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Recent Selected Results from Belle

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Abstract

We present recent results obtained using the data sample from the Belle detector at the KEKB asymmetric-energy e^+e^- collider in Tsukuba, Japan.

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1 Introduction

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a super-conducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM). The detector is described in detail elsewhere [1].

The Belle experiment successfully operated for more than a decade until 2010 at the asymmetric-energy e^+e^- collider KEKB [2] in various $\Upsilon(n\mathrm{S})$ resonances, having collected a world-record sample of data over $1\,\mathrm{ab}^{-1}$.

We present recent selected results from the Belle experiment, using the full data sample.

2 Search for the Decay $B^0 \to \phi\gamma$

In the Standard Model (SM), the decay $B^0 \to \phi\gamma$ proceeds through electroweak and gluonic $b \to d$ penguin annihilation processes These amplitudes are proportional to the small Cabibbo-Kobayashi-Maskawa [3] matrix element V_{td} and thus are highly suppressed. The branching fraction has been estimated based on naive QCD factorization [4] and perturbative QCD [5] and found to be in the range 10^{-12} to 10^{-11}. However, the internal loop can also be mediated by non-SM particles such as a charged Higgs boson or supersymmetric squarks, and thus the decay is sensitive to new physics (NP). It is estimated that such NP could enhance the branching fraction to the level of 10^{-9} to 10^{-8} [4]. Experimentally, no evidence for this decay has been found. We present a search for this decay using the full Belle data set of 711 fb^{-1} recorded on the $\Upsilon(4\mathrm{S})$ resonance.

Candidate ϕ mesons are reconstructed via $\phi \to K^+K^-$ decays. The K^+K^- invariant mass is required to be in the range $[1.000, 1.039]$ GeV$/c^2$, which corresponds to 4.5σ in resolution around the ϕ mass [6]. Candidate B mesons are identified using a modified beam-energy-constrained mass $M_{\mathrm{bc}} = \sqrt{E_{\mathrm{beam}}^2 - |\vec{p}_B c|^2}/c^2$, and the energy difference $\Delta E = E_B - E_{\mathrm{beam}}$, where E_{beam} is the beam energy and $\vec{p}_B$ and E_B are the momentum and energy, respectively, of the B^0 candidate. All quantities are evaluated in the CM frame. To improve the M_{bc} resolution, the momentum $\vec{p}_B$ is calculated as $\vec{p}_\phi + (\vec{p}_\gamma/|p_\gamma|)\sqrt{(E_{\mathrm{beam}} - E_\phi)^2}/c$, where $\vec{p}_\gamma$ is the photon momentum, and E_ϕ and $\vec{p}_\phi$ are the energy and momentum of the ϕ candidate. We require that events satisfy 5.25 GeV$/c^2 < M_{\mathrm{bc}} <$ 5.29 GeV$/c^2$ and -0.30 GeV $< \Delta E <$ 0.15 GeV. The signal yield is calculated in a smaller region 5.27 GeV$/c^2 < M_{\mathrm{bc}} <$ 5.29 GeV$/c^2$ and -0.20 GeV $< \Delta E <$ 0.10 GeV.

Charmless hadronic decays suffer from large backgrounds arising from continuum $e^+e^- \to q\bar{q}$ $(q = u, d, s, c)$ production. To suppress this background, we use a multivariate analyzer based on a neural network (NN) [7]. The NN generates an output variable C_{NN}, which ranges from -1 for background-like events to $+1$ for signal-like events. We require $C_{\mathrm{NN}} > 0.3$, which rejects 89% of continuum background while retaining 85% of the signal. We then translate C_{NN} to C'_{NN}, defined as $C'_{\mathrm{NN}} = \ln\left(\frac{C_{\mathrm{NN}} - C_{\mathrm{min}}}{C_{\mathrm{max}} - C_{\mathrm{NN}}}\right)$ where $C_{\mathrm{min}} = 0.3$ and $C_{\mathrm{max}} = 1.0$. After the above selections, 961 events remain. The remaining background consists of continuum events and rare charmless b-decay processes.

We calculate signal yields using an unbinned extended maximum likelihood fit to the observables M_{bc}, ΔE, C'_{NN}, and $\cos\theta_\phi$. The helicity angle θ_ϕ is the angle between the K^+ momentum and the opposite of the B flight direction in the ϕ rest frame. The resulting branching fraction is calculated as

$$\mathcal{B}\left(B^0 \to \phi\gamma\right) = \frac{Y_{\mathrm{sig}}}{N_{B\overline{B}} \cdot \varepsilon \cdot \mathcal{B}(\phi \to K^+K^-)}, \quad (1)$$

where $Y_{\mathrm{sig}} = 3.4\,^{+4.6}_{-3.8}$ is the signal yield in the signal region, $N_{B\overline{B}} = (772 \pm 11) \times 10^6$ is the number of $B\overline{B}$ events, $\varepsilon = 0.296 \pm 0.001$ is the signal efficiency as calculated from MC simulation, and $\mathcal{B}(\phi \to K^+K^-) = (48.9 \pm 0.5)\%$ is the branching fraction for $\phi \to K^+K^-$ [6].

We find no evidence for this decay and set an upper limit on the branching fraction of $\mathcal{B}(B^0 \to \phi\gamma) < 1.0 \times 10^{-7}$ at 90% C.L. This limit is almost an order of magnitude lower than the previous most stringent result [8].

3 Angular Analysis of $B^0 \to K^*(892)^0\ell^+\ell^-$

Rare decays of B are an ideal probe to search beyond the Standard Model (SM) of particle physics, since contributions from new particles lead to effects that are of similar size as the SM predictions. The rare decay $B^0 \to K^*(892)^0\ell^+\ell^-$ involves the quark transition $b \to s\ell^+\ell^-$, a flavor changing neutral current that is forbidden at tree level in the

Table 1: Fitted yields and statistical error for signal ($n_{\rm sig}$) and background ($n_{\rm bkg}$) events in the binning of q^2 for both the combined electron and muon channel.

Bin	q^2 range in GeV^2/c^4	$n_{\rm sig}$	$n_{\rm bkg}$
0	1.00 – 6.00	49.5 ± 8.4	30.3 ± 5.5
1	0.10 – 4.00	30.9 ± 7.4	26.4 ± 5.1
2	4.00 – 8.00	49.8 ± 9.3	35.6 ± 6.0
3	10.09 – 12.90	39.6 ± 8.0	19.3 ± 4.4
4	14.18 – 19.00	56.5 ± 8.7	16.0 ± 4.0

SM. Higher order SM processes such as penguin or W^+W^- box diagrams allow for such transitions, leading to branching fractions of less than one in a million. Various extensions to the SM predict contributions from new physics, which can interfere with the SM amplitudes and lead to enhanced or suppressed branching fractions or modified angular distributions of the decay products.

We present an angular analysis, using the decay modes $B^0 \to K^*(892)^0 e^+e^-$ and $B^0 \to K^*(892)^0 \mu^+\mu^-$, in a data sample recorded with the Belle detector. The LHCb collaboration reported a discrepancy in the angular distribution of the decay $B^0 \to K^*(892)^0\mu^+\mu^-$, corresponding to a 3.4σ deviation from the SM prediction [9]. In contrast to the LHCb measurement here the di-electron channel is also used in this analysis.

K^* candidates are formed in the channel $K^{*0} \to K^+\pi^-$. The large combinatoric background is suppressed by applying requirements on kinematic variables. Two independent variables in which signal events features a distinct distribution that can discriminate against background; These variables are the beam constrained mass, $M_{\rm bc}$, and the energy difference, ΔE.

Large irreducible background contributions arise from charmonium decays $B \to K^{(*)}J/\psi$ and $B \to K^{(*)}\psi(2S)$, in which the $c\bar{c}$ state decays into two leptons. To maximize signal efficiency and purity, neural networks are developed sequentially from the bottom to the top of the decay chain, transferring each time the output probability to the subsequent step.

Signal and background yields are extracted by an unbinned extended maximum likelihood fit to the $M_{\rm bc}$ distribution of $B^0 \to K^*(892)^0\ell^+\ell^-$ candidates. For the angular analysis the number of signal events $n_{\rm sig}$ and background events $n_{\rm bkg}$ in the signal region $M_{\rm bc} > 5.27~\mathrm{GeV}/c^2$ are obtained by a fit to $M_{\rm bc}$ in bins of q^2. The extracted yields and the definition of the bin ranges are presented in Table 1.

We perform an angular analysis of $B^0 \to K^*(892)^0\ell^+\ell^-$ including the electron and muon modes. The decay is kinematically described by three angles θ_ℓ, θ_K and ϕ and the invariant mass squared of the lepton pair q^2. The definitions of the angles and the full angular distribution are detailed in Ref. [10].

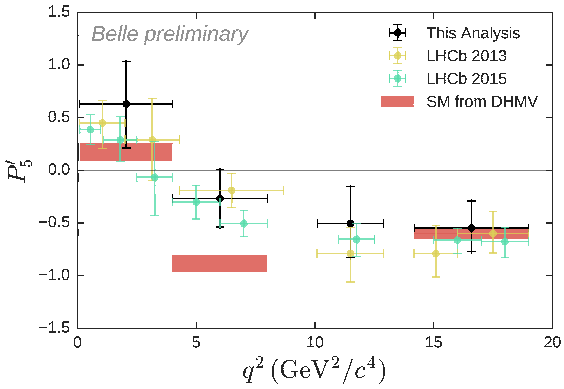

Figure 1: Result for the P_5' observable compared to SM predictions from various sources. Results from LHCb [9, 13] are shown for comparison.

The observables $P'_{i=4,5,6,8}$, introduced in Ref. [11], contain information about the short-distance effects and can be affected by new physics and are considered to be largely free from form-factor uncertainties [12]. The statistics in this analysis are not sufficient to perform an eight-dimensional fit, therefore a folding technique is used, detailed in Ref. [13].

All observables $P'_{4,5,6,8}$ are extracted from the data in the signal region using three-dimensional unbinned maximum likelihood fits in four bins of q^2 and the additional zeroth bin using the folded signal PDF, fixed background shapes and a fixed number of signal events. Each $P'_{4,5,6,8}$ is fitted with the longitudinal polarization,F_L, and the transverse polarization asymmetry $A_T^{(2)}$. A total of 20 measurements are performed.

We present results of the first angular analysis of $B^0 \to K^*(892)^0\ell^+\ell^-$ in three dimensions at B factories, including both the muon and electron modes. In total 117.6 ± 12.4 signal candidates for $B^0 \to K^*(892)^0\mu^+\mu^-$ and 69.4 ± 12.0 signal events for $B^0 \to K^*(892)^0e^+e^-$ are observed. The signal yields are consistent with those expected from previous measurements. The measurements of $P'_{4,5,6,8}$, F_L, and $A_T^{(2)}$ are compared with SM predictions and overall agreement is observed. One measurement is found to deviate by 2.1σ from the predicted value into the same direction and in the same q^2 region where the LHCb collaboration reported the so-called P_5' anomaly [9, 13].

4 Measurement of the branching ratio of $\bar{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$ relative to $\bar{B}^0 \to D^{*+}\ell^-\overline{\nu}_\ell$ decays with a semileptonic tagging method

Semitauonic B meson decays of the type $b \to c\tau\nu_\tau$ are sensitive probes to search for physics beyond the Standard Model (SM). Charged Higgs bosons, which appear in supersymmetry and other models with at least two Higgs doublets, may contribute to the decay due to large mass of the τ lepton and induce measurable effects in the branching fraction. Similarly, leptoquarks, which carry both baryon number and lepton number, may also contribute to this process. The ratio of branching fractions

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell)} \quad (\ell = e, \mu), \qquad (2)$$

is typically used instead of the absolute branching fraction of $\overline{B} \to D^{(*)+}\tau^-\overline{\nu}_\tau$, to reduce several systematic uncertainties such as those on the experimental efficiency, the CKM matrix elements $|V_{cb}|$, and on the form factors. The SM calculations on these ratios predict $\mathcal{R}(D^*) = 0.252 \pm 0.003$ [14] and $\mathcal{R}(D) = 0.297 \pm 0.017$ [15, 19] with precision of better than 2% and 6% for $\mathcal{R}(D^*)$ and $\mathcal{R}(D)$, respectively. Exclusive semitauonic B decays were first observed by the Belle Collaboration [17], with subsequent studies reported by Belle [18, 19], *BABAR* [16], and LHCb [20] Collaborations. All results are consistent with each other, and the average values of Refs. [19, 16, 20] have been found to be $\mathcal{R}(D^*) = 0.322 \pm 0.018 \pm 0.012$ and $\mathcal{R}(D) = 0.391 \pm 0.041 \pm 0.028$ [21], which exceed the SM predictions for $\mathcal{R}(D^*)$ and $\mathcal{R}(D)$ by 3.0σ and 1.7σ, respectively. The combined analysis of $\mathcal{R}(D^*)$ and $\mathcal{R}(D)$, taking into account measurement correlations, finds that the deviation is 3.9σ from the SM prediction.

So far, measurements of $\mathcal{R}(D^{(*)})$ at the B factories have been performed either using a hadronic [19, 16] or an inclusive tagging method [17, 18]. Semileptonic tagging methods have been employed for use in studies of $B^- \to \tau^-\overline{\nu}_\tau$ decays, and have been shown to be of similar experimental precision to that of the hadronic tagging method [22, 23]. In this paper, we report the first measurement of $\mathcal{R}(D^*)$ using the semileptonic tagging method. We reconstruct signal $B^0\overline{B}^0$ events in modes where one B decays semi-tauonically $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$ where $\tau^- \to \ell^-\overline{\nu}_\ell\nu_\tau$, and the the other B decays in a semileptonic channel $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\ell$. To reconstruct normalization $B^0\overline{B}^0$ events, which correspond to the denominator in $\mathcal{R}(D^*)$, we use both B mesons decaying to semileptonic decay modes $D^{*\pm}\ell^\mp\overline{\nu}_\ell$.

To separate reconstructed signal and normalization events, we employ a neural network. The most dominant background contribution arises from events with falsely reconstructed $D^{(*)}$ mesons. To separate signal and normalization events from background processes, we use the extra energy, $E_{\rm ECL}$, which is defined as the sum of the energies of neutral clusters detected in the electromagnetic calorimeter (ECL) that are not associated with reconstructed particles.

We extract the signal and normalization yields using a two-dimensional extended maximum-likelihood fit to the neural network output (NN) NN and $E_{\rm ECL}$. The yields of signal and normalization events are measured to be 231 ± 23(stat) and 2800 ± 57(stat), respectively. The ratio $\mathcal{R}(D^*)$ is therefore found to be $\mathcal{R}(D^*) = 0.302 \pm 0.030 \pm 0.011$ where the first and second errors correspond to statistical and systematic uncertainties, respectively. Our measurement is 1.6σ larger than the SM prediction.

We investigate the compatibility of the data samples with the type II 2HDM and the R_2 type leptoquark model. We find the most favored parameter points are around $\tan\beta/m_{H^+} = 0.7$ GeV^{-1} in the type II 2HDM and $C_T = -0.030$ and $+0.360$ in the R_2 type leptoquark model, although the latter is disfavored when considering the impact on the decay kinematics.

5 Observation of the decay $B_s^0 \to K^0\overline{K}^0$

The two-body decays $B_s^0 \to h^+h'^-$, where $h^{(\prime)}$ is either a pion or kaon, have now all been observed [6]. In contrast, the neutral-daughter decays $B_s^0 \to h^0h'^0$ have yet to be observed. The decay $B_s^0 \to K^0\overline{K}^0$ is of particular interest because the branching fraction is predicted to be relatively large. In the Standard model, the decay proceeds mainly via a $b \to s$ loop (or "penguin") transition and the branching fraction is predicted to be in the range $(16-27)\times 10^{-6}$ [25]. The presence of non-SM particles or couplings could enhance this value [26]. It has been pointed out that CP asymmetries in $B_s^0 \to K^0\overline{K}^0$ decays are promising observables in which to search for new physics [27].

The current upper limit on the branching fraction, $\mathcal{B}(B_s^0 \to K^0\overline{K}^0) < 6.6 \times 10^{-5}$ at 90% confidence level, was set by the Belle Collaboration using 23.6 fb^{-1} of data recorded at the $\Upsilon(5S)$ resonance [28]. In paper [24] Belle updates this result using the full data set of 121.4 fb^{-1} recorded

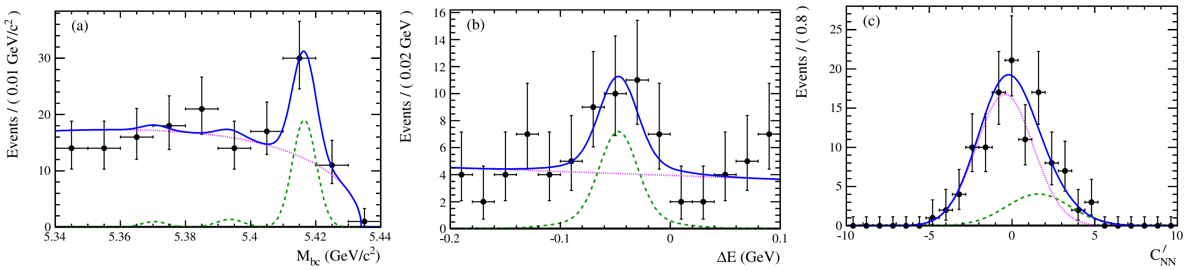

Figure 2: Projections of the 3D fit to the real data: (a) $M_{\rm bc}$ in -0.11 GeV $< \Delta E < 0.02$ GeV and $C'_{\rm NN} > 0.5$; (b) ΔE in 5.405 GeV$/c^2 < M_{\rm bc} <$ 5.427 GeV$/c^2$ and $C'_{\rm NN} > 0.5$; and (c) $C'_{\rm NN}$ in 5.405 GeV$/c^2 < M_{\rm bc} <$ 5.427 GeV$/c^2$ and -0.11 GeV $< \Delta E <$ 0.02 GeV. The points with error bars are data, the (green) dashed curves show the signal, (magenta) dotted curves show the continuum background, and (blue) solid curves show the total.

at the $\Upsilon(5S)$. The analysis presented here uses improved tracking, K^0 reconstruction, and continuum suppression algorithms. The data set corresponds to $(6.53 \pm 0.66) \times 10^6$ $B_s^0\overline{B}_s^0$ pairs [29] produced in three $\Upsilon(5S)$ decay channels: $B_s^0\overline{B}_s^0$, $B_s^{*0}\overline{B}_s^0$ or $B_s^0\overline{B}_s^{*0}$, and $B_0^{*0}\overline{B}_s^{*0}$. The latter two channels dominate, with production fractions of $f_{B_s^{*0}\overline{B}_s^0} = (7.3 \pm 1.4)\%$ and $f_{B_s^{*0}\overline{B}_s^{*0}} = (87.0 \pm 1.7)\%$ [30].

Candidate K^0 mesons are reconstructed via the decay $K_s \to \pi^+\pi^-$ using a NN technique. To suppress background arising from continuum $e^+e^- \to q\overline{q}$ $(q = u, d, s, c)$ production, we use a second NN. The NN has a single output variable ($C_{\rm NN}$) that ranges from -1 for background like events to $+1$ for signal-like events. We require $C_{\rm NN} > -0.1$, which rejects approximately 85% of $q\overline{q}$ background while retaining 83% of signal decays. We subsequently translate $C_{\rm NN}$ to $C'_{\rm NN}$.

We measure the signal yield by performing an unbinned extended maximum likelihood fit to the variables $M_{\rm bc}$, ΔE, and $C'_{\rm NN}$. The results of the fit are $29.0\,^{+8.5}_{-7.6}$ signal events and $1095.0\,^{+33.9}_{-33.4}$ continuum background events.The results of the fit are $29.0\,^{+8.5}_{-7.6}$ signal events and $1095.0\,^{+33.9}_{-33.4}$ continuum background events. The branching fraction is calculated via

$$\mathcal{B}(B_s^0 \to K^0\overline{K}^0) = \frac{Y_s}{2N_{B_s^0\overline{B}_s^0}(0.50)\mathcal{B}^2_{K^0}\varepsilon}, \quad (3)$$

where Y_s is the fitted signal yield; $N_{B_s^0\overline{B}_s^0} = (6.53 \pm 0.66) \times 10^6$ is the number of $B_s^0\overline{B}_s^0$ events; $\mathcal{B}_{K^0} = (69.20 \pm 0.05)\%$ is the branching fraction for $K_s \to \pi^+\pi^-$ [6]; and $\varepsilon = (46.3 \pm 0.1)\%$ is the signal efficiency as determined from MC simulation. The factor 0.50 accounts for the 50% probability for $K^0\overline{K}^0 \to K_sK_s$ (since $K^0\overline{K}^0$ is CP even).

The signal significance is calculated as $\sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{\rm max})}$, where $\mathcal{L}_0$ is the likelihood value when the signal yield is fixed to zero, and $\mathcal{L}_{\rm max}$ is the likelihood value of the nominal fit. We include systematic uncertainties in the significance by convolving the likelihood function with a Gaussian function whose width is equal to that part of the systematic uncertainty that affects the signal yield. We obtain a signal significance of 5.1 standard deviations.

We report the first observation of the decay $B_s^0 \to K^0\overline{K}^0$. The branching fraction is measured to be $\mathcal{B}(B_s^0 \to K^0\overline{K}^0) = (19.6\,^{+5.8}_{-5.1} \pm 1.0 \pm 2.0) \times 10^{-6}$, where the first uncertainty is statistical, the second is systematic, and the third reflects the uncertainty due to the total number of $B_s^0\overline{B}_s^0$ pairs. This value is in good agreement with the SM predictions [25], and it implies that the Belle II experiment [31] will reconstruct over 1000 of these decays. Such a sample would allow for a much higher sensitivity search for new physics in this $b \to s$ penguin-dominated decay.

6 Measurement of the branching fraction and CP asymmetry in radiative $D^0 \to V\gamma$ decays

CP violation in the charm sector has long been a neglected field of study, gaining a renewed interest only in recent years. The radiative decays $D^0 \to V\gamma$, where V is a vector meson, could be sensitive to New Physics via CP asymmetry. Theoretical studies [32, 33] predict that in Standard Model (SM) extensions with chromomagnetic dipole operators, $\mathcal{A}_{CP}$ can rise to several percent for $V = \phi, \rho^0$, compared to the $\mathcal{O}(10^{-3})$ SM expectation.

The radiative decay $D^0 \to V\gamma$ has been measured by the Belle and *BABAR* collaborations [34, 35]. *BABAR* also observed the decay $D^0 \to \overline{K}^{*0}$ [35], while CLEO II produced an upper limit for the $D^0 \to \rho^0\gamma$ branching fraction [36]. 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). For the ρ^0 mode, the upper limit is $\mathcal{B}(D^0 \to \rho^0\gamma) < 24 \times 10^{-5}$ (90% C.L.) [6]. No study of CP violation in decays $D^0 \to V\gamma$ has been conducted to date.

The D^0 mesons are required to originate from the decay $D^{*+} \to D^0\pi^+$ in order to provide a tag on the D^0 flavor and to suppress combinatorial background. The signal decays are reconstructed in the following decay chains of the vector mesons: $\phi \to K^+K^-$, $\overline{K}^{*0} \to K^-\pi^+$ and $\rho^0 \to \pi^+\pi^-$.

Both the branching fraction and $\mathcal{A}_{CP}$ are obtained via normalization to other decay channels. The signal branching fraction $\mathcal{B}_{\rm sig}$ is given by

$$\mathcal{B}_{\rm sig} = \mathcal{B}_{\rm norm} \times \frac{N_{\rm sig}}{N_{\rm norm}} \times \frac{\varepsilon_{\rm norm}}{\varepsilon_{\rm sig}} \quad , \tag{4}$$

where N is the extracted yield, ε the reconstruction efficiency and $\mathcal{B}$ the branching fraction for signal and normalization modes, respectively. For $\mathcal{B}_{\rm norm}$ the world-average value [6] is used. The extracted raw asymmetry

$$A_{\rm raw} = \frac{N(D^0) - N(\overline{D}^0)}{N(D^0) + N(\overline{D}^0)} \tag{5}$$

is given by $A_{\rm raw} = \mathcal{A}_{CP} + A_{\rm FB} + A_\varepsilon^{\pm}$. Here, $A_{\rm FB}$ is the forward-backward production asymmetry [6], and $A_\varepsilon^{\pm}$ is the asymmetry due to different reconstruction efficiencies for positively and negatively charged particles. Both can be eliminated through a relative measurement of $\mathcal{A}_{CP}$, if the charged final-state particles are identical. The chosen normalization 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 CP asymmetry of the signal modes is $\mathcal{A}_{CP}^{\rm sig} = A_{\rm raw}^{\rm sig} - A_{\rm raw}^{\rm norm} + \mathcal{A}_{CP}^{\rm norm}$, where $\mathcal{A}_{CP}^{\rm norm}$ is the nominal value of CP asymmetry of the normalization modes [6].

To extract the signal yield and CP asymmetry, a simultaneous two-dimensional unbinned extended maximum likelihood fit of D^0 and $\overline{D}^0$ samples is performed. The fit variables are the invariant-mass of the reconstructed D^0 meson and the cosine of the helicity angle θ_H, defined as the angle between the D^0 and the positively or negatively charged hadron in the rest frame of the V meson (for D^0, we take $K^+/K^-/\pi^+$ for $\phi/\overline{K}^{*0}/\rho^0$, and the opposite charged particles for $\overline{D}^0$)

The extracted signal yields are 524 ± 35 (ϕ mode), 9104 ± 396 ($\overline{K}^{*0}$ mode) and 500 ± 85 (ρ^0 mode).

We report branching fractions of the $D^0 \to \phi\gamma$ and $D^0 \to \overline{K}^{*0}\gamma$ modes and the first observation of the $D^0 \to \rho^0\gamma$ mode. The significance of the observation is greater than 5σ, including systematic uncertainties. The significance is calculated as $\sqrt{-2\ln(\frac{\mathcal{L}_0}{\mathcal{L}_{\rm max}})}$, where $\mathcal{L}_0$ is the likelihood value when the signal yield is fixed to zero and $\mathcal{L}_{\rm max}$ is the likelihood value of the nominal fit. The systematic uncertainties are included by convolving the likelihood function with a Gaussian whose width corresponds to the systematic uncertainty that affects the signal yield. The preliminary branching fractions are

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

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 [6]. 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, the obtained value is close to that of the ϕ mode, which is in accordance with the theoretical predictions.

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

$$\begin{aligned} \mathcal{A}_{CP}(D^0 \to \phi\gamma) &= -(0.094 \pm 0.066 \pm 0.001) \quad , \\ \mathcal{A}_{CP}(D^0 \to \overline{K}^{*0}\gamma) &= -(0.003 \pm 0.020 \pm 0.000) \quad , \\ \mathcal{A}_{CP}(D^0 \to \rho^0\gamma) &= \quad 0.056 \pm 0.151 \pm 0.006 \quad . \end{aligned}$$

We report no observation of CP asymmetry in any of the $D^0 \to V\gamma$ decay modes.

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References

[1] A. Abashian *et al.* (Belle Collab.), Nucl. Instr. and Meth. A **479**, 117 (2002).

[2] S. Kurokawa and E. Kikutani, Nucl. Instrum. Methods Phys. Res., Sect. A **499**, 1 (2003), and other papers included in this volume; T. Abe *et al.*, Prog. Theor. Exp. Phys. (2013) 03A001 and following articles up to 03A011.

[3] N. Cabibbo, Phys. Rev. Lett. **10**, 531 (1963); M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).

[4] X.-Q. Li, G.-R. Lu, R.-M. Wang, and Y. Yang, Eur. Phys. J. C **36**, 97 (2004); J. Hua, C. Kim, and Y. Li, Eur. Phys. J. C **69**, 139 (2010).

[5] C.-D. Lu, Y.-L. Shen, and W. Wang, Chin. Phys. Lett. **23**, 2684 (2006).

[6] K. A. Olive *et al.* (Particle Data Group), Chin. Phys. C **38**, 090001 (2014).

[7] M. Feindt and U. Kerzel, Nucl. Instrum. Methods Phys. Res. Sect. A **559**, 190 (2006).

[8] B. Aubert *et al.* (BaBar Collaboration), Phys. Rev. D **72**, 091103 (2005).

[9] R. Aaij *et al*. (LHCb), JHEP **02**, 104, 2016.

[10] R. Aaij *et al*. (LHCb), JHEP **08**, 131, 2013.

[11] S. Descotes-Genon, J. Matias, M. Ramon, and J. Virto, JHEP **01**, 048 (2013).

[12] S. Descotes-Genon, T. Hurth, J. Matias, and J. Virto. JHEP **1305**, 137 (2013).

[13] R. Aaij *et al.* Phys. Rev. Lett. **111**, 191801 (2013).

[14] S. Fajfer, J.F.Kamenik, and I. Nisandzic, Phys. Rev. D **85**, 094025 (2012).

[15] J.F. Kamenik, and F. Mescia, Phys. Rev. D **78**, 014003 (2008).

[16] J.P. Lees *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **109**, 101802 (2012); J.P. Lees *et al.* (*BABAR* Collaboration), Phys. Rev. D **88**, 072012 (2013);

[17] A. Matyja *et al.* (Belle Collaboration), Phys. Rev. Lett. **99**, 191807 (2007).

[18] A. Bozek *et al.* (Belle Collaboration), Phys. Rev. D **82**, 072005 (2010).

[19] M. Huschle *et al.* (Belle Collaboration), Phys. Rev. D **92**, 072014 (2015).

[20] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **115**, 111803 (2015).

[21] Y. Amhis *et al.*, arXiv:1412.7515 and online update at http://www.slac.stanford.edu/xorg/hfag/

[22] B. Kronenbitter *et al.* (Belle Collaboration), Phys. Rev. D **92**, 051102(R) (2015).

[23] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. D **81**, 051101(R) (2010).

[24] B. Pal *et al.* (Belle Collaboration), Phys. Rev. Lett. **116**, 161801 (2016).

[25] C. H. Chen, Phys. Lett. B **520**, 33 (2001); A. R. Williamson and J. Zupan, Phys. Rev. D **74**, 014003 (2006); A. Ali *et al.*, Phys. Rev. D **76**, 074018 (2007); C. K. Chua, Phys. Rev. D **78**, 076002 (2008); K. Wang and G. Zhu, Phys. Rev. D **88**, 014043 (2013); J. J. Wang, D. T. Lin, W. Sun, Z. J. Ji, S. Cheng and Z. J. Xiao, Phys. Rev. D **89**, 074046 (2014); Q. Chang, J. Sun, Y. Yang and X. Li, Phys. Lett. B **740**, 56 (2015); H. Y. Cheng, C. W. Chiang and A. L. Kuo, Phys. Rev. D **91**, 014011 (2015).

[26] Q. Chang, X. Q. Li and Y. D. Yang, J. Phys. G **41**, 105002 (2014).

[27] S. Baek, D. London, J. Matias and J. Virto, J. High Energy Phys. **12**, (2006) 019; A. Hayakawa, Y. Shimizu, M. Tanimoto and K. Yamamoto, Prog. Theor. Exp. Phys. **2014**, 023B04 (2014).

[28] C.-C. Peng *et al.* (Belle Collaboration), Phys. Rev. D **82**, 072007 (2010).

[29] C. Oswald *et al.* (Belle Collaboration), Phys. Rev. D **92**, 072013 (2015)

[30] S. Esen *et al.* (Belle Collaboration), Phys. Rev. D **87**, 031101(R) (2013).

[31] T. Abe *et al.* (Belle II Collaboration), arXiv:1011.0352.

[32] G. Isidor and J. F. Kamenik, Phys. Rev. Lett. **109**, 171801 (2012).

[33] J. Lyon and R. Zwicky, (2012), arXiv:1210.6546 [hep-phy].

[34] O. Tahima *et al.* (Belle Collaboration), Phys. Rev. Lett. **92**, 101803 (204)

[35] B. Aubert *etal*. (*BABAR*), Phys. Rev. **D78**, 071101 (2008)

[36] D. M. Asner *et al.* (CLEO), Phys. Rev. **58**, 092001 (1998)