EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2024-120
2024/05/21

CMS-BPH-23-005

Search for CP violation in $D^0 \to K^0_S K^0_S$ decays in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

Abstract

A search is reported for charge-parity CP violation in $D^0 \to K^0_S K^0_S$ decays, using data collected in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ recorded by the CMS experiment in 2018. The analysis uses a dedicated data set that corresponds to an integrated luminosity of $41.6\,\text{fb}^{-1}$, which consists of about 10 billion events containing a pair of b hadrons, nearly all of which decay to charm hadrons. The flavor of the neutral D meson is determined by the pion charge in the reconstructed decays $D^{*+} \to D^0\pi^+$ and $D^{*-} \to \overline{D}^0\pi^-$. The CP asymmetry in $D^0 \to K^0_S K^0_S$ is measured to be $A_{CP}(K^0_S K^0_S) = (6.2 \pm 3.0 \pm 0.2 \pm 0.8)\%$, where the three uncertainties represent the statistical uncertainty, the systematic uncertainty, and the uncertainty in the measurement of the CP asymmetry in the $D^0 \to K^0_S\pi^+\pi^-$ decay. This is the first CP asymmetry measurement by CMS in the charm sector as well as the first to utilize a fully hadronic final state.

Submitted to the European Physical Journal C

*See Appendix B for the list of collaboration members

1 Introduction

The noninvariance of fundamental interactions under the combined charge-parity (CP) transformation is one of the necessary conditions for the generation of the observed baryon asymmetry in the universe [1]. In the standard model (SM), the CP symmetry violation originates from a single phase in the Cabibbo–Kobayashi–Maskawa (CKM) quark mixing matrix [2, 3]. Extensive studies of CP violation in weak interaction decays of strange and beauty mesons have been performed by many experiments, with all results to date being consistent with the predictions based on the CKM formalism [4]. However, the magnitude of CP violation in the SM appears to be insufficient to explain the matter-antimatter asymmetry observed in the universe [5–7], suggesting the existence of sources of CP violation beyond the SM. Charmed meson decays are the only meson decays involving an up-type quark where CP violation can be studied, and are complementary to strange and beauty meson decays. In contrast to the K and B systems, CP violation in charm mesons is severely suppressed by the Glashow–Iliopoulos–Maiani mechanism [8] and by the magnitude of the CKM elements [3]. Given the strong SM suppression, an observation of a significant CP violation in D meson decays may indicate a contribution from new physics, which can be different from those relevant for down-type quark systems. The first observation of CP violation in charm decays was recently reported by the LHCb Collaboration in a measurement of the CP asymmetry (A_{CP}) difference between the $\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-$ and $\mathrm{D}^0 \to \pi^+\pi^-$ decays [9]. However, determining if this (or other) measurements of CP violation is an indication of new physics is hampered by large theoretical uncertainties associated with long-distance contributions and nonperturbative effects [10].

The $\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$ decay proceeds through the W boson exchange and penguin annihilation Feynman diagrams, some examples of which are shown in Fig. 1, which results in a relatively small branching fraction of $(1.41 \pm 0.05) \times 10^{-4}$ [4]. In this figure and throughout this paper, charge-conjugate states are implied, unless otherwise indicated. Theoretical predictions indicate similar amplitudes and different phases for the two diagrams, which can result in CP violation in this channel as large as a few percent [11–15] and therefore possibly within reach of current experiments.

The CP asymmetry A_{CP}, for the $\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$ decay, is defined as

$$A_{CP}(\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}) = \frac{\Gamma(\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}) - \Gamma(\overline{\mathrm{D}}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S})}{\Gamma(\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}) + \Gamma(\overline{\mathrm{D}}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S})}. \tag{1}$$

The current world average for the time-integrated CP asymmetry is $A_{CP}(\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}) = (-1.9 \pm 1.1)\,\%$ [4], which is dominated by results from the LHCb [16] and Belle [17] Collaborations.

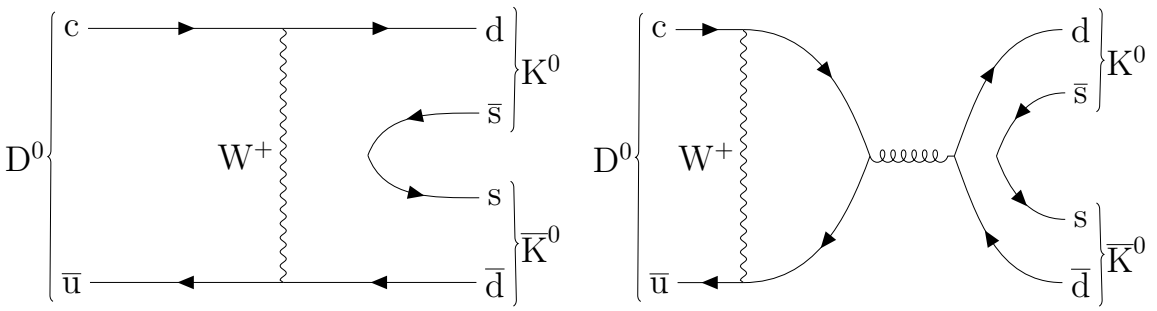

Figure 1: The decay of neutral charm meson to two neutral kaons: exchange (left) and penguin annihilation (right) diagrams.

This paper presents the first CP violation measurement by the CMS experiment in the charm sector. The flavor of the neutral D meson is determined from the pion charge found from reconstructing the decays $\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+$ and $\mathrm{D}^{*-} \to \overline{\mathrm{D}}^0\pi^-$. We measure the CP asymmetry difference, ΔA_{CP}, between the signal channel $\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$ and the reference channel $\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\pi^+\pi^-$. The $\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\pi^+\pi^-$ CP asymmetry has been previously measured [18] and found to be consistent with zero, as expected since this decay is not CKM-suppressed. Therefore, a significant deviation of ΔA_{CP} from 0 would indicate CP violation in the $\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$ decay.

In proton-proton (pp) collision data, the number of D^{*+} and D^{*-} decays (signal events, N) are measured, where both D^0 and $\overline{\mathrm{D}}^0$ are reconstructed in the $\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$ or $\mathrm{K}^0_\mathrm{S}\pi^+\pi^-$ decay modes. The "raw" asymmetry between these numbers, A_{CP}^{raw} (defined in Eq. (2)), is different from the true asymmetry A_{CP}, due to the slightly different production cross sections (σ) of D^{*+} and D^{*-} mesons, as well as to a possible difference in the detection efficiency (ϵ) between D^{*+} and D^{*-}. Because these three asymmetries are all small, the following relation can be written:

$$
\begin{aligned}
A_{CP} \approx & A_{CP}^{\mathrm{raw}} - A_{CP}^{\mathrm{pro}} - A_{CP}^{\mathrm{det}}, \quad \text{where} \\
A_{CP}^{\mathrm{raw}} = & \frac{N(\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+) - N(\mathrm{D}^{*-} \to \overline{\mathrm{D}}^0\pi^-)}{N(\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+) + N(\mathrm{D}^{*-} \to \overline{\mathrm{D}}^0\pi^-)}, \\
A_{CP}^{\mathrm{pro}} = & \frac{\sigma_{\mathrm{pp}\to\mathrm{D}^{*+}X} - \sigma_{\mathrm{pp}\to\mathrm{D}^{*-}X}}{\sigma_{\mathrm{pp}\to\mathrm{D}^{*+}X} + \sigma_{\mathrm{pp}\to\mathrm{D}^{*-}X}}, \quad \text{and} \\
A_{CP}^{\mathrm{det}} = & \frac{\epsilon(\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+) - \epsilon(\mathrm{D}^{*-} \to \overline{\mathrm{D}}^0\pi^-)}{\epsilon(\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+) + \epsilon(\mathrm{D}^{*-} \to \overline{\mathrm{D}}^0\pi^-)},
\end{aligned}
\tag{2}
$$

where measuring the difference of A_{CP} between the signal and reference channels, A_{CP}^{pro} ($\mathrm{D}^{*\pm}$ production asymmetry) and A_{CP}^{det} ($\mathrm{D}^{*\pm}$ detection asymmetry) cancel out, as they do not depend on the final state ($\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$ or $\mathrm{K}^0_\mathrm{S}\pi^+\pi^-$):

$$
\Delta A_{CP} \equiv A_{CP}(\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}) - A_{CP}(\mathrm{K}^0_\mathrm{S}\pi^+\pi^-) = A_{CP}^{\mathrm{raw}}(\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}) - A_{CP}^{\mathrm{raw}}(\mathrm{K}^0_\mathrm{S}\pi^+\pi^-). \tag{3}
$$

The reference channel was chosen to be as similar as possible in kinematics, topology, and final-state signature to the signal channel, to ensure that the reconstruction efficiency asymmetries cancel in the measured difference of asymmetries, ΔA_{CP}.

The analysis uses proton-proton collisions data recorded by the CMS detector during the CERN LHC Run 2 in 2018, at $\sqrt{s} = 13\,\mathrm{TeV}$. It utilizes the B parking data set [19, 20], collected with a set of single-muon triggers with different minimum thresholds on the muon transverse momentum (p_T) and impact parameter with respect to the beamline. Different triggers were enabled depending on the instantaneous luminosity: as the luminosity decreased, less restrictive triggers were enabled, as allowed by the limited event rate to be processed by the data acquisition system and recorded on tape. The data set contains about 1.2×10^{10} events and corresponds to an integrated luminosity of $41.6\,\mathrm{fb}^{-1}$. More details about this data set can be found in Ref. [19]. These triggers are intended to select events containing a semimuonic decay of a b hadron (or a semimuonic decay of c hadron that originated from a b-hadron decay). Since the trigger requires muons inconsistent with being produced in the primary interaction, most of such muons come from semileptonic decays of beauty hadrons, hence approximately 80% of the events in this sample include b hadrons [19, 20]. As beauty hadrons nearly always decay into charm hadrons, this data set also provides a rich sample of charm decays, making it suitable for CP violation studies in the charm sector.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. The reconstructed decays used by this analysis contain five pions in the final state. Pions are measured by the silicon tracker whose setup during the 2018 LHC running period, when the data used in this paper were recorded, consisted of 1856 silicon pixel [21] and 15 148 silicon strip detector modules. For non-isolated particles with $|\eta| < 3$ and $1 < p_{\mathrm{T}} < 10$ GeV, the track resolutions are typically 1.5% in p_{T} and 20–75 μm in the transverse impact parameter [22].

Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of 4 μs [23]. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and further reduces the event rate before data storage [24].

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [25].

3 Simulated event samples

The simulated event samples used in this analysis are generated with PYTHIA 8.230 [26]. The PYTHIA output is interfaced with EVTGEN [27] 1.3.0, which simulates various b and c hadron decays. The underlying event is also modeled with PYTHIA using the CP5 [28] tune. Final-state photon radiation is modeled with PHOTOS 3.61 [29]. Samples with inclusive decays $\mathrm{B}^{+} \to \mathrm{D}^{*\pm}(\to \mathrm{D}\pi^{\pm})X$, $\mathrm{B}^{0} \to \mathrm{D}^{*\pm}(\to \mathrm{D}\pi^{\pm})X$, and prompt $\mathrm{D}^{*\pm} \to \mathrm{D}\pi^{\pm}$ were generated. The events were then passed through a detailed GEANT4-based simulation [30] of the CMS detector, followed by the trigger and reconstruction algorithms identical to those used for the collision data.

4 Reconstruction of charm meson decays

The reconstruction starts with finding $\mathrm{K}^{0}_{\mathrm{S}} \to \pi^{+}\pi^{-}$ candidates as described in Ref. [31]. The two oppositely-charged pion tracks are fit to a common vertex that is required to have a χ^2 fit probability $P_{\mathrm{vtx}} > 1\%$. The dipion invariant mass must be within 20 MeV of the world average value of the $\mathrm{K}^{0}_{\mathrm{S}}$ meson mass [4], corresponding to approximately three times the mass resolution.

In the signal channel, two $\mathrm{K}^{0}_{\mathrm{S}} \to \pi^{+}\pi^{-}$ candidates are each fit again with kinematic constraints to the $\mathrm{K}^{0}_{\mathrm{S}}$ mass, and subsequently, the $\mathrm{K}^{0}_{\mathrm{S}}$ candidates are fitted as two virtual tracks to a common vertex, assumed to be the $\mathrm{D}^{0} \to \mathrm{K}^{0}_{\mathrm{S}}\mathrm{K}^{0}_{\mathrm{S}}$ decay vertex. The $\mathrm{K}^{0}_{\mathrm{S}}\mathrm{K}^{0}_{\mathrm{S}}$ invariant mass is required to be between 1.77 and 1.95 GeV, and the vertex fit probability must exceed 1%. Both $\mathrm{K}^{0}_{\mathrm{S}}$ decay vertices have to be displaced in three-dimensional (3D) space by at least one standard deviation (s.d.) from the fitted $\mathrm{K}^{0}_{\mathrm{S}}\mathrm{K}^{0}_{\mathrm{S}}$ vertex, and the corresponding pointing angle (the angle between the particle momentum and the vector joining the production vertex with its decay vertex) for each $\mathrm{K}^{0}_{\mathrm{S}}$ candidate is required to be less than 90°.

In the reference channel, after the single K^0_S selection, two additional high-purity [32] and opposite-sign tracks with $p_T > 0.6\,\text{GeV}$ (and at least one of them with $p_T > 0.7\,\text{GeV}$) are selected. The $K^0_S\pi^+\pi^-$ combination is then fit to a common vertex, assumed to be the D^0 decay vertex, which must have a $P_{vtx} > 5\%$, and an invariant mass between 1.823 and 1.908 GeV, assuming charged-pion mass [4] for both tracks, which corresponds to approximately twice the mass resolution.

The primary vertex (PV) is selected from the reconstructed pp interaction vertices as the one with the smallest pointing angle of the D^0 candidate. After the D^0 reconstruction, an additional track is added to form the $D^{*+} \to D^0\pi^+$ or $D^{*-} \to \overline{D}^0\pi^-$ candidates. A two-object vertex fit is performed to reconstruct the $D^{*\pm}$ decay vertex, which is required to have a $P_{vtx} > 1\%$. The D^{*+} candidate invariant mass is determined from the refitted pion and D^0 four-momenta and then corrected by subtracting the difference between the reconstructed D^0 candidate mass and the world-average D^0 mass, to remove the effect of the D^0 detector mass resolution. The candidates are rejected if they are compatible with an incorrect decay topology that assumes negligible decay time of any of the K^0_S candidates.

5 Final selection criteria

A mixture of different triggers with varying thresholds in the data set makes it challenging to properly model the kinematic distributions of charm mesons in the simulation. Therefore, an optimization of the selection criteria is done using the experimental data directly. A two-dimensional (2D) fit to the distribution of $m(D\pi^\pm)$ vs $m(K^0_SK^0_S)$, similar to the one described below, is performed for the data (with the D^{*+} and D^{*-} samples merged) while the selection criteria are varied. The variables used in the optimization include the candidate p_T, η, P_{vtx}, distances between production and decay vertices for K^0_S and D^0 candidates divided by their corresponding uncertainties, and corresponding pointing angles. The optimal criteria were chosen as those which result in the smallest relative uncertainty on the fitted signal yield. Cross-validation was used to ensure there is no bias due to statistical fluctuations in the data, via randomly splitting the data into six equal sub-samples, finding optimal criteria using five of them and applying them to the last part. The procedure is repeated six times (each time leaving out a different part of the full data set) and results in six almost identical sets of selection criteria. The average value for each selection is taken as the final selection criteria, presented in Table 1.

Similar selection criteria are applied to the reference channel, to minimize the differences in kinematic distributions between the signal and the reference channels: the only adjustment is that the scalar sum of the p_T of the two pions that are not from the K^0_S decay in the reference channel must exceed 1 GeV and the single K^0_S candidate in the reference channel must satisfy the requirements applied to the high-p_T K^0_S candidate in the signal channel.

6 A_{CP} measurement: reference channel

The signal and reference channels are found to have consistent η distributions, but slightly different $p_T(D^{*\pm})$ ones, and thus the detection and production asymmetries may not cancel out fully in the ΔA_{CP} measurement. In order to suppress this effect, the reference channel data are reweighted to match the $p_T(D^{*\pm})$ distribution found in the signal channel, before splitting the samples by the pion charge.

To extract the raw CP asymmetry, a simultaneous binned extended maximum likelihood fit is

Table 1: Optimized selection criteria in the signal channel $K^0_S K^0_S$. The requirements on the K^0_S candidates in the third and fourth lines are given first for the K^0_S with larger p_T, then for the K^0_S with lower p_T.

Variable	Requirement
$\|\eta\|$ of the tagging pion from $D^{*\pm} \to D\pi^\pm$	<1.2
p_T of the tagging pion from $D^{*\pm} \to D\pi^\pm$	>0.35 GeV
$p_T(K^0_S)$	>2.2 and >1.0 GeV
K^0_S vertex displacement significance from the D^0 vertex in xyz	>7 and >9
D^0 vertex displacement significance from the PV in xy	>2
D^0 vertex displacement significance from the PV in xyz	>9
$P_{vtx}(D\pi^\pm)$	$>5\%$
$P_{vtx}(K^0_S K^0_S)$	$>1\%$
$P_{vtx}(\pi^+\pi^-)$ for $K^0_S \to \pi^+\pi^-$	$>1\%$
Angle between D^0 momentum and displacement from PV in xyz	<0.205 rad
Angle between D^0 momentum and displacement from PV in xy	<0.237 rad
Angle between D^0 momentum and displacement from beamline in xy	<0.237 rad

performed on the invariant mass distributions $m(D\pi^\pm)$ of weighted D^{*+} and D^{*-} candidates. The signal in $x = m(D\pi^\pm)$ is fitted with the S_U Johnson transformation of the normal distribution [33], with the shape parameters shared between the D^{*+} and D^{*-} components while the signal yields are independent. The background is modeled with a modified threshold function $(x - x_0)^\alpha(1 + ax)$, where x_0 is the threshold value equal to the sum of the masses of D^0 and π^+, and α and a are floated in the fit and they are not shared between the D^{*+} and the D^{*-} background model. The results of the fit to the $m(D\pi^\pm)$ distributions are presented in Fig. 2 and Table 2. The measured raw asymmetry is $A^{raw}_{CP}(K^0_S\pi^+\pi^-) = (0.78 \pm 0.10)\%$, where the uncertainty is statistical only and accounts for the correlations found in the simultaneous fit.

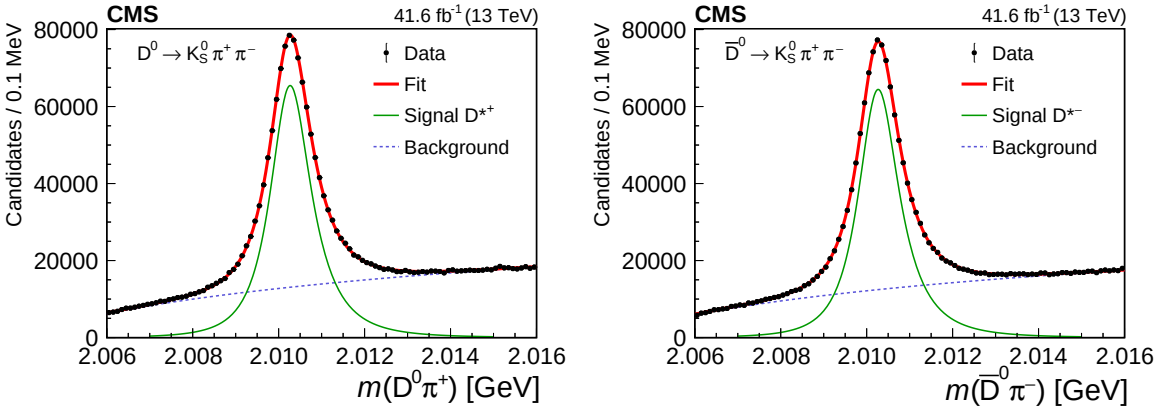

Figure 2: The $D^0\pi^+$ (left) and $\overline{D}^0\pi^-$ (right) invariant mass distributions for the $K^0_S\pi^+\pi^-$ channel, with the result of the fit to both distributions.

7 A_{CP} measurement: signal channel

To reduce the statistical uncertainty arising from the signal channel yield, which is the dominant uncertainty in the analysis, the signal extraction is performed using a 2D unbinned maximum likelihood fit performed simultaneously on the D^{*+} and D^{*-} samples to the distribution of $m(D\pi^\pm)$ *vs.* $m(K^0_S K^0_S)$. The fit function consists of the following components:

Table 2: Results of the fit to the selected $D^{*+} \to D^0\pi^+$ and $D^{*-} \to \overline{D}^0\pi^-$ candidates, where $D^0\,(\overline{D}^0) \to K^0_S\pi^+\pi^-$. The $D^{*\pm}$ signal yields N given in the second column are used in the evaluation of $A_{CP}^{\rm raw}$. The uncertainties are statistical only.

Decay	N	χ^2 with 100 bins
$D^{*+} \to D^0\pi^+$	$944\,800 \pm 3\,500$	78
$D^{*-} \to \overline{D}^0\pi^-$	$930\,150 \pm 3\,400$	93

- $D^0 \times D^{*+}$, the signal component;
- $D^0 \times bkg$, for events containing genuine D^0 and background pion combinations;
- $bkg \times bkg$, for the background in both dimensions,

where each component is a product of two one-dimensional (1D) functions. For the $D^{*\pm}$ signal, the Johnson function is used with all signal shape parameters fixed to those found in the fit to the reference channel. This approach is verified to be reasonable using simulated event samples. The D^0 signal is modeled with a sum of two Johnson functions, all parameters of which are fixed to values determined from the simulation, except for a single free parameter that is used to scale the width. The background in $x = m(D\pi^\pm)$ is modeled with the same function as in the reference channel. The background in $y = m(K^0_SK^0_S)$ is described with an exponential function $\exp(\beta y)$, where β is floating in the fit, plus a Gaussian function with free parameters to describe the partially-reconstructed background from the $D^\pm_s \to K^0_SK^0_S\pi^\pm$ decay producing an excess at about 1.83 GeV in the $K^0_SK^0_S$ invariant mass distribution.

The projections of the data and the 2D fit on both axes are shown in Fig. 3; additional projections in sub-ranges are shown in Appendix A. The fit results are listed in Table 3. The measured raw asymmetry is $A_{CP}^{\rm raw}(K^0_SK^0_S) = (7.1 \pm 3.0)\%$ and in combination with the results of Section 6 the A_{CP} difference is measured to be $\Delta A_{CP} = (6.3 \pm 3.0)\%$, where the uncertainty is statistical only and accounts for the correlations found in the simultaneous fit.

Table 3: Results of the 2D fit to the selected $D^{*+} \to D^0\pi^+$ and $D^{*-} \to \overline{D}^0\pi^-$ candidates, where $D^0\,(\overline{D}^0) \to K^0_SK^0_S$. The $D^{*\pm}$ signal yields N given in the second column are used in the evaluation of $A_{CP}^{\rm raw}$. The χ^2 corresponds to the fit projection with 100 bins in the $x = m(D\pi^\pm)$ axis and 90 bins in the $y = m(K^0_SK^0_S)$ axis, as shown in Fig 3. The uncertainties are statistical only.

Decay	N	χ^2 (x axis)	χ^2 (y axis)
$D^{*+} \to D^0\pi^+$	1095 ± 46	77	90
$D^{*-} \to \overline{D}^0\pi^-$	951 ± 44	93	62

8 Systematic uncertainties

The measured difference in the asymmetries is largely insensitive to many systematic uncertainties that would affect a measurement of A_{CP} in a single channel, such as the difficult-to-measure production and detection asymmetries that would need a dedicated calibration procedure.

Uncertainties related to the choice of the signal and background models are calculated separately using alternative models and assessing the observed variations in ΔA_{CP}.

In the baseline approach, the signal in the $m(D\pi^\pm)$ invariant mass distribution is modeled with the Johnson function [33]. As an alternative, we use a Johnson+Gaussian function with a

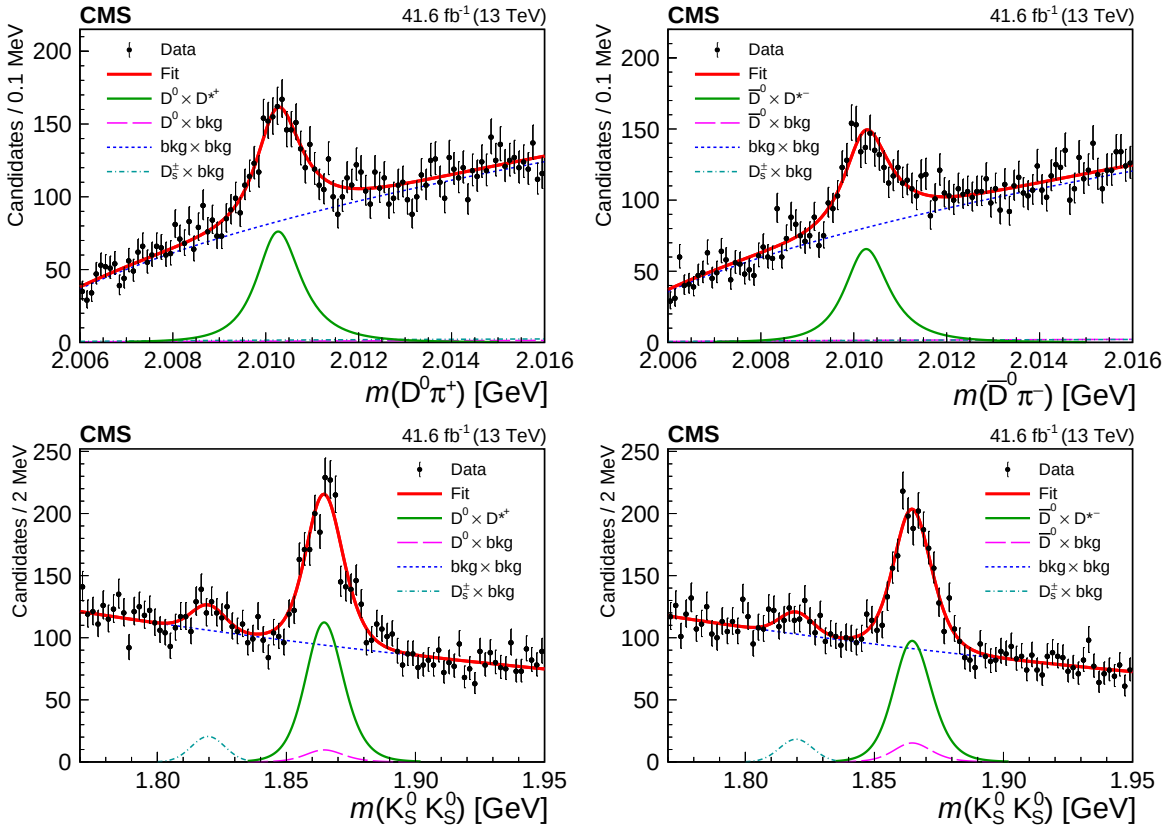

Figure 3: The invariant mass distributions for D^{*+} candidates (left) and D^{*-} candidates (right), with the $m(\mathrm{D}\pi^{\pm})$ distributions in the upper row and the $m(\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S})$ distributions in the lower row. Projections of the simultaneous 2D fit are also shown.

common mean. Another alternative is a sum of two Crystal Ball functions [34]. For each case, the reference channel is fit as a first step, then the obtained shape parameters are fixed in the 2D fit to the signal channel. Other components of the 2D fit remain unchanged from the baseline fit. The largest deviation in ΔA_{CP} from the baseline value is taken as a systematic uncertainty.

The baseline signal function for the $m(\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S})$ invariant mass distribution is a sum of two Johnson functions. As an alternative, we use a Johnson+Gaussian function or a sum of two Crystal Ball functions. These variations have no effect on the fit of the reference channel, just on that of the signal channel. The largest deviation in ΔA_{CP} from the baseline value is taken as a systematic uncertainty.

The baseline background model in the $x = m(\mathrm{D}\pi^{\pm})$ distribution is $(x - x_0)^{\alpha}(1 + ax)$. An alternative background model is obtained by changing the function multiplying the threshold function from a linear polynomial to an exponential function. The baseline background model in the $m(\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S})$ distribution is an exponential function and an exponential multiplied by a linear polynomial is used as an alternative. These variations are taken as independent systematic uncertainties.

In the signal channel fit, there is a contribution from the $\mathrm{D}^{\pm}_\mathrm{s} \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}\pi^{\pm}$ decay, which is modeled by a Gaussian with free parameters. As an alternative, we remove this reflection by restricting the fit range to be $m(\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}) > 1.835\,\mathrm{GeV}$, and the deviation from the baseline is included as a systematic uncertainty.

To assess the systematic uncertainty related to the p_T reweighting, we vary the parameters of

the reweighting function within their uncertainties. As an alternative, we consider the weights depending on the p_{T} of the low-momentum pion that is used for the flavor tagging instead of $p_{\mathrm{T}}(\mathrm{D}^{*\pm})$. The largest change is taken as a systematic uncertainty related to the reweighting.

The value of ΔA_{CP} was calculated from simulated events, where its input value is zero. Both p_{T}- and η-dependent asymmetries, as well as the integrated value of $(-0.13 \pm 0.34)\%$, and therefore no systematic uncertainty is assessed.

If multiple candidates in the same event are removed by keeping only the one with the highest $\mathrm{D}^{*\pm}$ vertex fit probability, the resulting ΔA_{CP} changes negligibly and no corresponding systematic uncertainty is assigned. Pion charge misidentification was shown to have a negligible effect as well.

All systematic uncertainties described above are uncorrelated and summarized in Table 4 together with the total systematic uncertainty, calculated as the sum in quadrature of the different contributions.

Table 4: Absolute systematic uncertainties in the measurement of ΔA_{CP}.

Source	Uncertainty (%)
$m(\mathrm{D}\pi^{\pm})$ signal model	0.10
$m(\mathrm{D}\pi^{\pm})$ background model	0.02
$m(\mathrm{K^0_S K^0_S})$ signal model	0.04
$m(\mathrm{K^0_S K^0_S})$ background model	0.02
$m(\mathrm{K^0_S K^0_S})$ fit range	0.06
Reweighting	0.09
Total	0.16

9 Summary

A measurement of CP violation in D^0 decays is reported, using proton-proton collision data collected at $\sqrt{s} = 13\,\mathrm{TeV}$ with a novel high-rate data stream (B parking). These data correspond to an integrated luminosity of $41.6\,\mathrm{fb}^{-1}$ and include about 10 billion events containing beauty hadron decays. The difference in the CP asymmetries between $\mathrm{D}^0 \to \mathrm{K^0_S K^0_S}$ and $\mathrm{D}^0 \to \mathrm{K^0_S}\pi^+\pi^-$ is measured to be:

$$\Delta A_{CP} \equiv A_{CP}(\mathrm{K^0_S K^0_S}) - A_{CP}(\mathrm{K^0_S}\pi^+\pi^-) = (6.3 \pm 3.0\,(\mathrm{stat}) \pm 0.2\,(\mathrm{syst}))\,\%. \tag{4}$$

Using the world-average value of $A_{CP}(\mathrm{K^0_S}\pi^+\pi^-) = (-0.1 \pm 0.8)\%$ [4, 18, 35], we report the measurement

$$A_{CP}(\mathrm{K^0_S K^0_S}) = (6.2 \pm 3.0 \pm 0.2 \pm 0.8)\%, \tag{5}$$

where the three uncertainties represent the statistical uncertainty, the systematic uncertainty, and the uncertainty in the measurement of the CP asymmetry in the $\mathrm{D}^0 \to \mathrm{K^0_S}\pi^+\pi^-$ decay. The measured value is consistent with no CP violation within 2.0 standard deviations. Likewise, it is consistent with the LHCb [16] and the Belle measurements [17] at the level of 2.7 and 1.8 standard deviations, respectively. Tabulated results are provided in the HEPData record for this analysis [36]. This is the first CMS search for CP violation in the charm sector, paving the way for future measurements with more data, using new techniques, and in other channels.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: SC (Armenia), BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); ERC PRG, RVTT3 and MoER TK202 (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); SRNSF (Georgia); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LMTLT (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, 101115353, 101002207, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Science Committee, project no. 22rl-037 (Armenia); the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science – EOS" – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010 and Fundamental Research Funds for the Central Universities (China); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Shota Rustaveli National Science Foundation, grant FR-22-985 (Georgia); the Deutsche Forschungsgemeinschaft (DFG), under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306, and under project number 400140256 - GRK2497; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Hungarian Academy of Sciences, the New National Excellence Program - ÚNKP, the NKFIH research grants K 131991, K 133046, K 138136, K 143460, K 143477, K 146913, K 146914, K 147048, 2020-2.2.1-ED-2021-00181, and TKP2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India; ICSC – National Research Center for High Performance Computing, Big Data and Quantum Computing and FAIR – Future Artificial Intelligence Research, funded by the NextGenerationEU program (Italy); the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369 and 2021/43/B/ST2/01552 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MCIN/AEI/10.13039/501100011033, ERDF "a way of making Europe", and the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias

(Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, and the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B37G660013 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

[1] A. D. Sakharov, "Violation of CP invariance, C asymmetry, and baryon asymmetry of the universe", *Pisma Zh. Eksp. Teor. Fiz.* **5** (1967) 32, doi:10.1070/PU1991v034n05ABEH002497.

[2] N. Cabibbo et al., "Unitary symmetry and leptonic decays", *Phys. Rev. Lett.* **10** (1963) 531, doi:10.1103/PhysRevLett.10.531.

[3] M. Kobayashi and T. Maskawa, "CP-violation in the renormalizable theory of weak interaction", *Prog. Theor. Phys.* **49** (1973) 652, doi:10.1143/PTP.49.652.

[4] Particle Data Group, "Review of particle physics", *PTEP* **2022** (2022) 083C01, doi:10.1093/ptep/ptac097.

[5] A. G. Cohen, D. B. Kaplan, and A. E. Nelson, "Progress in electroweak baryogenesis", *Ann. Rev. Nucl. Part. Sci.* **43** (1993) 27, doi:10.1146/annurev.ns.43.120193.000331, arXiv:hep-ph/9302210.

[6] A. Riotto and M. Trodden, "Recent progress in baryogenesis", *Ann. Rev. Nucl. Part. Sci.* **49** (1999) 35, doi:10.1146/annurev.nucl.49.1.35, arXiv:hep-ph/9901362.

[7] W.-S. Hou, "Source of CP violation for the baryon asymmetry of the Universe", *Chin. J. Phys.* **47** (2009) 134, arXiv:0803.1234.

[8] S. L. Glashow, J. Iliopoulos, and L. Maiani, "Weak interactions with lepton-hadron symmetry", *Phys. Rev. D* **2** (1970) 1285, doi:10.1103/PhysRevD.2.1285.

[9] LHCb Collaboration, "Observation of CP violation in charm decays", *Phys. Rev. Lett.* **122** (2019) 211803, doi:10.1103/PhysRevLett.122.211803, arXiv:1903.08726.

[10] A. Lenz and G. Wilkinson, "Mixing and CP violation in the charm system", *Ann. Rev. Nucl. Part. Sci.* **71** (2021) 59, doi:10.1146/annurev-nucl-102419-124613, arXiv:2011.04443.

[11] U. Nierste and S. Schacht, "CP violation in $D^0 \to K_S K_S$", *Phys. Rev. D* **92** (2015) 054036, doi:10.1103/PhysRevD.92.054036, arXiv:1508.00074.

[12] H.-n. Li, C.-D. Lu, and F.-S. Yu, "Branching ratios and direct CP asymmetries in $D \to PP$ decays", *Phys. Rev. D* **86** (2012) 036012, doi:10.1103/PhysRevD.86.036012, arXiv:1203.3120.

[13] H.-Y. Cheng and C.-W. Chiang, "Revisiting CP violation in $D \to PP$ and VP decays", *Phys. Rev. D* **100** (2019) 093002, doi:10.1103/PhysRevD.100.093002, arXiv:1909.03063.

[14] F. Buccella, A. Paul, and P. Santorelli, "$SU(3)_F$ breaking through final state interactions and CP asymmetries in $D \to PP$ decays", *Phys. Rev. D* **99** (2019) 113001, doi:10.1103/PhysRevD.99.113001, arXiv:1902.05564.

[15] J. Brod, A. L. Kagan, and J. Zupan, "Size of direct CP violation in singly Cabibbo-suppressed D decays", *Phys. Rev. D* **86** (2012) 014023, doi:10.1103/PhysRevD.86.014023, arXiv:1111.5000.

[16] LHCb Collaboration, "Measurement of CP asymmetry in $D^0 \to K^0_S K^0_S$ decays", *Phys. Rev. D* **104** (2021) L031102, doi:10.1103/PhysRevD.104.L031102, arXiv:2105.01565.

[17] Belle Collaboration, "Search for CP violation and measurement of the branching fraction in the decay $D^0 \to K^0_S K^0_S$", *Phys. Rev. Lett.* **119** (2017) 171801, doi:10.1103/PhysRevLett.119.171801, arXiv:1705.05966.

[18] CDF Collaboration, "Measurement of CP-violation asymmetries in $D^0 \to K^0_S \pi^+ \pi^-$", *Phys. Rev. D* **86** (2012) 032007, doi:10.1103/PhysRevD.86.032007, arXiv:1207.0825.

[19] CMS Collaboration, "Test of lepton flavor universality in $\mathrm{B}^\pm \to \mathrm{K}^\pm \mu^+ \mu^-$ and $\mathrm{B}^\pm \to \mathrm{K}^\pm \mathrm{e}^+ \mathrm{e}^-$ decays in proton-proton collisions at $\sqrt{s} = 13$ TeV", 2024. arXiv:2401.07090. Submitted to *Phys. Rep.*

[20] CMS Collaboration, "Enriching the physics program of the CMS experiment via data scouting and data parking", 2024. arXiv:2403.16134. Submitted to *Phys. Rep.*

[21] CMS Tracker Group Collaboration, "The CMS Phase-1 pixel detector upgrade", *JINST* **16** (2021) P02027, doi:10.1088/1748-0221/16/02/P02027, arXiv:2012.14304.

[22] CMS Collaboration, "Track impact parameter resolution for the full pseudo rapidity coverage in the 2017 dataset with the CMS Phase-1 pixel detector", CMS Detector Performance Note CMS-DP-2020-049, 2020.

[23] CMS Collaboration, "Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$", *JINST* **15** (2020) P10017, doi:10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.

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

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

[26] T. Sjöstrand et al., "An introduction to PYTHIA 8.2", *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.

[27] D. J. Lange, "The EvtGen particle decay simulation package", *Nucl. Instrum. Meth. A* **462** (2001) 152, doi:10.1016/S0168-9002(01)00089-4.

[28] CMS Collaboration, "Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements", *Eur. Phys. J. C* **80** (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.

[29] E. Barberio and Z. Wąs, "PHOTOS — a universal Monte Carlo for QED radiative corrections: version 2.0", *Comput. Phys. Commun.* **79** (1994) 291, doi:10.1016/0010-4655(94)90074-4.

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

[31] CMS Collaboration, "CMS tracking performance results from early LHC operation", *Eur. Phys. J. C* **70** (2010) 1165, doi:10.1140/epjc/s10052-010-1491-3, arXiv:1007.1988.

[32] CMS Collaboration, "Description and performance of track and primary-vertex reconstruction with the CMS tracker", *JINST* **9** (2014) P10009, doi:10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.

[33] N. L. Johnson, "Systems of frequency curves generated by methods of translation", *Biometrika* **36** (1949) 149, doi:10.2307/2332539.

[34] M. J. Oreglia, "A study of the reactions $\psi' \to \gamma\gamma\psi$". PhD thesis, Stanford University, 1980. SLAC Report SLAC-R-236.

[35] CLEO Collaboration, "Search for CP violation in $D^0 \to K^0_S\pi^+\pi^-$", *Phys. Rev. D* **70** (2004) 091101, doi:10.1103/PhysRevD.70.091101, arXiv:hep-ex/0311033.

[36] HEPData record for this analysis, 2024. doi:10.17182/hepdata.147012.

A Additional projections of the 2D fit

Figures A.1 and A.2 show the projections of the 2D fit in the signal channel in subranges of the mass variables. The top and middle rows show 1D projections of the 2D fit on $m(\mathrm{D}\pi^{\pm})$ in ranges of $m(\mathrm{K^0_S K^0_S})$: left sideband, region of $\mathrm{D_s^{\pm}} \to \mathrm{K^0_S K^0_S}\pi^{\pm}$ contamination, signal region of $\mathrm{K^0_S K^0_S}$, and right sideband. The lower three plots show 1D projections of the 2D fit on $m(\mathrm{K^0_S K^0_S})$ in ranges of $m(\mathrm{D}\pi^{\pm})$: left sideband, signal region of $\mathrm{D}\pi^{\pm}$, and right sideband.

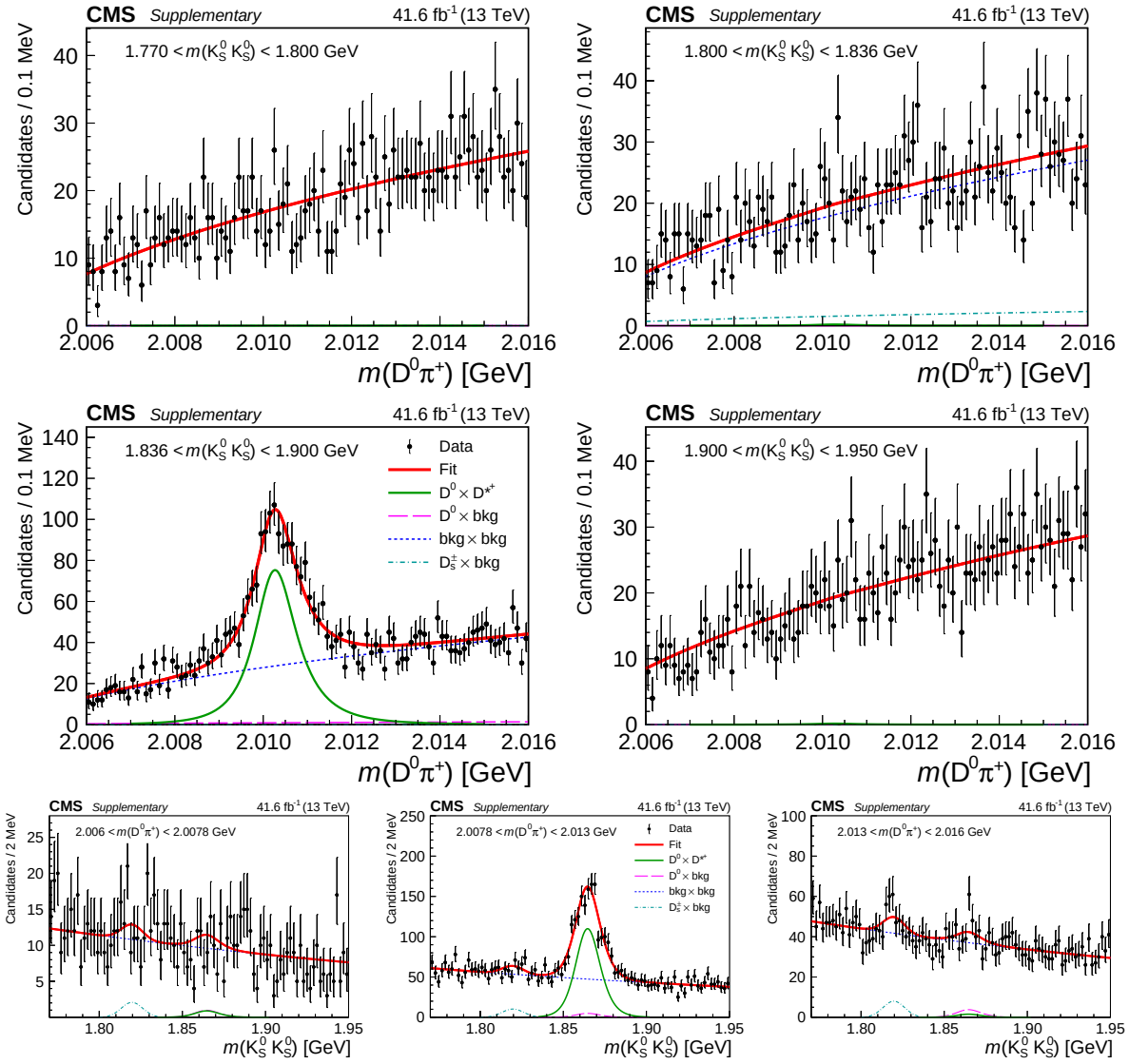

Figure A.1: Results of the 2D fit to the $m(\mathrm{D}\pi^{\pm}) \times m(\mathrm{K^0_S K^0_S})$ for the signal channel, D^{*+} candidates. Upper and middle rows show 1D projections of the 2D fit on $m(\mathrm{D^0}\pi^{+})$ in ranges of $m(\mathrm{K^0_S K^0_S})$: left sideband (upper left), region of $\mathrm{D_s^{\pm}} \to \mathrm{K^0_S K^0_S}\pi^{\pm}$ contamination (upper right), signal region of $\mathrm{K^0_S K^0_S}$ (middle left), and right sideband (middle right). Lower row shows 1D projections of the 2D fit on $m(\mathrm{K^0_S K^0_S})$ in ranges of $m(\mathrm{D^0}\pi^{+})$: left sideband (left), signal region of $\mathrm{D^0}\pi^{+}$ (center), and right sideband (right).

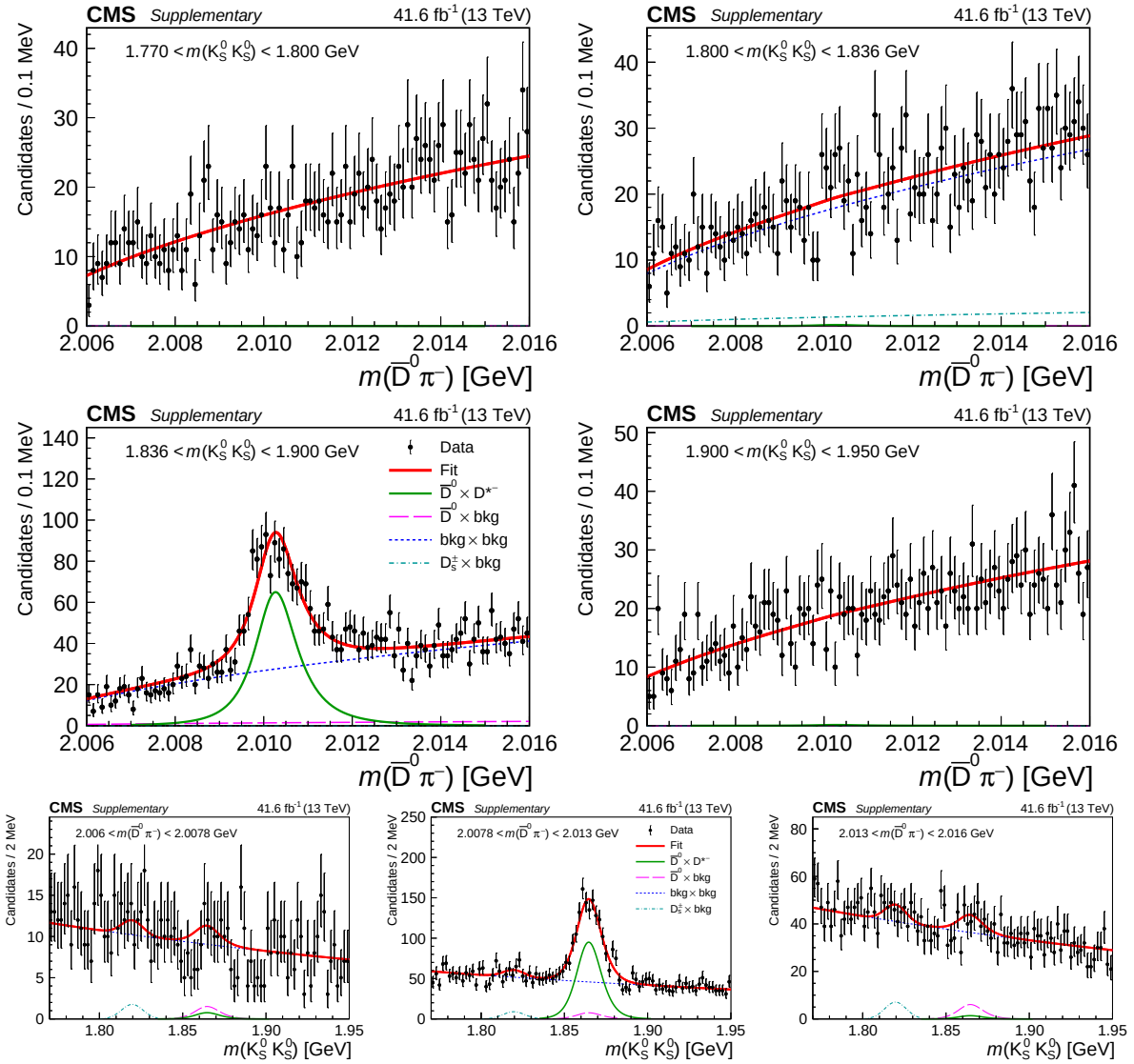

Figure A.2: Results of the 2D fit to the $m(\mathrm{D}\pi^{\pm}) \times m(\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S})$ for the signal channel, D^{*-} candidates. Upper and middle rows show 1D projections of the 2D fit on $m(\overline{\mathrm{D}}^0\pi^-)$ in ranges of $m(\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S})$: left sideband (upper left), region of $\mathrm{D}^{\pm}_\mathrm{s} \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}\pi^{\pm}$ contamination (upper right), signal region of $\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$ (middle left), and right sideband (middle right). Lower row shows 1D projections of the 2D fit on $m(\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S})$ in ranges of $m(\overline{\mathrm{D}}^0\pi^-)$: left sideband (left), signal region of $\overline{\mathrm{D}}^0\pi^-$ (center), and right sideband (right).

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, P.S. Hussain, M. Jeitler[2], N. Krammer, A. Li, 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, T. Van Laer, P. Van Mechelen

Vrije Universiteit Brussel, Brussel, Belgium
N. Breugelmans, J. D'Hondt, S. Dansana, A. De Moor, M. Delcourt, F. Heyen, S. Lowette, I. Makarenko, D. Müller, S. Tavernier, M. Tytgat[4], G.P. Van Onsem, S. Van Putte, D. Vannerom

Université Libre de Bruxelles, Bruxelles, Belgium
B. Bilin, B. Clerbaux, A.K. Das, G. De Lentdecker, H. Evard, L. Favart, P. Gianneios, J. Jaramillo, A. Khalilzadeh, F.A. Khan, K. Lee, M. Mahdavikhorrami, A. Malara, S. Paredes, M.A. Shahzad, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer

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

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

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

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[6], E.M. Da Costa, G.G. Da Silveira[7], D. De Jesus Damiao, S. Fonseca De Souza, R. Gomes De Souza, M. Macedo, J. Martins[8], L. Mundim, H. Nogima, J.P. Pinheiro, A. Santoro, A. Sznajder, M. Thiel

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

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

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

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

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

Department of Physics, Tsinghua University, Beijing, China
Z. Hu, Z. Liang, J. Liu, K. Yi[9,10]

Institute of High Energy Physics, Beijing, China
G.M. Chen[11], H.S. Chen[11], M. Chen[11], F. Iemmi, C.H. Jiang, A. Kapoor[12], H. Liao, Z.-A. Liu[13], R. Sharma[14], J.N. Song[13], J. Tao, C. Wang[11], J. Wang, Z. Wang[11], H. Zhang, J. Zhao

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

Guangdong Provincial Key Laboratory of Nuclear Science and Guangdong-Hong Kong Joint Laboratory of Quantum Matter, South China Normal University, Guangzhou, China
S. Yang

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

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

Nanjing Normal University, Nanjing, China
G. Bauer[15], B. Li, J. Zhang

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

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

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

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

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

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

Institute Rudjer Boskovic, Zagreb, Croatia
P. Bargassa, V. Brigljevic, B.K. Chitroda, D. Ferencek, K. Jakovcic, S. Mishra, A. Starodumov[17], T. Susa

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

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

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

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran[18,19], B. El-mahdy, S. Elgammal[19]

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
K. Ehataht, M. Kadastik, T. Lange, S. Nandan, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

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

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

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

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, M. Kumar, V. Lohezic, J. Malcles, F. Orlandi, L. Portales, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[20], P. Simkina, M. Titov, M. Tornago

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
F. Beaudette, G. Boldrini, P. Busson, A. Cappati, C. Charlot, M. Chiusi, F. Damas, O. Davignon, A. De Wit, I.T. Ehle, B.A. Fontana Santos Alves, S. Ghosh, A. Gilbert, R. Granier de Cassagnac, A. Hakimi, B. Harikrishnan, L. Kalipoliti, G. Liu, M. Nguyen, C. Ochando, R. Salerno, J.B. Sauvan, Y. Sirois, L. Urda Gómez, E. Vernazza, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[21], J. Andrea, D. Apparu, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, S. Falke, U. Goerlach, R. Haeberle, A.-C. Le Bihan, M. Meena, O. Poncet, G. Saha, M.A. Sessini, P. Van Hove, P. Vaucelle

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

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France

D. Amram, S. Beauceron, B. Blancon, G. Boudoul, N. Chanon, D. Contardo, P. Depasse, C. Dozen[22], H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, C. Greenberg, G. Grenier, B. Ille, E. Jourd'huy, I.B. Laktineh, M. Lethuillier, L. Mirabito, S. Perries, A. Purohit, M. Vander Donckt, P. Verdier, J. Xiao

Georgian Technical University, Tbilisi, Georgia
I. Lomidze, T. Toriashvili[23], Z. Tsamalaidze[17]

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
S. Baradia, S. Barman[37], S. Bhattacharya, S. Das Gupta, S. Dutta, S. Dutta, S. Sarkar

Indian Institute of Technology Madras, Madras, India
M.M. Ameen, P.K. Behera, S.C. Behera, S. Chatterjee, G. Dash, P. Jana, P. Kalbhor, S. Kamble, J.R. Komaragiri[38], D. Kumar[38], P.R. Pujahari, N.R. Saha, A. Sharma, A.K. Sikdar, R.K. Singh, P. Verma, S. Verma, A. Vijay

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

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

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

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

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

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Bashiri, S. Chenarani[45], S.M. Etesami, Y. Hosseini, M. Khakzad, E. Khazaie[46], M. Mohammadi Najafabadi, S. Tizchang[47]

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

INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy
M. Abbrescia[a,b], A. Colaleo[a,b], D. Creanza[a,c], B. D'Anzi[a,b], N. De Filippis[a,c], M. De Palma[a,b], W. Elmetenawee[a,b,48], L. Fiore[a], G. Iaselli[a,c], L. Longo[a], M. Louka[a,b], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a], V. Mastrapasqua[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pellecchia[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a,b], D. Ramos[a], A. Ranieri[a], L. Silvestris[a], F.M. Simone[a,c], Ü. Sözbilir[a], A. Stamerra[a,b], D. Troiano[a,b], R. Venditti[a,b], P. Verwilligen[a], A. Zaza[a,b]

INFN Sezione di Bologna[a], Università di Bologna[b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], P. Capiluppi[a,b], A. Castro[†a,b], F.R. Cavallo[a], M. Cuffiani[a,b], G.M. Dallavalle[a], T. Diotalevi[a,b], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a], P. Giacomelli[a], L. Giommi[a,b], C. Grandi[a], L. Guiducci[a,b], S. Lo Meo[a,49], 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,50], A. Di Mattia[a], A. Lapertosa[a], R. Potenza[a,b], A. Tricomi[a,b,50], C. Tuve[a,b]

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

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, S. Meola[51], D. Piccolo

INFN Sezione di Genova[a], Università di Genova[b], Genova, Italy
P. Chatagnon[a], F. Ferro[a], E. Robutti[a], S. Tosi[a,b]

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

INFN Sezione di Napoli[a], Università di Napoli 'Federico II'[b], Napoli, Italy; Università della Basilicata[c], Potenza, Italy; Scuola Superiore Meridionale (SSM)[d], Napoli, Italy
S. Buontempo[a], A. Cagnotta[a,b], F. Carnevali[a,b], N. Cavallo[a,c], F. Fabozzi[a,c], A.O.M. Iorio[a,b], L. Lista[a,b,52], P. Paolucci[a,30]

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,53], M. Bellato[a], P. Bortignon[a], G. Bortolato[a,b], A. Bragagnolo[a,b], A.C.M. Bulla[a], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a], U. Gasparini[a,b], 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], M. Sgaravatto[a], F. Simonetto[a,b], M. Tosi[a,b], A. Triossi[a,b], S. Ventura[a], M. Zanetti[a,b], P. Zotto[a,b], A. Zucchetta[a,b], G. Zumerle[a,b]

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

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

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

INFN Sezione di Torino[a], Università di Torino[b], Torino, Italy; Università del Piemonte Orientale[c], Novara, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a], R. Bellan[a,b], A. Bellora[a,b], C. Biino[a], C. Borca[a,b], N. Cartiglia[a], M. Costa[a,b],

R. Covarelli[a,b], N. Demaria[a], L. Finco[a], M. Grippo[a,b], B. Kiani[a,b], F. Legger[a], F. Luongo[a,b], C. Mariotti[a], L. Markovic[a,b], S. Maselli[a], A. Mecca[a,b], L. Menzio[a,b], P. Meridiani[a], E. Migliore[a,b], M. Monteno[a], R. Mulargia[a], M.M. Obertino[a,b], G. Ortona[a], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], M. Ruspa[a,c], F. Siviero[a,b], V. Sola[a,b], A. Solano[a,b], A. Staiano[a], C. Tarricone[a,b], D. Trocino[a], G. Umoret[a,b], R. White[a,b]

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

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

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

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

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

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

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

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

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

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

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

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

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

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

University of Latvia (LU), Riga, Latvia

N.R. Strautnieks

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

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Yusuff[55], Z. Zolkapli

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

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
G. Ayala, H. Castilla-Valdez, H. Crotte Ledesma, E. De La Cruz-Burelo, I. Heredia-De La Cruz[56], R. Lopez-Fernandez, J. Mejia Guisao, C.A. Mondragon Herrera, A. Sánchez Hernández

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

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

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

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

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

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

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

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

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

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

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

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

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT),

Madrid, Spain
J. Alcaraz Maestre, Cristina F. Bedoya, Oliver M. Carretero, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, D. Fernández Del Val, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, E. Martin Viscasillas, D. Moran, C. M. Morcillo Perez, Á. Navarro Tobar, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, S. Sánchez Navas, J. Sastre, J. Vazquez Escobar

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

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
B. Alvarez Gonzalez, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, P. Leguina, E. Palencia Cortezon, J. Prado Pico, C. Ramón Álvarez, V. Rodríguez Bouza, A. Soto Rodríguez, A. Trapote, C. Vico Villalba, P. Vischia

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

University of Colombo, Colombo, Sri Lanka
B. Kailasapathy[57], D.D.C. Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G.D. Dharmaratna[58], K. Liyanage, N. Perera

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

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

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

T.K. Aarrestad, K. Androsov[60], M. Backhaus, G. Bonomelli, A. Calandri, C. Cazzaniga, K. Datta, P. De Bryas Dexmiers D'archiac[60], A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, M. Galli, K. Gedia, F. Glessgen, C. Grab, N. Härringer, T.G. Harte, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, M. Marchegiani, L. Marchese, C. Martin Perez, A. Mascellani[60], F. Nessi-Tedaldi, F. Pauss, V. Perovic, S. Pigazzini, C. Reissel, B. Ristic, F. Riti, R. Seidita, J. Steggemann[60], A. Tarabini, D. Valsecchi, R. Wallny

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

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

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

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

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

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

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

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

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

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

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

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

University of Bristol, Bristol, United Kingdom

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

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

Imperial College, London, United Kingdom
I. Andreou, R. Bainbridge, P. Bloch, C.E. Brown, O. Buchmuller, V. Cacchio, C.A. Carrillo Montoya, G.S. Chahal[79], D. Colling, J.S. Dancu, I. Das, P. Dauncey, G. Davies, J. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, A. Howard, G. Iles, C.R. Knight, J. Langford, J. León Holgado, L. Lyons, A.-M. Magnan, S. Mallios, M. Mieskolainen, J. Nash[80], M. Pesaresi, P.B. Pradeep, B.C. Radburn-Smith, A. Richards, A. Rose, K. Savva, C. Seez, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, L.H. Vage, T. Virdee[30], M. Vojinovic, N. Wardle, D. Winterbottom

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

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

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

The University of Alabama, Tuscaloosa, Alabama, USA
B. Bam, A. Buchot Perraguin, R. Chudasama, S.I. Cooper, C. Crovella, S.V. Gleyzer, E. Pearson, C.U. Perez, P. Rumerio[81], E. Usai, R. Yi

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

Brown University, Providence, Rhode Island, USA
G. Benelli, D. Cutts, L. Gouskos, M. Hadley, U. Heintz, J.M. Hogan[82], T. Kwon, G. Landsberg, K.T. Lau, D. Li, J. Luo, S. Mondal, N. Pervan, T. Russell, S. Sagir[83], F. Simpson, M. Stamenkovic, N. Venkatasubramanian, X. Yan

University of California, Davis, Davis, California, USA
S. Abbott, C. Brainerd, R. Breedon, H. Cai, M. Calderon De La Barca Sanchez, M. Chertok, M. Citron, J. Conway, P.T. Cox, R. Erbacher, F. Jensen, O. Kukral, G. Mocellin, M. Mulhearn, S. Ostrom, W. Wei, Y. Yao, S. Yoo, F. Zhang

University of California, Los Angeles, California, USA
M. Bachtis, R. Cousins, A. Datta, G. Flores Avila, J. Hauser, M. Ignatenko,

M.A. Iqbal, T. Lam, E. Manca, A. Nunez Del Prado, D. Saltzberg, V. Valuev

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

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

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

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

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

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

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

Fermi National Accelerator Laboratory, Batavia, Illinois, USA
M. Albrow, M. Alyari, O. Amram, G. Apollinari, A. Apresyan, L.A.T. Bauerdick, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, G. Cummings, J. Dickinson, I. Dutta, V.D. Elvira, Y. Feng, J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, A. Grummer, S. Grünendahl, D. Guerrero, O. Gutsche, R.M. Harris, R. Heller, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, D. Lincoln, R. Lipton, T. Liu, C. Madrid, K. Maeshima, C. Mantilla, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, D. Noonan, S. Norberg, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[84], F. Ravera, A. Reinsvold Hall[85], L. Ristori, M. Safdari, E. Sexton-Kennedy, N. Smith, A. Soha, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, I. Zoi

University of Florida, Gainesville, Florida, USA
C. Aruta, P. Avery, D. Bourilkov, P. Chang, V. Cherepanov, R.D. Field, E. Koenig, M. Kolosova, J. Konigsberg, A. Korytov, K. Matchev, N. Menendez, G. Mit-

selmakher, K. Mohrman, A. Muthirakalayil Madhu, N. Rawal, S. Rosenzweig, Y. Takahashi, J. Wang

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

Florida Institute of Technology, Melbourne, Florida, USA
B. Alsufyani, M.M. Baarmand, S. Butalla, S. Das, T. Elkafrawy[86], M. Hohlmann, E. Yanes

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

The University of Iowa, Iowa City, Iowa, USA
M. Alhusseini, D. Blend, K. Dilsiz[87], L. Emediato, G. Karaman, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[88], O. Neogi, H. Ogul[89], Y. Onel, A. Penzo, C. Snyder, E. Tiras[90]

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

The University of Kansas, Lawrence, Kansas, USA
A. Abreu, L.F. Alcerro Alcerro, J. Anguiano, S. Arteaga Escatel, P. Baringer, A. Bean, Z. Flowers, D. Grove, J. King, G. Krintiras, M. Lazarovits, C. Le Mahieu, J. Marquez, M. Murray, M. Nickel, M. Pitt, S. Popescu[91], C. Rogan, C. Royon, R. Salvatico, S. Sanders, C. Smith, G. Wilson

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

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

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

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

University of Nebraska-Lincoln, Lincoln, Nebraska, USA

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

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

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

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

University of Notre Dame, Notre Dame, Indiana, USA
G. Agarwal, R. Band, R. Bucci, S. Castells, A. Das, R. Goldouzian, M. Hildreth, K.W. Ho, K. Hurtado Anampa, T. Ivanov, C. Jessop, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, C. Moore, Y. Musienko[17], H. Nelson, M. Osherson, A. Piccinelli, R. Ruchti, A. Townsend, Y. Wan, M. Wayne, H. Yockey, M. Zarucki, L. Zygala

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

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

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

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

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

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

University of Rochester, Rochester, New York, USA
A. Bodek, P. de Barbaro, R. Demina, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, N. Parmar, P. Parygin[92], E. Popova[92], R. Taus

Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
B. Chiarito, J.P. Chou, S.V. Clark, D. Gadkari, Y. Gershtein, E. Halkiadakis,

M. Heindl, C. Houghton, D. Jaroslawski, S. Konstantinou, I. Laflotte, A. Lath, R. Montalvo, K. Nash, J. Reichert, H. Routray, P. Saha, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, J. Vora, H. Wang

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

Texas A&M University, College Station, Texas, USA
D. Aebi, M. Ahmad, T. Akhter, O. Bouhali[93], R. Eusebi, J. Gilmore, T. Huang, T. Kamon[94], H. Kim, S. Luo, R. Mueller, D. Overton, D. Rathjens, A. Safonov

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

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

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

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

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

Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN
S. Afanasiev, V. Alexakhin, V. Andreev, Yu. Andreev, T. Aushev, M. Azarkin, A. Babaev, 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[84], L. Dudko, A. Ershov, G. Gavrilov, V. Gavrilov, S. Gninenko, V. Golovtcov, N. Golubev, I. Golutvin†, I. Gorbunov, A. Gribushin, Y. Ivanov, V. Kachanov, 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], V. Murzin, A. Nikitenko[99,97], S. Obraztsov, V. Oreshkin, V. Palichik, V. Perelygin, S. Petrushanko, S. Polikarpov[95], V. Popov, O. Radchenko[95], M. Savina, V. Savrin, V. Sergeychik, V. Shalaev, S. Shmatov, S. Shulha, Y. Skovpen[95], S. Slabospitskii, V. Smirnov, A. Snigirev, D. Sosnov, V. Sulimov, A. Terkulov, O. Teryaev, I. Tlisova, A. Toropin, A. Tulupov, L. Uvarov, A. Uzunian, A. Vorobyev†, N. Voytishin, B.S. Yuldashev[100], 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 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 UFMS, Nova Andradina, Brazil
[9]Also at Nanjing Normal University, Nanjing, China
[10]Now at The University of Iowa, Iowa City, Iowa, USA
[11]Also at University of Chinese Academy of Sciences, Beijing, China
[12]Also at China Center of Advanced Science and Technology, Beijing, China
[13]Also at University of Chinese Academy of Sciences, Beijing, China
[14]Also at China Spallation Neutron Source, Guangdong, China
[15]Now at Henan Normal University, Xinxiang, China
[16]Also at Université Libre de Bruxelles, Bruxelles, Belgium
[17]Also at an institute or an international laboratory covered by a cooperation agreement with CERN
[18]Also at Suez University, Suez, Egypt
[19]Now at British University in Egypt, Cairo, Egypt
[20]Also at Purdue University, West Lafayette, Indiana, USA
[21]Also at Université de Haute Alsace, Mulhouse, France
[22]Also at Istinye University, Istanbul, Turkey
[23]Also at Tbilisi State University, Tbilisi, Georgia
[24]Also at The University of the State of Amazonas, Manaus, Brazil
[25]Also at University of Hamburg, Hamburg, Germany
[26]Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
[27]Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
[28]Also at Brandenburg University of Technology, Cottbus, Germany
[29]Also at Forschungszentrum Jülich, Juelich, Germany
[30]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
[31]Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
[32]Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
[33]Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
[34]Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
[35]Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
[36]Also at Punjab Agricultural University, Ludhiana, India
[37]Also at University of Visva-Bharati, Santiniketan, India
[38]Also at Indian Institute of Science (IISc), Bangalore, India
[39]Also at IIT Bhubaneswar, Bhubaneswar, India
[40]Also at Institute of Physics, Bhubaneswar, India
[41]Also at University of Hyderabad, Hyderabad, India
[42]Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
[43]Also at Isfahan University of Technology, Isfahan, Iran
[44]Also at Sharif University of Technology, Tehran, Iran
[45]Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
[46]Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran
[47]Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran

[48]Also at Helwan University, Cairo, Egypt
[49]Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
[50]Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
[51]Also at Università degli Studi Guglielmo Marconi, Roma, Italy
[52]Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
[53]Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
[54]Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
[55]Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
[56]Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
[57]Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
[58]Also at Saegis Campus, Nugegoda, Sri Lanka
[59]Also at National and Kapodistrian University of Athens, Athens, Greece
[60]Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
[61]Also at Universität Zürich, Zurich, Switzerland
[62]Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
[63]Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
[64]Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
[65]Also at Konya Technical University, Konya, Turkey
[66]Also at Izmir Bakircay University, Izmir, Turkey
[67]Also at Adiyaman University, Adiyaman, Turkey
[68]Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
[69]Also at Marmara University, Istanbul, Turkey
[70]Also at Milli Savunma University, Istanbul, Turkey
[71]Also at Kafkas University, Kars, Turkey
[72]Now at Istanbul Okan University, Istanbul, Turkey
[73]Also at Hacettepe University, Ankara, Turkey
[74]Also at Erzincan Binali Yildirim University, Erzincan, Turkey
[75]Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
[76]Also at Yildiz Technical University, Istanbul, Turkey
[77]Also at Vrije Universiteit Brussel, Brussel, Belgium
[78]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
[79]Also at IPPP Durham University, Durham, United Kingdom
[80]Also at Monash University, Faculty of Science, Clayton, Australia
[81]Also at Università di Torino, Torino, Italy
[82]Also at Bethel University, St. Paul, Minnesota, USA
[83]Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
[84]Also at California Institute of Technology, Pasadena, California, USA
[85]Also at United States Naval Academy, Annapolis, Maryland, USA
[86]Also at Ain Shams University, Cairo, Egypt
[87]Also at Bingol University, Bingol, Turkey
[88]Also at Georgian Technical University, Tbilisi, Georgia
[89]Also at Sinop University, Sinop, Turkey
[90]Also at Erciyes University, Kayseri, Turkey
[91]Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH),

Bucharest, Romania
[92]Now at an institute or an international laboratory covered by a cooperation agreement with CERN
[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]Also at Imperial College, London, United Kingdom
[100]Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan