wang, K. Wong

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
J. Bendavid, W. Busza, I.A. Cali, Y. Chen, M. D'Alfonso, J. Eysermans, C. Freer, G. Gomez-Ceballos, M. Goncharov, P. Harris, D. Hoang, D. Kovalskyi, J. Krupa, L. Lavezzo, Y.-J. Lee, K. Long, C. Mironov, C. Paus, D. Rankin, C. Roland, G. Roland, S. Rothman, Z. Shi, G.S.F. Stephans, J. Wang, Z. Wang, B. Wyslouch, T. J. Yang

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

University of Mississippi, Oxford, Mississippi, USA
L.M. Cremaldi

University of Nebraska-Lincoln, Lincoln, Nebraska, USA
K. Bloom, M. Bryson, D.R. Claes, C. Fangmeier, F. Golf, C. Joo, I. Kravchenko, I. Reed, J.E. Siado, G.R. Snow[†], W. Tabb, A. Wightman, F. Yan, A.G. Zecchinelli

State University of New York at Buffalo, Buffalo, New York, USA
G. Agarwal, H. Bandyopadhyay, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, M. Morris, D. Nguyen, J. Pekkanen, S. Rappoccio, H. Rejeb Sfar, A. Williams

Northeastern University, Boston, Massachusetts, USA
G. Alverson, E. Barberis, Y. Haddad, Y. Han, A. Krishna, J. Li, M. Lu, G. Madigan, B. Marzocchi, D.M. Morse, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari, A. Tishelman-Charny, B. Wang, D. Wood

Northwestern University, Evanston, Illinois, USA

S. Bhattacharya, J. Bueghly, Z. Chen, K.A. Hahn, Y. Liu, Y. Miao, D.G. Monk, M.H. Schmitt, A. Taliercio, M. Velasco

University of Notre Dame, Notre Dame, Indiana, USA
R. Band, R. Bucci, S. Castells, M. Cremonesi, A. Das, R. Goldouzian, M. Hildreth, K.W. Ho, K. Hurtado Anampa, C. Jessop, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, K. Mohrman, C. Moore, Y. Musienko[13], H. Nelson, M. Osherson, R. Ruchti, A. Townsend, M. Wayne, H. Yockey, M. Zarucki, L. Zygala

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

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

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

Purdue University, West Lafayette, Indiana, USA
A.S. Bakshi, V.E. Barnes, S. Chandra, R. Chawla, S. Das, A. Gu, L. Gutay, M. Jones, A.W. Jung, D. Kondratyev, A.M. Koshy, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, A. Purohit, J.F. Schulte, M. Stojanovic[17], J. Thieman, A. K. Virdi, F. Wang, W. Xie

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

Rice University, Houston, Texas, USA
D. Acosta, A. Baty, T. Carnahan, S. Dildick, K.M. Ecklund, P.J. Fernández Manteca, S. Freed, P. Gardner, F.J.M. Geurts, A. Kumar, W. Li, O. Miguel Colin, B.P. Padley, R. Redjimi, J. Rotter, E. Yigitbasi, Y. Zhang

University of Rochester, Rochester, New York, USA
A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, P. Parygin, E. Popova, R. Taus, G.P. Van Onsem

The Rockefeller University, New York, New York, USA
K. Goulianos

Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
B. Chiarito, J.P. Chou, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, D. Jaroslawski, O. Karacheban[26], I. Laflotte, A. Lath, R. Montalvo, K. Nash, H. Routray, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, J. Vora, H. Wang

University of Tennessee, Knoxville, Tennessee, USA
H. Acharya, A.G. Delannoy, S. Fiorendi, T. Holmes, N. Karunarathna, L. Lee, E. Nibigira, S. Spanier

Texas A&M University, College Station, Texas, USA

D. Aebi, M. Ahmad, O. Bouhali[93], M. Dalchenko, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[94], H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, Texas, USA
N. Akchurin, J. Damgov, V. Hegde, A. Hussain, Y. Kazhykarim, K. Lamichhane, S.W. Lee, A. Mankel, T. Mengke, S. Muthumuni, T. Peltola, I. Volobouev, A. Whitbeck

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

University of Virginia, Charlottesville, Virginia, USA
B. Cardwell, B. Cox, J. Hakala, R. Hirosky, A. Ledovskoy, A. Li, C. Neu, C.E. Perez Lara

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

University of Wisconsin - Madison, Madison, Wisconsin, USA
A. Aravind, S. Banerjee, K. Black, T. Bose, S. Dasu, I. De Bruyn, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Herve, C.K. Koraka, A. Lanaro, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, A. Mohammadi, S. Mondal, G. Parida, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, H.F. Tsoi, W. Vetens, A. Warden

Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN
S. Afanasiev, V. Andreev, Yu. Andreev, T. Aushev, M. Azarkin, A. Babaev, A. Belyaev, V. Blinov[95], E. Boos, V. Borshch, D. Budkouski, V. Bunichev, V. Chekhovsky, R. Chistov[95], M. Danilov[95], A. Dermenev, T. Dimova[95], D. Druzhkin[96], M. Dubinin[86], L. Dudko, A. Ershov, G. Gavrilov, V. Gavrilov, S. Gninenko, V. Golovtcov, N. Golubev, I. Golutvin, I. Gorbunov, A. Gribushin, Y. Ivanov, V. Kachanov, L. Kardapoltsev[95], V. Karjavine, A. Karneyeu, V. Kim[95], M. Kirakosyan, D. Kirpichnikov, M. Kirsanov, V. Klyukhin, O. Kodolova[97], D. Konstantinov, V. Korenkov, A. Kozyrev[95], N. Krasnikov, A. Lanev, P. Levchenko[98], N. Lychkovskaya, V. Makarenko, A. Malakhov, V. Matveev[95,99], V. Murzin, A. Nikitenko[100,97], S. Obraztsov, V. Oreshkin, A. Oskin, V. Palichik, V. Perelygin, S. Polikarpov[95], V. Popov, O. Radchenko[95], M. Savina, V. Savrin, D. Selivanova, V. Shalaev, S. Shmatov, S. Shulha, Y. Skovpen[95], S. Slabospitskii, V. Smirnov, A. Snigirev, D. Sosnov, V. Sulimov, E. Tcherniaev, A. Terkulov, O. Teryaev, I. Tlisova, A. Toropin, L. Uvarov, A. Uzunian, A. Vorobyev[†], N. Voytishin, B.S. Yuldashev[101], A. Zarubin, I. Zhizhin, A. Zhokin

†: Deceased
[1]Also at Yerevan State University, Yerevan, Armenia
[2]Also at TU Wien, Vienna, Austria
[3]Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt
[4]Also at Ghent University, Ghent, Belgium
[5]Also at Universidade Estadual de Campinas, Campinas, Brazil
[6]Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

[7]Also at UFMS, Nova Andradina, Brazil
[8]Also at Nanjing Normal University, Nanjing, China
[9]Now at The University of Iowa, Iowa City, Iowa, USA
[10]Also at University of Chinese Academy of Sciences, Beijing, China
[11]Also at University of Chinese Academy of Sciences, Beijing, China
[12]Also at Université Libre de Bruxelles, Bruxelles, Belgium
[13]Also at an institute or an international laboratory covered by a cooperation agreement with CERN
[14]Also at Suez University, Suez, Egypt
[15]Now at British University in Egypt, Cairo, Egypt
[16]Also at Birla Institute of Technology, Mesra, Mesra, India
[17]Also at Purdue University, West Lafayette, Indiana, USA
[18]Also at Université de Haute Alsace, Mulhouse, France
[19]Also at Department of Physics, Tsinghua University, Beijing, China
[20]Also at The University of the State of Amazonas, Manaus, Brazil
[21]Also at Erzincan Binali Yildirim University, Erzincan, Turkey
[22]Also at University of Hamburg, Hamburg, Germany
[23]Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
[24]Also at Isfahan University of Technology, Isfahan, Iran
[25]Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
[26]Also at Brandenburg University of Technology, Cottbus, Germany
[27]Also at Forschungszentrum Jülich, Juelich, Germany
[28]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
[29]Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
[30]Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
[31]Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
[32]Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
[33]Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
[34]Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary
[35]Also at Punjab Agricultural University, Ludhiana, India
[36]Also at UPES - University of Petroleum and Energy Studies, Dehradun, India
[37]Also at University of Visva-Bharati, Santiniketan, India
[38]Also at University of Hyderabad, Hyderabad, India
[39]Also at Indian Institute of Science (IISc), Bangalore, India
[40]Also at IIT Bhubaneswar, Bhubaneswar, India
[41]Also at Institute of Physics, Bhubaneswar, India
[42]Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
[43]Now at Department of Physics, Isfahan University of Technology, Isfahan, Iran
[44]Also at Sharif University of Technology, Tehran, Iran
[45]Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
[46]Also at 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 Università di Napoli 'Federico II', Napoli, Italy

[53]Also at Ain Shams University, Cairo, Egypt
[54]Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
[55]Also at Riga Technical University, Riga, Latvia
[56]Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
[57]Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
[58]Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
[59]Also at Saegis Campus, Nugegoda, Sri Lanka
[60]Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
[61]Also at National and Kapodistrian University of Athens, Athens, Greece
[62]Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
[63]Also at Universität Zürich, Zurich, Switzerland
[64]Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
[65]Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
[66]Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
[67]Also at Konya Technical University, Konya, Turkey
[68]Also at Izmir Bakircay University, Izmir, Turkey
[69]Also at Adiyaman University, Adiyaman, Turkey
[70]Also at Necmettin Erbakan University, Konya, Turkey
[71]Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
[72]Also at Marmara University, Istanbul, Turkey
[73]Also at Milli Savunma University, Istanbul, Turkey
[74]Also at Kafkas University, Kars, Turkey
[75]Also at Hacettepe University, Ankara, Turkey
[76]Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
[77]Also at Ozyegin University, Istanbul, Turkey
[78]Also at Vrije Universiteit Brussel, Brussel, Belgium
[79]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
[80]Also at University of Bristol, Bristol, United Kingdom
[81]Also at IPPP Durham University, Durham, United Kingdom
[82]Also at Monash University, Faculty of Science, Clayton, Australia
[83]Also at Università di Torino, Torino, Italy
[84]Also at Bethel University, St. Paul, Minnesota, USA
[85]Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
[86]Also at California Institute of Technology, Pasadena, California, USA
[87]Also at United States Naval Academy, Annapolis, Maryland, USA
[88]Also at Bingol University, Bingol, Turkey
[89]Also at Georgian Technical University, Tbilisi, Georgia
[90]Also at Sinop University, Sinop, Turkey
[91]Also at Erciyes University, Kayseri, Turkey
[92]Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania
[93]Also at Texas A&M University at Qatar, Doha, Qatar
[94]Also at Kyungpook National University, Daegu, Korea
[95]Also at another institute or international laboratory covered by a cooperation agreement with CERN

[96]Also at Universiteit Antwerpen, Antwerpen, Belgium
[97]Also at Yerevan Physics Institute, Yerevan, Armenia
[98]Also at Northeastern University, Boston, Massachusetts, USA
[99]Now at another institute or international laboratory covered by a cooperation agreement with CERN
[100]Also at Imperial College, London, United Kingdom
[101]Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan