New *CP* Violation Results from Combined *BABAR*+Belle Measurements
&
Search for Invisible Dark Photon Decays at *BABAR*

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We present the results of a novel analysis campaign, which combines the final data samples collected by the B factory experiments *BABAR* and Belle in single physics analyses to achieve a unique sensitivity in time-dependent *CP* violation measurements. We present new results on $\sin(2\beta)$ and $\cos(2\beta)$ by a time-dependent Dalitz plot analysis of $\overline{B}^0 \to D^{(*)}h^0$ with $D \to K_S^0\pi^+\pi^-$ decays. A first evidence for $\cos(2\beta) > 0$, the exclusion of trigonometric multifold solutions of the Unitarity Triangle and an observation of *CP* violation are reported. In addition, a low-energy, high-intensity collider search for light dark matter particles by the *BABAR* experiment is presented. New results of a search for invisible decays of the dark photon are reported. No dark photon is observed and constraints on dark sector models are set.

1 New *CP* Violation Results from Combined *BABAR*+Belle Measurements

The B factory experiments *BABAR* and Belle established *CP* violation in the neutral B meson system [1,2]. In particular, the *BABAR* and Belle experiments precisely determined the parameter $\sin(2\beta)$ [3] by time-dependent *CP* violation measurements, where the angle β of the CKM Unitarity Triangle is defined as $\arg\left[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*\right]$ and V_{ij} denotes the CKM matrix element of quarks i, j [4]. The determination of β from the measurements of $\sin(2\beta)$ results in the trigonometric ambiguity, β and $(\pi/2-\beta)$, on the CKM Unitarity Triangle.

An elegant approach to resolve this ambiguity is provided by $\overline{B}^0 \to D^{(*)}h^0$ with $D \to K_S^0\pi^+\pi^-$ decays and $h^0 \in \{\pi^0, \eta, \omega\}$ denoting a light neutral hadron. The $D \to K_S^0\pi^+\pi^-$ decay exhibits a rich and complex interference structure involving various intermediate *CP* and flavor eigenstates contributing to the three-body final state. Exploiting the knowledge of the variations of the relative strong phases as a function of the $D \to K_S^0\pi^+\pi^-$ Dalitz phase space enables to measure $\cos(2\beta)$ in addition to $\sin(2\beta)$ from the time evolution of the $\overline{B}^0 \to D[K_S^0\pi^+\pi^-]^{(*)}h^0$ multi-body final state [5]. Precise experimental knowledge of $\cos(2\beta)$ enables to resolve the trigonometric ambiguity on the CKM Unitarity Triangle.

In $\overline{B}^0 \to D[K_S^0\pi^+\pi^-]^{(*)}h^0$ decays, the time-dependent decay rate of neutral B mesons as a function of the weak *CP* violating phase β and the D^0 and $\bar{D}^0$ Dalitz plot amplitudes is:

$$\begin{aligned} g(\Delta t) =& \frac{e^{\Gamma\Delta t}}{2}|\mathcal{A}_B|^2 \left[|\mathcal{A}_{\bar{D}^0}|^2 + |\mathcal{A}_{D^0}|^2\right] \mp \left(|\mathcal{A}_{\bar{D}^0}|^2 - |\mathcal{A}_{D^0}|^2\right)\cos(\Delta m\Delta t) \\ & \pm 2\eta_{h^0}\,(-1)^L \left[\mathrm{Im}\left(\mathcal{A}_{D^0}\mathcal{A}^*_{\bar{D}^0}\right)\cos(2\beta) - \mathrm{Re}\left(\mathcal{A}_{D^0}\mathcal{A}^*_{\bar{D}^0}\right)\sin(2\beta)\right]\sin(\Delta m\Delta t) \end{aligned} \quad (1)$$

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The $q = +1\,(-1)$ denotes the b-flavor content when the accompanying B meson is tagged as a B^0 ($\overline{B}^0$). The Δt is the proper time interval between the decays of the two B mesons in an $e^+e^- \to \Upsilon(4S) \to B^0\overline{B}^0$ event. The D^0 and $\bar{D}^0$ decay amplitudes are represented by $\mathcal{A}_{D^0} := \mathcal{A}(m_+^2, m_-^2)$ and $\mathcal{A}_{\bar{D}^0} := \mathcal{A}(m_-^2, m_+^2)$ and are functions of the Lorentz-invariant Dalitz plot variables $m_+^2 := (p_{K_S^0} + p_{\pi^+})^2$ and $m_-^2 := (p_{K_S^0} + p_{\pi^-})^2$. The L is the orbital momentum of the Dh^0 or D^*h^0 systems, where we only consider $D^* \to D\pi^0$ decays in the presented analysis, and η_{h^0} is the CP eigenvalue of the h^0.

Measurements of $\sin(2\beta)$ and $\cos(2\beta)$ by time-dependent Dalitz plot analyses of $\overline{B}^0 \to D^{(*)}h^0$ with $D \to K_S^0\pi^+\pi^-$ decays are experimentally challenging. The involved B and D meson branching fractions are low [$\mathcal{O}(10^{-4})$ and $\mathcal{O}(\leq 10^{-2})$, respectively], and the measurements have to cope with low reconstruction efficiencies and large backgrounds due to many neutral particles in the final state and due to sizable contributions from $e^+e^- \to q\bar{q}$ ($q \in \{u, d, s, c\}$) continuum events. In addition, determining the $D \to K_S^0\pi^+\pi^-$ Dalitz amplitude model from data is technically demanding. The *BABAR* and Belle collaborations have previously performed time-dependent Dalitz plot analyses of $\overline{B}^0 \to D^{(*)}h^0$ with $D \to K_S^0\pi^+\pi^-$ decays [6,7,8], but neither experiment alone was sensitive enough to establish CP violation. Some of the results were located outside of the physical region of the parameter space [6], and the measurements used different Dalitz plot amplitude models [6,7], which complicates the combination of the individual results.

At the 52$^{\text{nd}}$ Rencontres de Moriond, we presented new results on $\sin(2\beta)$ and $\cos(2\beta)$ obtained by a time-dependent Dalitz plot analysis of $\overline{B}^0 \to D^{(*)}h^0$ with $D \to K_S^0\pi^+\pi^-$ decays. The presented analysis combines the large final data samples collected by the *BABAR* and Belle experiments in a single measurement. This novel combined approach enables for a unique sensitivity to $\cos(2\beta)$ by the increase in statistics and by applying common assumptions and the same $D \to K_S^0\pi^+\pi^-$ Dalitz amplitude model to the data collected by both experiments. The analysis is performed in two steps. First, the $D \to K_S^0\pi^+\pi^-$ Dalitz plot amplitude model is extracted from a high-statistics charm data sample collected by Belle. Second, $\sin(2\beta)$ and $\cos(2\beta)$ are measured by a time-dependent Dalitz plot analysis of $\overline{B}^0 \to D^{(*)}h^0$ with $D \to K_S^0\pi^+\pi^-$ decays reconstructed from *BABAR* and Belle data. The analysis is briefly described in the following.

1.1 Extraction of the $D \to K_S^0\pi^+\pi^-$ Dalitz plot amplitude model from Belle charm data

The $D \to K_S^0\pi^+\pi^-$ Dalitz plot amplitude model is directly obtained from data using a high-statistics $e^+e^- \to c\bar{c}$ sample corresponding to $924\,\text{fb}^{-1}$ collected at or near the $\Upsilon(4S)$ and $\Upsilon(5S)$ resonances with the Belle detector. $D^{*+} \to D^0\pi_s^+$ with $D^0 \to K_S^0\pi^+\pi^-$ decays are reconstructed, where the positive (negative) charge of the slow pion emitted from $D^{*+} \to D^0\pi_s^+$ decays determines the flavor of the neutral D meson as D^0 ($\bar{D}^0$). The signal and background yields are estimated by two-dimensional fits of the D^0 candidate mass and of the D^{*+}-D^0 mass-difference $\Delta\text{M}_{D^{*+}-D^0}$ distributions. A yield of 1217329 ± 2015 signal decays is obtained. The signal purity is about 94%.

As Dalitz plot amplitude model for $D \to K_S^0\pi^+\pi^-$ decays a combination of the K-matrix approach [9] for the $\pi\pi$ S-wave, the LASS parametrization [10] for the $K\pi$ S-wave and an isobar ansatz is chosen. In the isobar ansatz, the P- and D-waves are modeled by Breit-Wigner lineshapes and account for 14 intermediate two-body resonances. The Dalitz plot amplitude model parameters are estimated by an unbinned maximum likelihood fit using the flavor-tagged D^0 sample with the signal probability density function constructed from the Dalitz plot amplitude model with a correction to account for reconstruction efficiency variations in the Dalitz plot phase space due to experimental acceptance effects and an additional term to account for wrong flavor-tags of D mesons. The background is modeled using distributions taken from the M_{D^0} and $\Delta\text{M}_{D^{*+}-D^0}$ data sidebands. The $D \to K_S^0\pi^+\pi^-$ distributions reconstructed from Belle $e^+e^- \to c\bar{c}$ data and projections of the Dalitz fit are shown in Fig. 1. The obtained $D \to K_S^0\pi^+\pi^-$ Dalitz plot amplitude model parameters are used as input for the time-dependent Dalitz plot analysis of

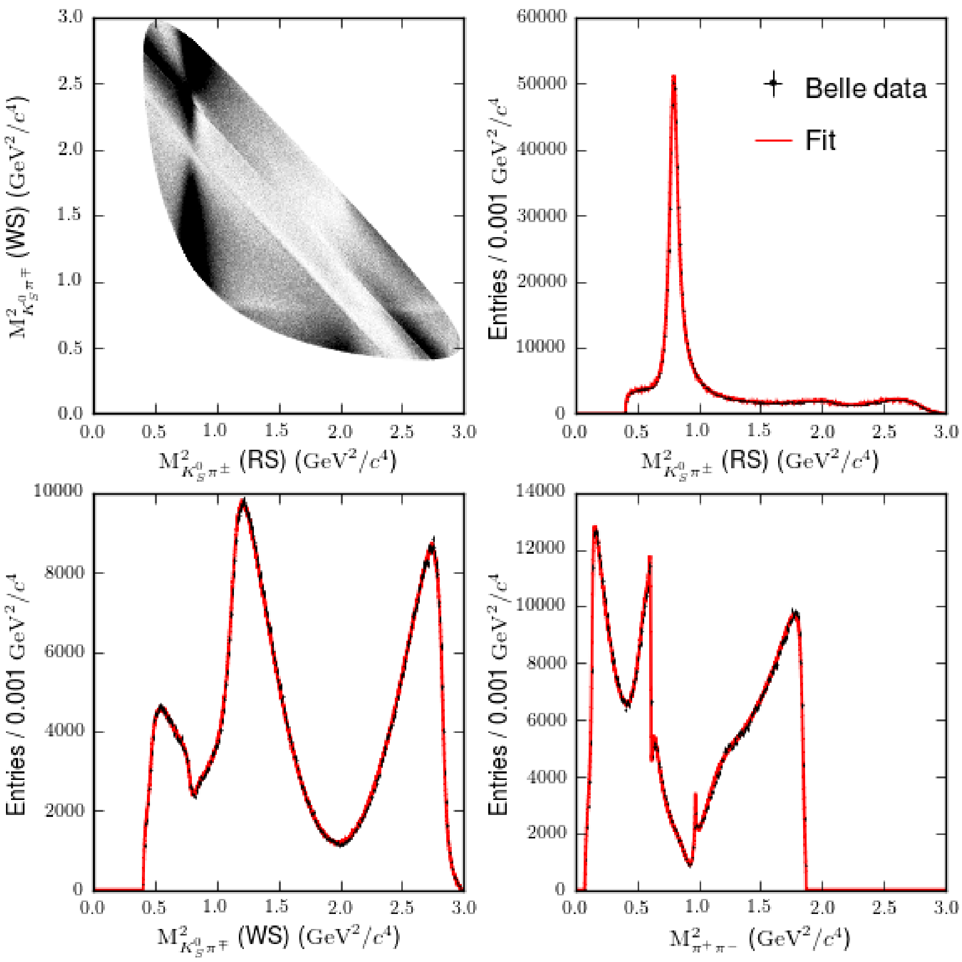

Figure 1 – Preliminary result of the Dalitz fit using the high-statistics flavor-tagged sample of $D \to K^0_S\pi^+\pi^-$ decays reconstructed from $e^+e^- \to c\bar{c}$ events collected by Belle. The $D \to K^0_S\pi^+\pi^-$ Dalitz amplitude model accounts for 14 intermediate two-body resonances. The $\pi\pi$ and $K\pi$ S-wave contributions are modeled by the K-matrix and LASS approaches, respectively.

$\overline{B}^0 \to D^{(*)}h^0$ with $D \to K^0_S\pi^+\pi^-$ decays combining *BABAR* and Belle data described below.

1.2 Time-dependent Dalitz plot analysis of $\overline{B}^0 \to D^{(*)}h^0$ with $D \to K^0_S\pi^+\pi^-$ decays

The combined *BABAR*+Belle analysis of the B meson decay is performed using data samples that contain $(471 \pm 3) \times 10^6$ $B\overline{B}$ pairs recorded with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- (3.1 on 9 GeV) collider at SLAC and $(772 \pm 11) \times 10^6$ $B\overline{B}$ pairs recorded with the Belle detector at the KEKB asymmetric-energy e^+e^- (3.5 on 8 GeV) collider at KEK collected at the $\Upsilon(4S)$ resonance. The similar performance of the two detectors allows a coherent analysis strategy and the use of almost identical selection requirements in the two data sets. The analysis benefits from the techniques established in the previous combined *BABAR*+Belle *CP* violation measurement of $\overline{B}^0 \to D^{(*)}_{CP}h^0$ decays [11].

The light neutral h^0 is reconstructed in the decay modes $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$ and $\pi^+\pi^-\pi^0$, and $\omega \to \pi^+\pi^-\pi^0$. Neutral D mesons are reconstructed in the decay mode $D \to K^0_S\pi^+\pi^-$, and neutral D^* mesons are reconstructed in the decay mode $D^* \to D\pi^0$. Neutral B mesons are reconstructed in the decay modes $\overline{B}^0 \to D\pi^0$, $D\eta$, $D\omega$, $D^*\pi^0$ and $D^*\eta$.

The signal and background yields are determined by three-dimensional unbinned maximum likelihood fits to the distributions of the observables $M'_{\rm bc}$, ΔE and $NN'_{\rm out}$. The fit model accounts for contributions from $\overline{B}^0 \to D^{(*)}h^0$ signal decays, cross-feed from partially reconstructed $\overline{B}^0 \to$

D^*h^0 decays, background from partially reconstructed $B^+ \to D^{(*)0}\rho^+$ decays, combinatorial background from $B\bar{B}$ decays, and background from $e^+e^- \to q\overline{q}$ ($q \in \{u,d,s,c\}$) continuum events. In total, $\overline{B}^0 \to D^{(*)}h^0$ yields of 1129 ± 48 events for *BABAR* and of 1567 ± 56 events for Belle are obtained, respectively.

The time-dependent Dalitz plot analysis of $\overline{B}^0 \to D^{(*)}h^0$ with $D \to K^0_S\pi^+\pi^-$ decays to extract $\sin(2\beta)$ and $\cos(2\beta)$ is performed by maximizing the log-likelihood function constructed from both experiments:

$$\ln\mathcal{L} = \sum_i \ln\mathcal{P}_i^{BABAR} + \sum_j \ln\mathcal{P}_j^{\text{Belle}}, \tag{2}$$

The $\mathcal{P}$ are p.d.f.s describing the proper time interval distributions, and the indices i and j denote the events reconstructed from *BABAR* and Belle data, respectively. The signal p.d.f.s are constructed from Eq. 1 convoluted with experiment specific resolution functions to account for the finite vertex resolution and including the effect of incorrect flavor assignments. The Dalitz plot amplitude model parameters are fixed to the results of the $D \to K^0_S\pi^+\pi^-$ Dalitz plot fit described above. Free parameters in the fit are $\sin(2\beta)$ and $\cos(2\beta)$, and the preliminary result of the measurement is:

$$\begin{aligned}\sin(2\beta) &= 0.80 \pm 0.14\,(\text{stat.}) \pm 0.06\,(\text{syst.}) \pm 0.03\,(\text{model})\\ \cos(2\beta) &= 0.91 \pm 0.22\,(\text{stat.}) \pm 0.09\,(\text{syst.}) \pm 0.07\,(\text{model})\end{aligned} \tag{3}$$

The result of an alternative fit to measure directly the *CP* violating phase β is:

$$\beta = (22.5 \pm 4.4\,(\text{stat.}) \pm 1.2\,(\text{syst.}) \pm 0.6\,(\text{model}))^\circ \tag{4}$$

The evaluation of the experimental systematic uncertainties on the *CP* violation parameters follows the methods established in the previous combined *BABAR*+Belle measurement of $\overline{B}^0 \to D^{(*)}_{CP}h^0$ decays [11]. The evaluation of the uncertainties on the *CP* violation parameters due to the applied Dalitz plot amplitude model follows approaches established before by *BABAR* in model-dependent measurements of the Unitarity Triangle angle γ using $B^\mp \to D^{(*)}K^{(*)\mp}$ decays with multi-body D decays [12,13].

The significance of the results on the *CP* violation parameters is estimated by a likelihood-ratio approach that includes the experimental systematic uncertainties and the Dalitz plot amplitude model uncertainties. The measured value of $\sin(2\beta)$ agrees within 0.7 standard deviations with the world average of $\sin(2\beta) = 0.691 \pm 0.017$ [14] measured from $b \to c\bar{c}s$ transitions. The first evidence for $\cos(2\beta) > 0$ is obtained by excluding the hypothesis of $\cos(2\beta) \leq 0$ at a confidence level of 2.45×10^{-4}, corresponding to a significance of 3.7 standard deviations. The measurement excludes the hypothesis of $\beta = 0^\circ$ at a confidence level of 3.60×10^{-7}, corresponding to a significance of 5.1 standard deviations, and *CP* violation is observed in $\overline{B}^0 \to D^{(*)}h^0$ decays. The measured value of β is in very good agreement with the world average of $(21.9 \pm 0.7)^\circ$ of the preferred solution of the Unitarity Triangle [14]. The second solution $(\pi/2 - \beta) = (68.1 \pm 0.7)^\circ$ is excluded at a confidence level of 2.31×10^{-13}, corresponding to a significance of 7.3 standard deviations. Thus the measurement reduces the trigonometric ambiguity of the CKM Unitarity Triangle.

2 Search for Invisible Dark Photon Decays *BABAR*

The origin and nature of dark matter are an important open problem of modern physics and subject of intense experimental and theoretical research. Dark sector models provide dark matter candidate alternatives to WIMPs and can exhibit a complex structure beyond that of the Standard Model (SM). A possible dark sector scenario is to extend the SM by an additional $U(1)$ gauge symmetry which introduces an additional boson A' as mediator [15,16]. This so-called dark photon may have a gauge coupling of electroweak strength to dark matter, and it could be

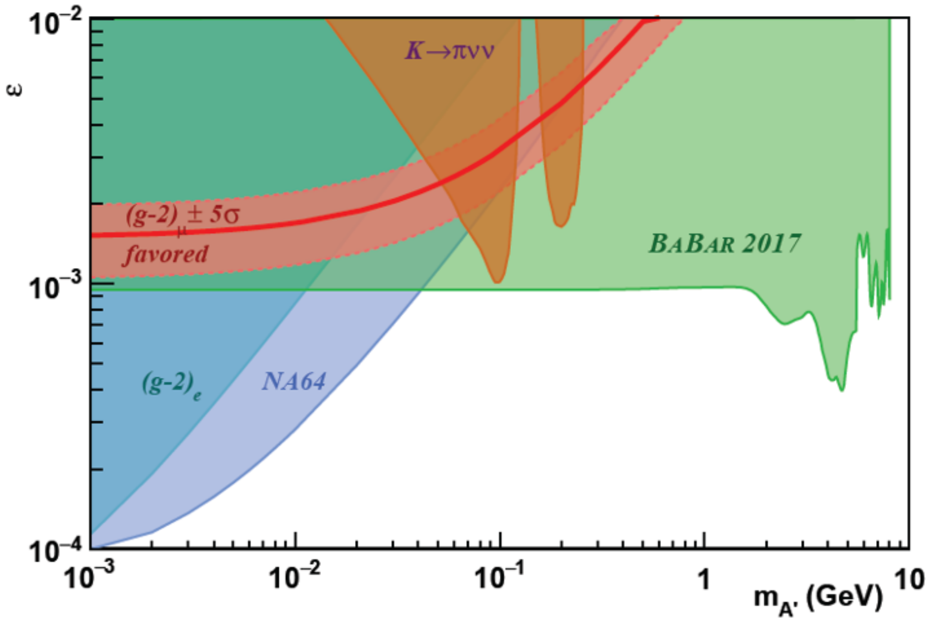

Figure 2 – Preliminary results (green area) for the upper limit on the mixing parameter ϵ at 90% confidence level as a function of the dark photon mass $m_{A'}$ and previous constraints on invisible dark photon decays.

possibly light with a mass in the sub-GeV regime. The dark photon may kinetically mix with the hypercharge of the SM with a mixing strength $\epsilon \ll 1$. Depending on the properties of the dark sector model such as the particle spectrum and the mass and the couplings of the dark photon, the dark photon will exhibit different decay modes. If there are lighter accessible dark sector states χ with $m_\chi < m_{A'}/2$, then the dark photon will predominately decay invisibly via $A' \to \chi\bar{\chi}$. Experiments at e^+e^- colliders are particularly suited to perform searches for invisible dark photon decays. The reaction $e^+e^- \to \gamma A'$ with $A' \to$ invisible can be probed by detecting a single monochromatic photon and nothing else in the e^+e^- annihilation.

At the 52$^{\text{nd}}$ Rencontres de Moriond, we presented new results of a search for invisible dark photon decays. The measurement uses an integrated luminosity of about 53 fb^{-1} collected by the *BABAR* experiment at the PEP-II asymmetric-energy e^+e^- at SLAC. The data was taken with dedicated single photon triggers employed during the last year of operation of *BABAR* at center-of-mass (CM) energies close to the $\Upsilon(2S)$, $\Upsilon(3S)$ and $\Upsilon(4S)$ resonances. The search strategy of the measurement is to select events with single photon final states accompanied by significant missing energy and momentum. Then the dark photon is probed by looking for a narrow peak in the missing mass defined as $M_{\text{miss}} = \sqrt{s - 2E^*_\gamma\sqrt{s}}$, where s is the square of the CM energy of the accelerator and E^*_γ is the energy of the detected photon in the CM frame. In the analysis, the main backgrounds originate from $e^+e^- \to \gamma\gamma$ events and from low-angle radiative Bhabha $e^+e^- \to \gamma e^+e^-$ events, in which the electrons and positrons escape the detector undetected. A Boosted Decision Tree classifier that combines information on the kinematics of the events and information on the detected electromagnetic showers is used to discriminate between signal and background events.

The dark photon signal is extracted by simultaneous fits to the distributions of the missing mass in independent regions of the data collected at different CM energies. No significant signal is observed. In the fits, the most significant signal obtained is at a dark photon mass of $m_{A'} = 6.22$ GeV with a local (global) significance of 3.1 (2.6) standard deviations, corresponding to a p-value of 1%. Using a Bayesian technique, upper limits on the mixing parameter ϵ at 90% confidence level are estimated as a function of $m_{A'}$. The preliminary results and a comparison to previous constraints on invisible dark photon decays are shown in Fig. 2. The measurement significantly improves the experimental constraints on the mixing parameter ϵ and excludes a wide range of the parameter space allowed by dark sector models. In particular, the measurement rules out the dark photon interpretation of the $(g-2)_\mu$ anomaly [17]. A paper summarizing the measurement has been submitted to Physical Review Letters [18].

3 Summary

The combined usage of the large *BABAR* and Belle data sets in single physics measurements enables for an unprecedented sensitivity in time-dependent *CP* violation measurements of neutral B meson decays. Using the final *BABAR* and Belle data samples, a time-dependent Dalitz plot analysis of $\overline{B}^0 \to D^{(*)}h^0$ decays with $D \to K_S^0\pi^+\pi^-$ decays has been performed. The preliminary results of the measurement are $\sin(2\beta) = 0.80 \pm 0.14\,(\text{stat.}) \pm 0.06\,(\text{syst.}) \pm 0.03\,(\text{model})$ and $\cos(2\beta) = 0.91 \pm 0.22\,(\text{stat.}) \pm 0.09\,(\text{syst.}) \pm 0.07\,(\text{model})$. The first evidence for $\cos(2\beta) > 0$ and an observation of *CP* violation in $\overline{B}^0 \to D^{(*)}h^0$ decays have been reported. The measurement directly excludes the trigonometric multifold solution of $(\pi/2-\beta)$ and thus reduces the ambiguity of the CKM Unitarity Triangle.

The *BABAR* experiment has pioneered the low-energy, high-intensity collider search in various signatures of light dark matter and has put tight constraints on dark sector models. New results for the search for invisible decays of the dark photon have been presented, and no dark photons have been observed. Stringent constraints on the mixing parameter ϵ as a function of the dark photon mass $m_{A'}$ and an exclusion of the dark photon interpretation of the $(g-2)_\mu$ anomaly have been reported.

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