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

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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 $\sqrt{s} = 13$ 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.

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 $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ 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 $D^0 \to K^0_S K^0_S$ 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 $D^0 \to K^0_S K^0_S$ decay, is defined as

$$A_{CP}(K^0_S K^0_S) = \frac{\Gamma(D^0 \to K^0_S K^0_S) - \Gamma(\overline{D}^0 \to K^0_S K^0_S)}{\Gamma(D^0 \to K^0_S K^0_S) + \Gamma(\overline{D}^0 \to K^0_S K^0_S)}. \quad (1)$$

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

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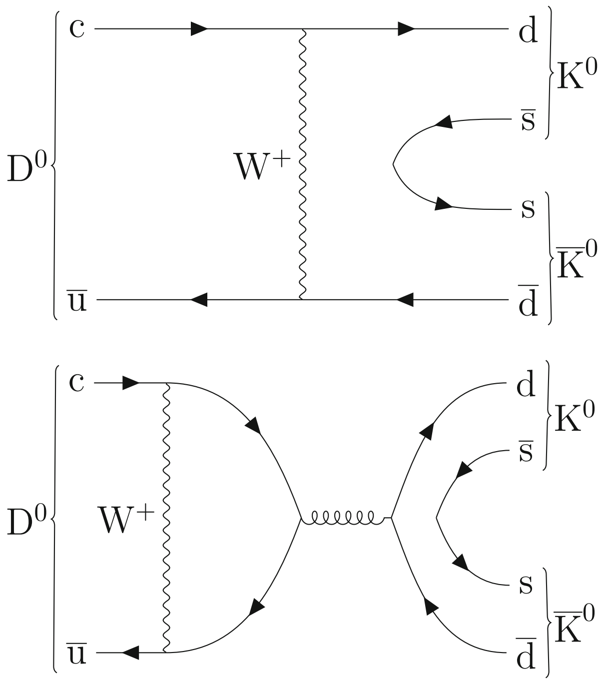

Fig. 1 The decay of neutral charm meson to two neutral kaons: exchange (upper) and penguin annihilation (lower) diagrams

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 $D^{*+} \to D^0\pi^+$ and $D^{*-} \to \overline{D}^0\pi^-$. We measure the *CP* asymmetry difference, ΔA_{CP}, between the signal channel $D^0 \to K^0_S K^0_S$ and the reference channel $D^0 \to K^0_S\pi^+\pi^-$. The $D^0 \to K^0_S\pi^+\pi^-$ *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 $D^0 \to K^0_S K^0_S$ decay.

In proton–proton (pp) collision data, the number of D^{*+} and D^{*-} decays (signal events, N) are measured, where both D^0 and $\overline{D}^0$ are reconstructed in the $K^0_S K^0_S$ or $K^0_S\pi^+\pi^-$ decay modes. The "raw" asymmetry between these numbers, A^{raw}_{CP} (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:

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

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

$$
\begin{aligned}
\Delta A_{CP} &\equiv A_{CP}(K^0_S K^0_S) - A_{CP}(K^0_S\pi^+\pi^-) \\
&= A^{\text{raw}}_{CP}(K^0_S K^0_S) - A^{\text{raw}}_{CP}(K^0_S\pi^+\pi^-).
\end{aligned} \tag{3}
$$

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 $\sqrt{s} = 13$ 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 $41.6\,\text{fb}^{-1}$. 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 $1 < p_{\mathrm{T}} < 10\,\mathrm{GeV}$, 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 K^0_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 K^0_S mass, and subsequently, the K^0_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 K^0_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 K^0_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 $p_{\mathrm{T}} > 0.6\,\mathrm{GeV}$ (and at least one of them with $p_{\mathrm{T}} > 0.7\,\mathrm{GeV}$) are selected. The $\mathrm{K}^0_\mathrm{S}\pi^+\pi^-$ combination is then fit to a common vertex, assumed to be the D^0 decay vertex, which must have a $P_{\mathrm{vtx}} > 5\%$, 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 $\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+$ or $\mathrm{D}^{*-} \to \overline{\mathrm{D}}^0\pi^-$ candidates. A two-object vertex fit is performed to reconstruct the $\mathrm{D}^{*\pm}$ decay vertex, which is required to have a $P_{\mathrm{vtx}} > 1\%$. 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 $m(\mathrm{D}\pi^\pm)$ vs $m(\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S})$, similar to the one

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

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 and ϕ 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 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.

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:

- $D^0 \times D^{*+}$, 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,

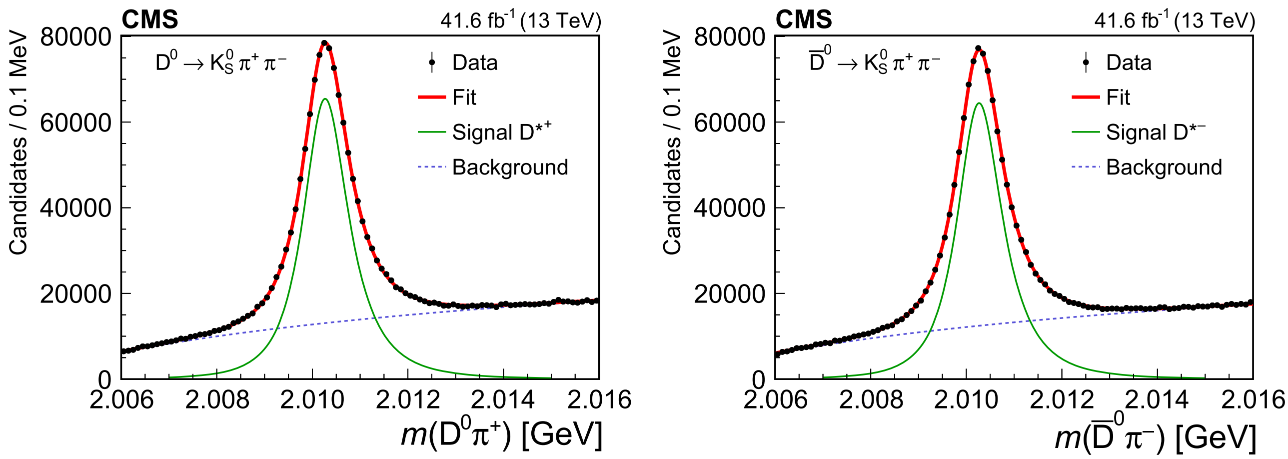

Fig. 2 The $D^0\pi^+$ (left) and $\overline{D}^0\pi^-$ (right) invariant mass distributions for the $K^0_S\pi^+\pi^-$ channel, with the result of the fit to both distributions

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^{raw}_{CP}. 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

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 $y = m(K^0_S K^0_S)$ 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 $D^\pm_s \to K^0_S K^0_S \pi^\pm$ decay producing an excess at about 1.83 GeV in the $K^0_S K^0_S$ 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 $A^{raw}_{CP}(K^0_S K^0_S) = (7.1 \pm 3.0)\%$ and in combination with the results of Sect. 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.

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 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 $m(K^0_S K^0_S)$ 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 $x = m(D\pi^\pm)$ 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 $m(K^0_S K^0_S)$ distribution is an exponential function and an exponential multiplied by a linear polynomial is used as an alternative.

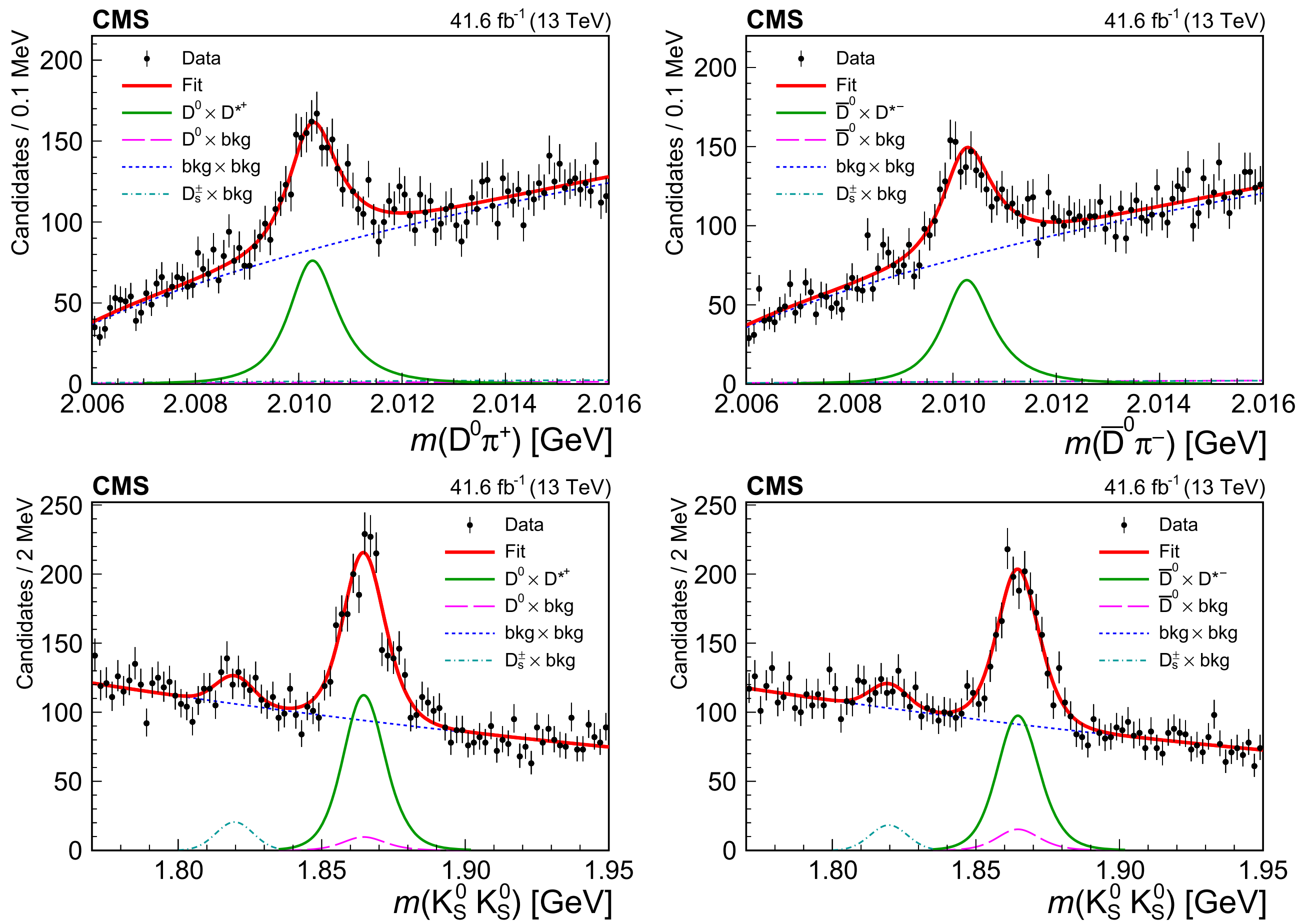

Fig. 3 The invariant mass distributions for D^{*+} candidates (left) and D^{*-} candidates (right), with the $m(\mathrm{D}\pi^{\pm})$ distributions in the upper row and the $m(\mathrm{K^0_S K^0_S})$ distributions in the lower row. Projections of the simultaneous 2D fit are also shown

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

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

These variations are taken as independent systematic uncertainties.

In the signal channel fit, there is a contribution from the $\mathrm{D_s^{\pm}} \to \mathrm{K^0_S K^0_S}\pi^{\pm}$ decay, which is modeled by a Gaussian with free parameters. As an alternative, we remove this reflection by restricting the fit range to be $m(\mathrm{K^0_S K^0_S}) > 1.835\,\mathrm{GeV}$, 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.

Differences in A_{CP}^{pro} and A_{CP}^{det} between the two channels are expected to be reproduced by the simulation of the processes and the detector. Checking the reweighted reference channel and signal channel in simulation show that the p_{T}-, η-, and ϕ-dependent asymmetries are consistent with zero as is the integrated value of $(-0.13 \pm 0.34)\%$. 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

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
$m(\mathrm{K_S^0K_S^0})$ signal model	0.04
$m(\mathrm{K_S^0K_S^0})$ background model	0.02
$m(\mathrm{K_S^0K_S^0})$ fit range	0.06
Reweighting	0.09
Total	0.16

systematic uncertainty, calculated as the sum in quadrature of the different contributions.

9 Summary

A measurement of *CP* violation in D^0 decays is reported, using proton–proton collision data collected at $\sqrt{s} = 13$ 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 $\mathrm{D}^0 \to \mathrm{K_S^0K_S^0}$ and $\mathrm{D}^0 \to \mathrm{K_S^0}\pi^+\pi^-$ is measured to be:

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

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

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

where the three uncertainties represent the statistical uncertainty, the systematic uncertainty, and the uncertainty in the measurement of the *CP* asymmetry in the $\mathrm{D}^0 \to \mathrm{K_S^0}\pi^+\pi^-$ 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.

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Declarations

Conflict of interest The authors declare that they have no Conflict of interest.

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Appendix A: Additional projections of the 2D fit

Figures 4 and 5 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

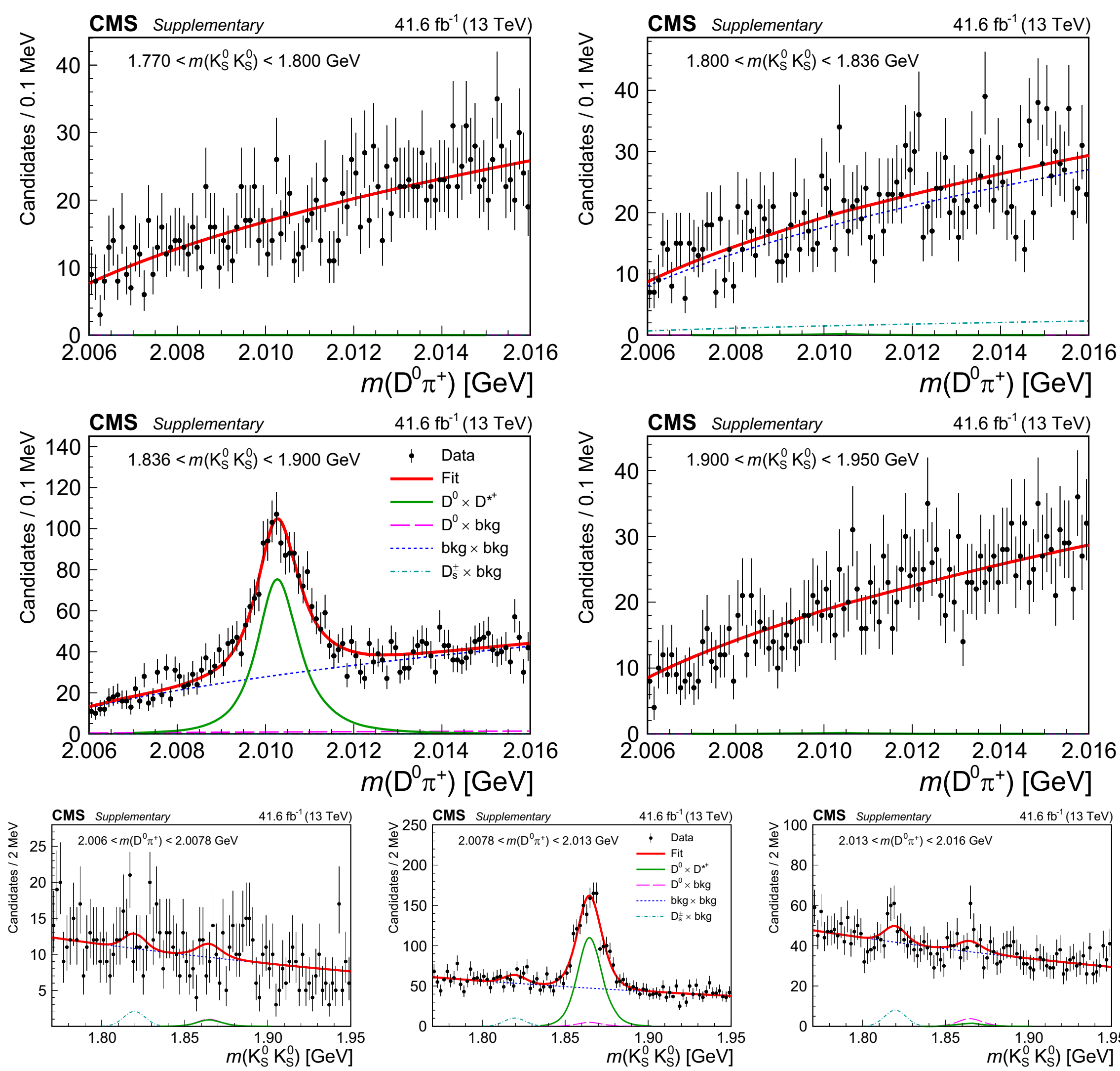

Fig. 4 Results of the 2D fit to the $m(\mathrm{D}\pi^{\pm}) \times m(\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S})$ for the signal channel, D^{*+} candidates. Upper and middle rows show 1D projections of the 2D fit on $m(\mathrm{D}^0\pi^+)$ in ranges of $m(\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S})$: 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 $m(\mathrm{D}^0\pi^+)$: left sideband (left), signal region of $\mathrm{D}^0\pi^+$ (center), and right sideband (right)

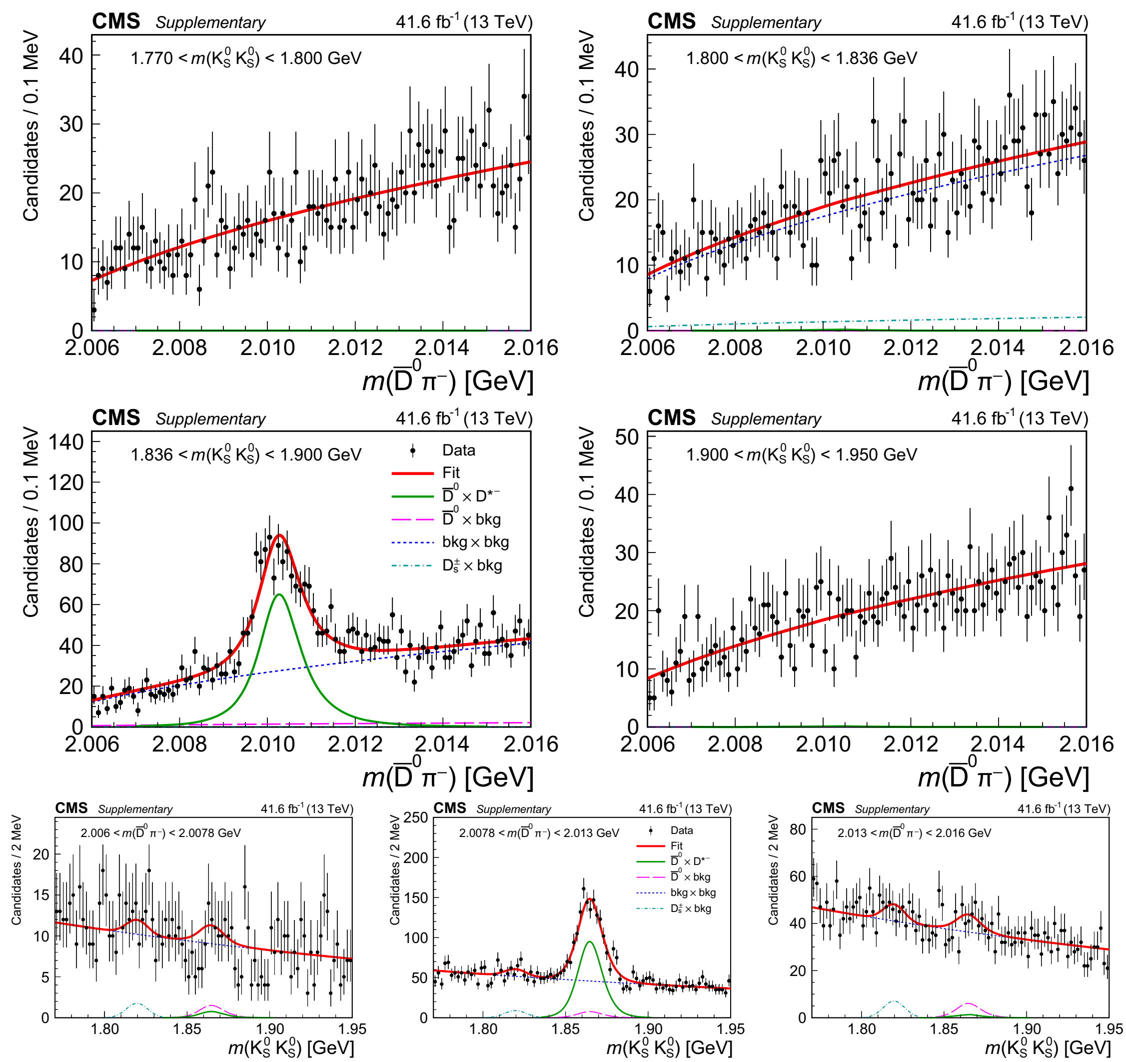

Fig. 5 Results of the 2D fit to the $m(\mathrm{D}\pi^{\pm}) \times m(\mathrm{K_S^0K_S^0})$ for the signal channel, D^{*-} candidates. Upper and middle rows show 1D projections of the 2D fit on $m(\overline{\mathrm{D}}^0\pi^-)$ in ranges of $m(\mathrm{K_S^0K_S^0})$: left sideband (upper left), region of $\mathrm{D_s^{\pm}} \to \mathrm{K_S^0K_S^0}\pi^{\pm}$ contamination (upper right), signal region of $\mathrm{K_S^0K_S^0}$ (middle left), and right sideband (middle right). Lower row shows 1D projections of the 2D fit on $m(\mathrm{K_S^0K_S^0})$ 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)

$m(\mathrm{D}\pi^{\pm})$ in ranges of $m(\mathrm{K_S^0K_S^0})$: left sideband, region of $\mathrm{D_s^{\pm}} \to \mathrm{K_S^0K_S^0}\pi^{\pm}$ contamination, signal region of $\mathrm{K_S^0K_S^0}$, and right sideband. The lower three plots show 1D projections of the 2D fit on $m(\mathrm{K_S^0K_S^0})$ in ranges of $m(\mathrm{D}\pi^{\pm})$: left sideband, signal region of $\mathrm{D}\pi^{\pm}$, and right sideband.

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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, Rome, Italy
52: Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Naples, Italy
53: Also at Fermi National Accelerator Laboratory, Batavia, IL, 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 Faculty of Engineering, Istanbul University-Cerrahpasa, 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, UK
79: Also at IPPP Durham University, Durham, UK
80: Also at Faculty of Science, Monash University, Clayton, Australia
81: Also at Università di Torino, Turin, Italy
82: Also at Bethel University, St. Paul, MN, USA
83: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
84: Also at California Institute of Technology, Pasadena, CA, USA
85: Also at United States Naval Academy, Annapolis, MD, 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, Geneva, Switzerland
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, Geneva, Switzerland
96: Also at Universiteit Antwerpen, Antwerpen, Belgium
97: Also at Yerevan Physics Institute, Yerevan, Armenia
98: Also at Northeastern University, Boston, MA, USA
99: Also at Imperial College, London, UK
100: Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
† Deceased