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Search for CP violation in D^0 decays to radiative and hadronic decays at Belle

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We report a preliminary measurement of the branching fractions of the radiative decays $D^0 \to V\gamma$, where $V = \phi$, $\overline{K}^{*0}$ or ρ^0. This is the first observation of the decay $D^0 \to \rho^0\gamma$. We also present the preliminary results of the first measurement of CP asymmetry in these decays. We present the results of the search for the rare charm decay $D^0 \to \gamma\gamma$, resulting in the most restrictive upper limit to date. Finally, we present the results of the measurement of CP asymmetry in the decay $D^0 \to \pi^0\pi^0$.

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1. Introduction

The radiative charm decay $D^0 \to \phi\gamma$ has been first observed by the Belle Collaboration [1]. In a subsequent analysis, the BaBar Collaboration measured both the decay $D^0 \to \phi\gamma$ and $D^0 \to \overline{K}^{*0}\gamma$ [2]. The current world-average values of the branching fractions are $(2.70 \pm 0.35) \times 10^{-5}$ (ϕ mode) and $(32.7 \pm 3.4) \times 10^{-5}$ ($\overline{K}^{*0}$ mode) [3]. The decay to $D^0 \to \rho^0\gamma$ has not been observed up to date; the established upper limit by CLEO II is $\mathscr{B}\left(D^0 \to \rho^0\gamma\right) < 24 \times 10^{-5}$ at 90% confidence level [4]. As radiative charm decays are dominated by non-perturbative long range dynamics, measurements of branching fractions can be a useful test of the QCD-based theoretical calculations of the branching fractions. Further motivation for a study of radiative decays $D^0 \to V\gamma$, where V is a vector meson, is that these decays could be sensitive to New Physics (NP) via CP asymmetry ($\mathscr{A}_{CP}$). Theoretical studies [5, 6] predict that in Standard Model (SM) extensions with chromomagnetic dipole operators, $\mathscr{A}_{CP}$ can rise to several percent for $V = \phi, \rho^0$, compared to the $\mathscr{O}(10^{-3})$ SM expectation. However, there has been no study of CP violation in $D^0 \to V\gamma$ decays conducted up to this point.

We present here the preliminary results of the measurement of the branching fractions and CP asymmetries in decays $D^0 \to V\gamma$, where $V \in \left\{\phi,\ \overline{K}^{*0},\ \rho^0\right\}$. This is the first observation of the decay $D^0 \to \rho^0\gamma$. The analysis is based on 943 fb^{-1} of data collected by the Belle detector, operating at the asymmetric KEKB e^+e^- collider [7].

We also present a search for the rare charm decay $D^0 \to \gamma\gamma$ [8]. This decay has not been observed yet. The best upper limit to date was set by BaBar at $\mathscr{B}(D^0 \to \gamma\gamma) < 2.2 \times 10^{-6}$ (90% C.L.) [9]. The decay $D^0 \to \gamma\gamma$ represents a good probe for NP, as the SM prediction for the branching fraction, which is of the order of 10^{-8}, can be enhanced by several orders of magnitude by NP contributions. The Minimal Supersymmetric Standard Model suggests that the exchange of gluinos can enhance the $D^0 \to \gamma\gamma$ branching ratio up to 6×10^{-6} [10, 11]. The present measurement, conducted on 832 fb^{-1} of Belle data, represents the most stringent upper limit for this decay.

Finally, we present the results of the measurement of the CP asymmetry in decays $D^0 \to \pi^0\pi^0$ [12]. As singly Cabibbo-suppressed, these decays have an enhanced possibility of NP contributions to the CP asymmetry. A measurement of $\mathscr{A}_{CP}$ in these decays has been conducted by the CLEO Collaboration, yielding the result $A_{CP}(D^0 \to \pi^0\pi^0) = (0.1 \pm 4.8)\%$ [13]. The present measurement, conducted on 966 fb^{-1} of Belle data, represents the first measurement of $\mathscr{A}_{CP}$ in these decays at B-factories, and greatly improves the precision of the preceding result.

2. Analysis $D^0 \to V\gamma$

Both the branching fraction and $\mathscr{A}_{CP}$ are measured relative to other well measured decay channels. Such an approach enables the cancellation of several sources of systematic uncertainties that are common to both the signal and normalisation mode. In this scope, the chosen normalisation modes are decays that feature the same charged final state particles as the signal decay. The signal decays are reconstructed in the following sub-decay channels of the vector meson: $\phi \to K^+K^-$, $\overline{K}^{*0} \to K^-\pi^+$ and $\rho^0 \to \pi^+\pi^-$. In accordance, the corresponding normalisation modes are $D^0 \to K^+K^-$ (ϕ mode), $D^0 \to K^-\pi^+$ ($\overline{K}^{*0}$ mode) and $D^0 \to \pi^+\pi^-$ (ρ^0 mode). The candidate D^0 mesons are required to originate from the decay $D^{*+} \to D^0\pi_S^+$ in order to identify the flavour of the D^0. Additionally, this can provide further suppression of the combinatorial background with a constraint imposed on the mass difference $\Delta m = m(D^{*+})\ m(D^0)$.

The signal branching fraction $\mathscr{B}_{\text{sig}}$ is given by

$$\mathscr{B}_{\text{sig}} = \mathscr{B}_{\text{norm}} \times \frac{N_{\text{sig}}}{N_{\text{norm}}} \times \frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}} \quad , \tag{2.1}$$

where N is the extracted yield, ε the reconstruction efficiency and $\mathscr{B}$ the branching fraction for the corresponding mode. For $\mathscr{B}_{\text{norm}}$ the world-average value [3] is used.

The quantity extracted from data is not directly the *CP* asymmetry, but the raw asymmetry

$$A_{\text{raw}} = \frac{N(D^0) - N(\overline{D}^0)}{N(D^0) + N(\overline{D}^0)} \quad , \tag{2.2}$$

which contains beside the physical *CP* asymmetry also terms that arise from the production asymmetry (A_{FB}) and from different reconstruction efficiencies for positively and negatively charged particles ($A_\varepsilon^\pm$):

$$A_{\text{raw}} = \mathscr{A}_{CP} + A_{\text{FB}} + A_\varepsilon^\pm \quad . \tag{2.3}$$

The forward-backward production asymmetry is assumed to be the same for all charm mesons. Since normalisation modes are chosen to contain the same set of charged final state particles, also the $A_\varepsilon^\pm$ term is equal for both the signal and normalisation mode. It then follows that the *CP* asymmetry of signal decays $\mathscr{A}_{CP}^{\text{sig}}$ can be obtained as

$$\mathscr{A}_{CP}^{\text{sig}} = A_{\text{raw}}^{\text{sig}} - A_{\text{raw}}^{\text{norm}} + \mathscr{A}_{CP}^{\text{norm}} \quad . \tag{2.4}$$

For the *CP* asymmetry of normalisation modes $\mathscr{A}_{CP}^{\text{norm}}$ the world-average values are taken [14].

2.1 Signal extraction

Signal is extracted via a simultaneous 2-dimensional fit in the variables $m(D^0)$ and cosine of the helicity angle $\cos(\theta_H)$. The latter is defined as the angle between the mother (D^0) and daughter (positively or negatively charged final state hadron) particle of the V meson in the rest frame of the V meson.

The dominant background arises from decays which comprise a π^0 instead of the photon in the final state, with the π^0 subsequently decaying into a pair of photons. As one photon is missed in the reconstruction, the reconstructed $m(D^0)$ peak is shifted slightly toward lower values, but still overlaps with the signal peak. As lots of decay modes can contribute to this type of background, some with branching fractions significantly higher than that of signal decays, suppression of such background is of vital importance. For this purpose, a dedicated π^0 veto is developed, comprising a neural network variable obtained from two mass veto variables. The signal photon is paired once with each other photon in the event with an energy above 30 MeV, and once with each photon with an energy above 75 MeV. The pair in each set whose diphoton mass lies closest to $m(\pi^0)$ is fed to the neural network. The final criterion on the veto variable rejects about 60% of background, while retaining 85% of signal. Background of $\pi^0(\to \gamma\gamma)$ type can be further reduced by suppressing events where the two photons form a merged cluster in the electromagnetic calorimeter (ECL). This is done by imposing a constraint on ratio of the energy deposited in a 3×3 array of ECL crystals versus the energy deposited in the enclosing 5×5 array, E_9/E_{25}.

The fit results are shown in Figures 1, 2 and 3 for the ϕ, $\overline{K}^{*0}$ and ρ^0 modes, respectively. The signal component is denoted with the dashed red line. The extracted signal yields are 524 ± 35 (ϕ mode), 9104 ± 396 ($\overline{K}^{*0}$ mode) and 500 ± 85 (ρ^0 mode). The extracted raw asymmetries are -0.091 ± 0.066 (ϕ mode), -0.002 ± 0.020 ($\overline{K}^{*0}$ mode) and 0.064 ± 0.151 (ρ^0 mode). Here, the uncertainties are statistical only. The reconstruction efficiencies are 9.7% (ϕ mode), 7.8% ($\overline{K}^{*0}$ mode) and 6.8% (ρ^0 mode).

Figure 4 shows the signal enhanced plots of the $m(D^0)$ distribution in a reduced range of $\cos\theta_H$, for all three signal modes.

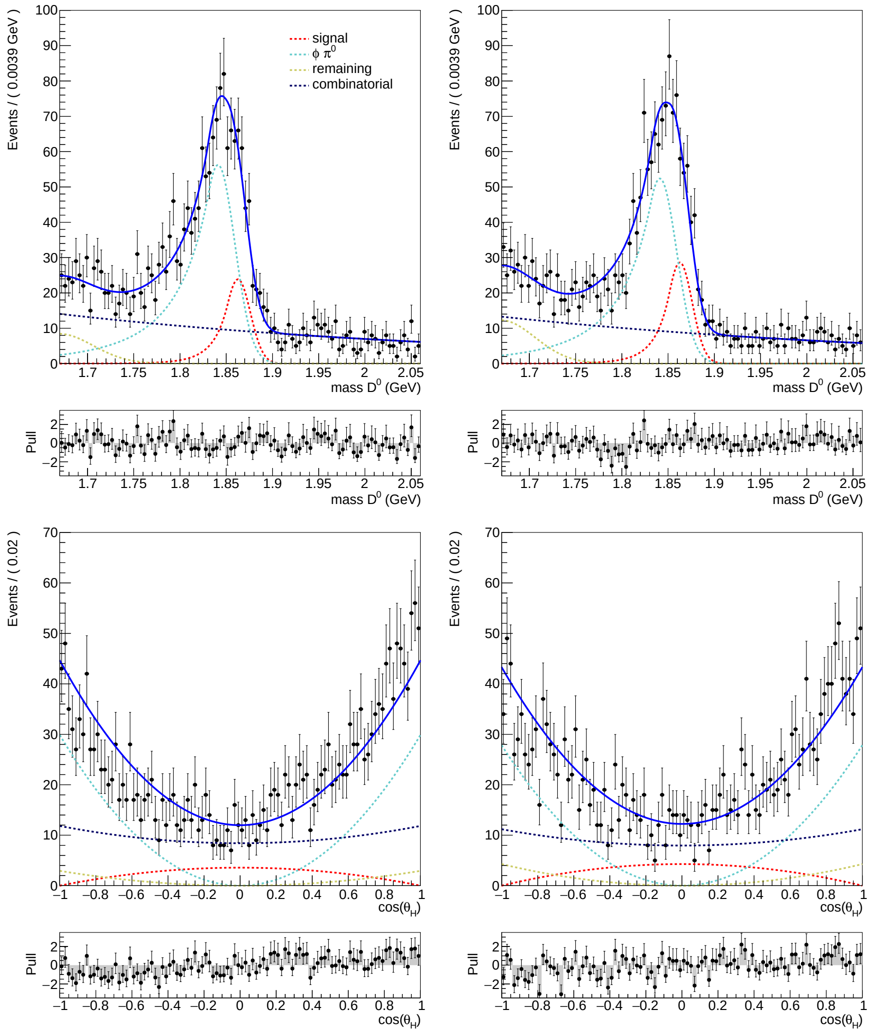


Figure 1: The $m(D^0)$ (top row) and $\cos(\theta_H)$ (bottom row) distributions for the ϕ mode for D^0 (left) and $\overline{D}^0$ (right), with fit results superimposed.

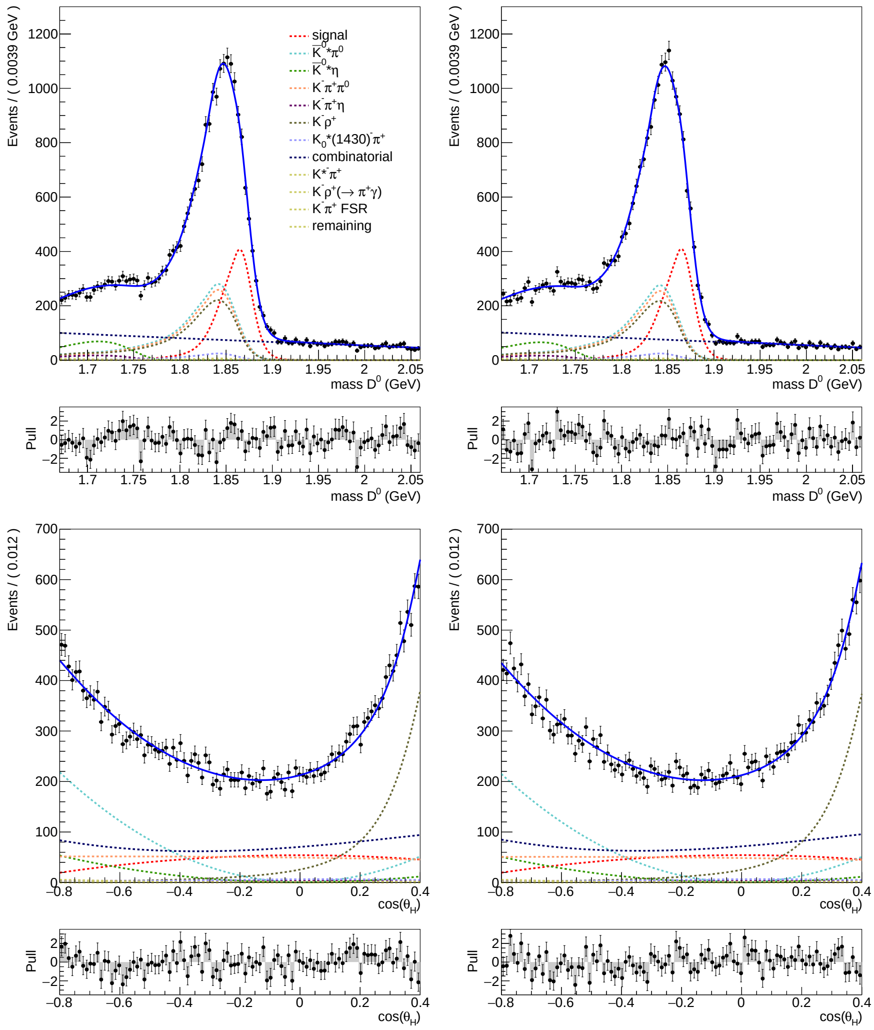


Figure 2: The $m(D^0)$ (top row) and $\cos(\theta_H)$ (bottom row) distributions for the $\overline{K}^{*0}$ mode for D^0 (left) and $\overline{D}^0$ (right), with fit results superimposed.

2.2 Analysis of normalisation modes

The analysis of the normalisation modes is based on the previous analysis of the same modes by the Belle Collaboration [15]. Signal is extracted via background subtraction in the signal window (SW). On simulation, the fraction of background events in the signal window compared to all events in symmetrical upper and lower sidebands (USB and LSB) is determined: $f = \frac{(N_{\rm SW}^{\rm bkg})_{MC}}{(N_{\rm LSB}+N_{\rm USB})_{MC}}$. This fraction is subsequently used to determine the number of background events in the signal window in data, by counting events in sidebands: $(N_{\rm SW}^{\rm bkg})_{\rm DATA} = f \times (N_{\rm LSB} + N_{\rm USB})_{\rm DATA}$.

We extract a signal yield of 362 274 events for K^+K^-, 4.02×10^6 events for $K^-\pi^+$ and 127 683 events for $\pi^+\pi^-$. The extracted raw asymmetries are $(2.2 \pm 1.7) \times 10^{-3}$ (K^+K^-), $(1.3 \pm 0.5) \times 10^{-3}$ ($K^-\pi^+$) and $(8.1 \pm 3.0) \times 10^{-3}$ ($\pi^+\pi^-$). The efficiencies are 22.7% for K^+K^-, 27.0% for $K^-\pi^+$ and 21.4% for $\pi^+\pi^-$.

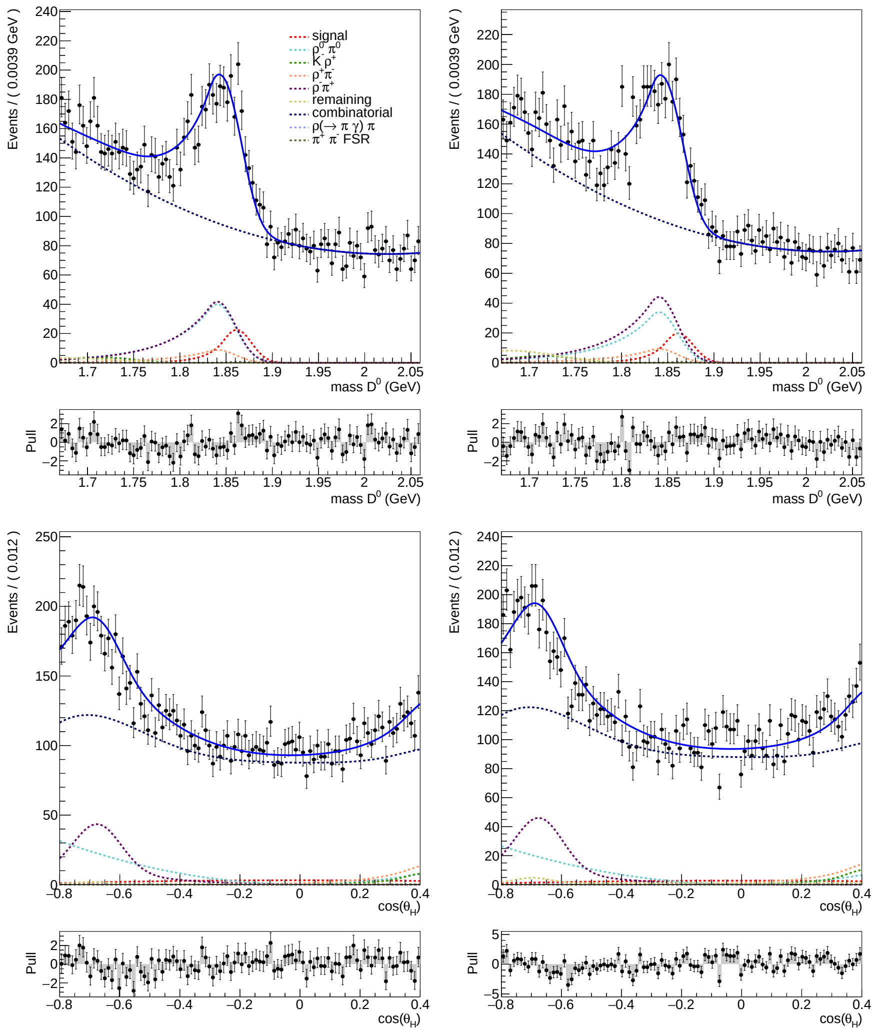


Figure 3: The $m(D^0)$ (top row) and $\cos(\theta_H)$ (bottom row) distributions for the ρ^0 mode for D^0 (left) and $\overline{D}^0$ (right), with fit results superimposed.

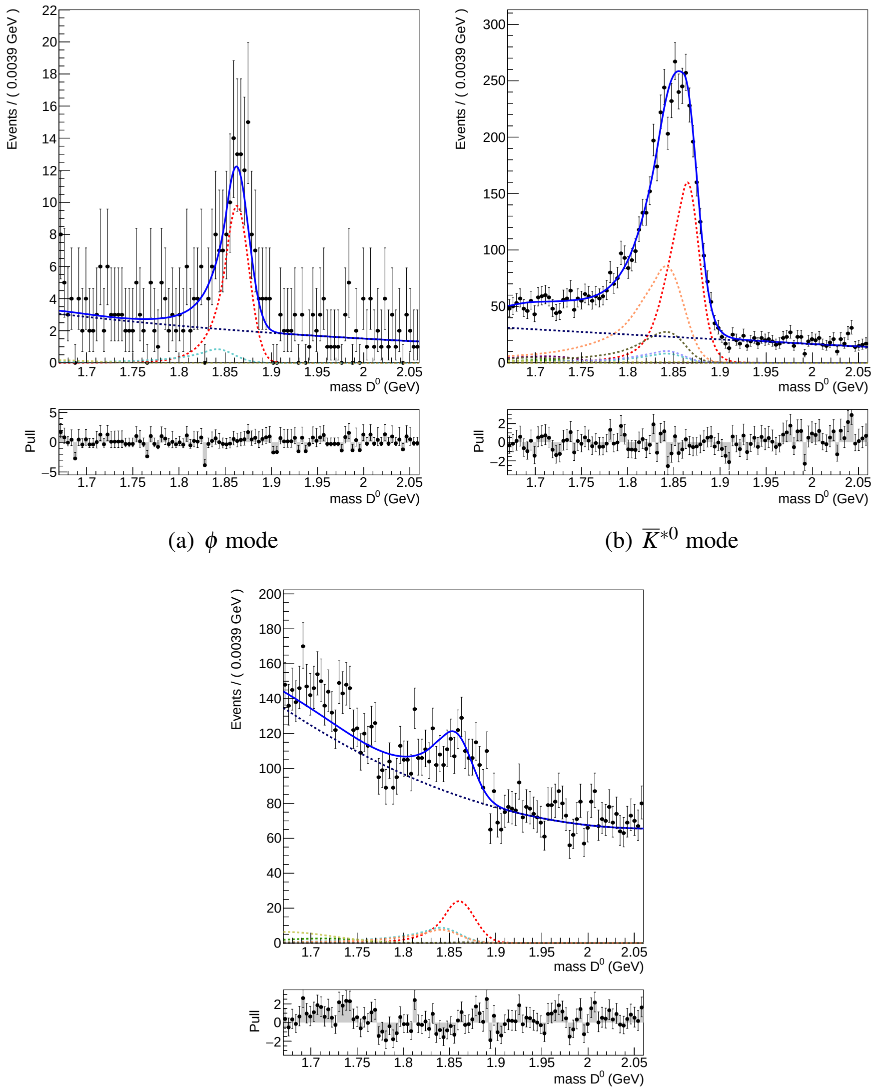
2.3 Systematic uncertainties

All systematic uncertainties are summarized in Table 1. They can be roughly divided in three groups: uncertainties arising from reconstruction efficiencies (photon reconstruction efficiency, Δm, the π^0 veto and E_9/E_{25}), uncertainties arising from signal and background parametrisation and uncertainties arising from the analysis of the normalisation modes.

2.4 Results

The preliminary branching fractions are

$$\mathscr{B}\left(D^0 \to \phi\gamma\right) = (2.76 \pm 0.20 \pm 0.08) \times 10^{-5} \quad ,$$
$$\mathscr{B}\left(D^0 \to \overline{K}^{*0}\gamma\right) = (4.66 \pm 0.21 \pm 0.18) \times 10^{-4} \quad ,$$
$$\mathscr{B}\left(D^0 \to \rho^0\gamma\right) = (1.77 \pm 0.30 \pm 0.08) \times 10^{-5} \quad ,$$



(a) ϕ mode

(b) $\overline{K}^{*0}$ mode

(c) ρ^0 mode

Figure 4: Signal enhanced plots of $m(D^0)$ in a reduced $\cos(\theta_H)$ window for all three signal modes.

where the first uncertainty is statistical and the second systematic. The result of the ϕ mode is improved compared to the previous Belle result and is consistent with the world average value [3]. Our branching fraction of the $\overline{K}^{*0}$ mode is 3.3σ away from the result of the BaBar analysis. For the ρ^0 mode, this analysis reports the first observation of the decay. The significance of the observation is greater than 5σ, including systematic uncertainties.

We also report the first-ever measurement of $\mathscr{A}_{CP}$ in the decays $D^0 \to V\gamma$. The preliminary values are

$$\mathscr{A}_{CP}\left(D^0 \to \phi\gamma\right) = -(0.094 \pm 0.066 \pm 0.001) \quad ,$$
$$\mathscr{A}_{CP}\left(D^0 \to \overline{K}^{*0}\gamma\right) = -(0.003 \pm 0.020 \pm 0.000) \quad ,$$
$$\mathscr{A}_{CP}\left(D^0 \to \rho^0\gamma\right) = +(0.056 \pm 0.151 \pm 0.006) \quad .$$

	ϕ mode		$\overline{K}^{*0}$ mode		ρ^0 mode	
	$\mathscr{B}$ [%]	$\mathscr{A}_{CP}$ [$\times 10^{-3}$]	$\mathscr{B}$ [%]	$\mathscr{A}_{CP}$ [$\times 10^{-3}$]	$\mathscr{B}$ [%]	$\mathscr{A}_{CP}$ [$\times 10^{-3}$]
γ rec. eff.	2	–	2	–	2	–
q	1.16	–	1.16	–	1.16	–
π^0 veto	0.5	–	0.5	–	0.5	–
E_9/E_{25}	0.96	–	0.96	–	0.96	–
signal parametrisation	1.39	0.32	–	–	2.33	4.29
background parametrisation	0.95	0.30	2.81	0.41	3.00	3.78
norm. modes systematics	0.05	0.46	0.00	0.01	0.14	0.54
total	3.06	0.64	3.8	0.41	4.58	5.74

Table 1: Systematic uncertainties for the analysis $D^0 \to V\gamma$.

and are consistent with no CP asymmetry in any of the $D^0 \to V\gamma$ decay modes.

3. Analysis of $D^0 \to \gamma\gamma$

The analysis of the decay $D^0 \to \gamma\gamma$ is in a lot of points similar to that of $D^0 \to V\gamma$. The D^0 mesons are required to originate from the decay $D^{*+} \to D^0\pi_S^+$ in order to suppress combinatorial background. Peaking background arises from decays comprising a π^0 and/or η meson, which decays to a pair of photons: $D^0 \to \pi^0\pi^0, D^0 \to \eta\pi^0, D^0 \to \eta\eta, D^0 \to K_S^0(\to \pi^0\pi^0)\pi^0$, $D^0 \to K_L^0\pi^0$. These background types are suppressed with a $\pi^0(\eta)$ veto [16] and suppression of merged ECL clusters through the ratio E_9/E_{25}.

The branching fraction is calculated relative to the normalisation mode $D^0 \to K_S^0\pi^0$.

3.1 Signal extraction

Signal is extracted through a 2-dimensional fit in $m(D^0)$ and Δm. The efficiency is 7.3%. We extract a signal yield of 4 ± 15 events. The fit results are shown in Figure 5.

The same fit is used for the normalisation channel. The efficiency is 7.2%. We extract a yield of 343050 ± 673 events.

The systematic uncertainties are summarised in Table 2.

3.2 Calculation of upper limit

In the absence of signal, a frequentist method is used to estimate the upper limit on the branching fraction at a 90% confidence level. The systematic uncertainties are included in the calculation. The final result is

$$\mathscr{B}r(D^0 \to \gamma\gamma) < 8.4 \times 10^{-7} \tag{3.1}$$

at 90% C.L [8]. This result represents by far the most stringent upper limit to date.

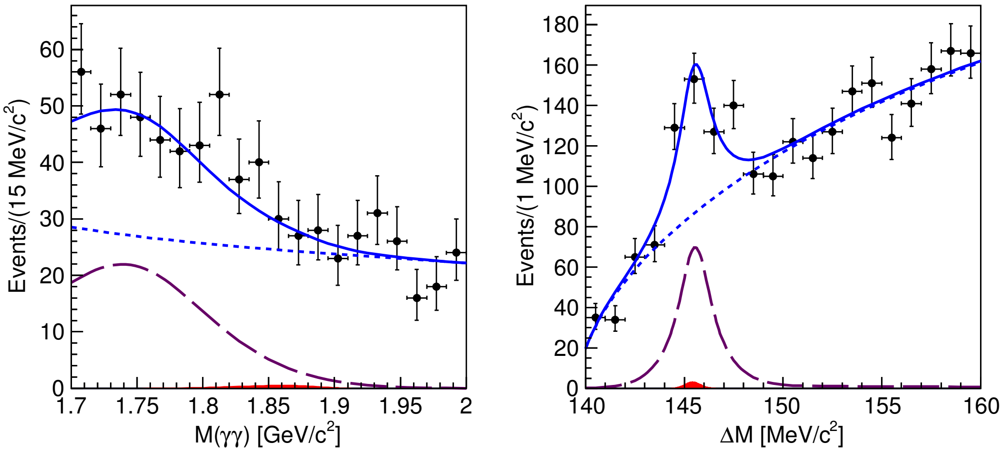


Figure 5: 2-dimensional fit in $m(D^0)$ (left) and Δm (right). Blue (purple) dashed line denotes the combinatorial (peaking) background, while red histogram shows the signal component.

cut variation	$\pm 6.8\%$
signal PDF shape	$^{+4.0}_{-2.4}$ events
γ rec. eff.	$\pm 4.4\%$
K_S^0 reconstruction	$\pm 0.7\%$
π^0 identification	$\pm 4.0\%$
$\mathscr{B}r(D^0 \to K_S^0 \pi^0)$	$\pm 3.3\%$

Table 2: Systematic uncertainties for the analysis $D^0 \to \gamma\gamma$.

4. Analysis of $D^0 \to \pi^0\pi^0$

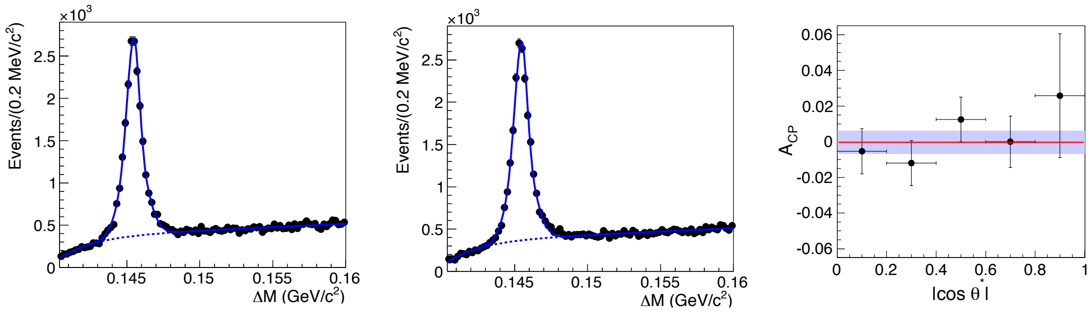
The D^0 mesons are required to originate from the decay $D^{*+} \to D^0\pi_S^+$ in order to provide information on the flavour of the D^0. Signal is extracted via a simultaneous fit in Δm. The raw asymmetry is extracted in bins of $(\cos(\theta^*), p_T^{\pi_S}, \cos(\theta^{\pi_S}))$. Such a method enables the elimination of the production assymetry A_{FB} and asymmetry arising from charged particle efficiencies $A_\varepsilon^\pm$ from Eq. 2.3. $A_\varepsilon^\pm$ arises only from the charged pion in the $D^{*+} \to D^0\pi^+$ decay. It is determined from an analysis of tagged and untagged $D^0 \to K^-\pi^+$ decays in bins of $p_T^{\pi_S}$ and $\cos(\theta^{\pi_S})$. After the subtraction of this term, we obtain the corrected raw asymmetry $A_{raw}^{corr} = A_{CP} + A_{\rm FB}$ in bins of $\cos(\theta^*)$. As $A_{\rm FB}$ is an odd function in $\cos(\theta^*)$, it holds that

$$A_{CP} = \frac{1}{2}(A_{raw}^{corr}(\cos(\theta^*)) + A_{raw}^{corr}(-\cos(\theta^*)) \quad . \tag{4.1}$$

The average A_{CP} is obtained via a fit to constant on values in bins of $\cos(\theta^*)$.

The corresponding plots are shown in Figure 6.

The systematic uncertainties are summarised in Table 3.



(a) (b) (c)

Figure 6: Projection of the simultaneous fit in Δm to the D^0 (left) and $\overline{D}^0$ (middle), and A_{CP} in bins of $\cos(\theta^*)$ (right).

signal shape	0.03
π_S correction	0.07
A_{CP} extraction method	0.07
Total	0.10

Table 3: Systematic uncertainties for the analysis $D^0 \to \pi^0\pi^0$.

4.1 Results

The final result for the CP asymmetry in decays $D^0 \to \pi^0\pi^0$ is

$$A_{CP} = [-0.03 \pm 0.64(\text{stat.}) \pm 0.10(\text{syst.})]\% \quad , \tag{4.2}$$

which is consistent with no CP violation [12]. It is by far the most accurate measurement to date.

Acknowledgments

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