New Measurements Using External Photon Conversion at a High Luminosity B Factory

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We propose two novel methods for testing the standard model using external photon conversion at a high-luminosity $e^+e^-$ B factory proposed recently. The first method is to measure the mixing-induced $CP$-violation parameter $S_{\pi^0\pi^0}$ in $B^0 \rightarrow \pi^0\pi^0$ decays. The precision of $S_{\pi^0\pi^0}$ is estimated to be 0.23 from a Monte Carlo study for a data sample containing $5 \times 10^9 B\bar{B}$ pairs. We demonstrate that this measurement is crucial for reducing the discrete ambiguity of the Cabibbo-Kobayashi-Maskawa angle $\phi_2$ determined from the isospin analysis with $B^0$ decays. The second method is to measure photon polarization in $B^0 \rightarrow K^{\ast 0}(\rightarrow K^+\pi^-)\gamma$ decays using the external photon conversion, and combine it with $S_{K^\gamma}$ from $B^0 \rightarrow K^{\ast 0}(\rightarrow K_S^0\pi^0)\gamma$ decays. This offers a promising way of determining the hypothetical right-handed current amplitude and phase beyond the standard model.

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Recent experimental efforts made by two $B$ factory experiments, BaBar and Belle, have been providing crucial tests of the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1] in the standard model (SM). Although no compelling evidence for new physics (NP) beyond the SM has been found so far, further accurate tests of the SM quark flavor sector are necessary in the next decade in which the NP search will also be extensively performed at the LHC experiments.

In this Letter, we present two proposals of the novel SM tests using external photon conversion (PC) that can be carried out only at a high luminosity $B$ factory. Photons from $B$ decays are converted into $e^+e^-$ pairs by the interaction with the detector at a certain probability, which is known as the Bethe-Heitler process [2]. The converted photon provides additional information such as the $B$ vertex position and photon polarization. The photon energy resolution is also improved. The first proposal is to measure the mixing-induced $CP$-violation parameter $S_{\pi^0\pi^0}$ in $B^0 \rightarrow \pi^0\pi^0$ decays [3] with PC, which is otherwise difficult since the $B^0$ decay vertex cannot be determined. We demonstrate that $S_{\pi^0\pi^0}$ is crucial for an unambiguous determination of the CKM angle $\phi_2$ [4].

The second proposal is to measure the photon polarization in the $B^0 \rightarrow K^{\ast 0}(\rightarrow K^+\pi^-)\gamma$ decays. This allows us to determine the hypothetical right-handed current amplitude and phase beyond the SM, when it is combined with a measurement of the mixing-induced $CP$-violation. For both proposals, we estimate the precision of the measurements for a data sample containing $50 \times 10^9 B\bar{B}$ pairs (50 ab$^{-1}$ data), which is expected at a future high luminosity $B$ factory [5].

The angle $\phi_2$ has been measured using $B$ meson decays into $\pi\pi$ [6, 7]. In the decay $B^0 \rightarrow \pi\pi$, where $\pi\pi$ denotes either $\pi^+\pi^-$ or $\pi^0\pi^0$, $\phi_2$ is obtained from $S_{\pi\pi} = \sqrt{1 - \mathcal{A}_{\pi\pi}^2} \sin(2\phi_2 + \kappa_{\pi\pi})$. Here $\mathcal{A}_{\pi\pi}$ is the direct $CP$-violation parameter, and the phase $\kappa_{\pi\pi}$ can be measured using isospin relations [8] with the branching fractions for $B^0 \rightarrow \pi^+\pi^-, \pi^0\pi^0$ and $B^+ \rightarrow \pi^+\pi^0$ decays, and the direct $CP$-violation parameters $A_{\pi^+\pi^-}$ and $A_{\pi^0\pi^0}$.

In general, we have eightfold ambiguity in the $\phi_2$ solutions obtained from the isospin analysis in $B \rightarrow \pi\pi$ decays without $S_{\pi^0\pi^0}$ information. Measuring $S_{\pi^0\pi^0}$ can reduce the ambiguity to two, providing us not only more stringent $\phi_2$ constraints but also a severe consistency check of the $\phi_2$ measurements with $B \rightarrow \rho\pi$ [9] or $B \rightarrow \rho\rho$ [10]. The $\pi\pi$ system is free from systematic and theoretical uncertainties due to the finite width of the $\rho$ meson. The $S_{\pi^0\pi^0}$ measurement can also probe the $\Delta I = 5/2$ contribution in $B \rightarrow \pi\pi$ decays [11].

To estimate the measurement precision of $S_{\pi^0\pi^0}$, we employ a Geant detector Monte Carlo (MC) simulation developed by the Belle collaboration. The MC simulation involves the Belle detector [12] at the KEKB $e^+e^-$ asymmetric-energy collider [13] operating at the $\Upsilon(4S)$ resonance produced with a Lorentz boost factor of $\beta_\gamma = 0.425$ along the electron beam direction ($z$ axis). The Belle detector consists of a 1.5 cm radius beryllium beampipe, a four-layer silicon vertex detector (SVD) and devices for tracking, particle identification and electromagnetic shower detection.

In the Geant MC simulation, we generate a large number of $\Upsilon(4S) \rightarrow B\bar{B}$ decays, where one of the $B^0$ mesons decays into $\pi^0\pi^0$ and the other decays into a flavor specific state $f_{\text{tag}}$. The time dependent decay rate
TABLE I: Branching fractions and CP-violation parameters for \( B \rightarrow \pi \pi \) decays used in our study. The first (second) errors represent statistical (systematic) uncertainties.

| \( B(B^0 \rightarrow \pi^+ \pi^-) \) | \( 5.21 \pm 0.02 \pm 0.10 \times 10^{-6} \) |
| \( B(B^+ \rightarrow \pi^0 \pi^0) \) | \( 5.61 \pm 0.04 \pm 0.17 \times 10^{-6} \) |
| \( B(B^0 \rightarrow \pi^0 \pi^0) \) | \( 1.35 \pm 0.02 \pm 0.05 \times 10^{-6} \) |
| \( S_{\pi^0 \pi^0} \) | \(-0.66 \pm 0.01 \pm 0.01 \) |
| \( \mathcal{A}_{\pi^0 \pi^0} \) | \(+0.37 \pm 0.01 \pm 0.01 \) |
| \( \mathcal{A}_{\pi^0 \pi^0} \) | \(+0.92 \) |

We assume the effective tagging efficiency \( \epsilon = 30\% \), i.e. \( w = (1 - \sqrt{\epsilon})/2 = 0.23 \).

We also take into account the continuum \( e^+e^- \rightarrow q\bar{q} \) \( (q = u,d,s,c) \) and \( B^+ \rightarrow \rho^+ \pi^0 \) rare decays [21]. Using a large Geant MC sample, the expected yield of the continuum \( (B^+ \rightarrow \rho^+ \pi^0) \) background is estimated to be \( 20000 \) (300). We employ the \( \Delta t \) PDF for the backgrounds in Ref. [21], which contains prompt and lifetime components convolved with a resolution function composed of a sum of two Gaussians.

To distinguish between the signal and the continuum events, we construct a likelihood function \( \mathcal{L}_S (\mathcal{L}_{BG}) \) for the signal (continuum) events from the event topology and the \( B \) flight direction in the CMS with respect to the \( z \) axis, and form a likelihood ratio \( \mathcal{R} = \mathcal{L}_S/(\mathcal{L}_S + \mathcal{L}_{BG}) \) for the candidate events.

We generate 2000 MC pseudo experiments with the input values of \( S_{\pi^+ \pi^-} \) and \( \mathcal{A}_{\pi^+ \pi^-} \) listed in Table I. Each pseudo experiment contains the signal, continuum and \( B^+ \rightarrow \rho^+ \pi^0 \) events with the yields estimated above. The MC events are generated according to the PDFs of \( \Delta E \), \( M_{bc} \) and \( \mathcal{R} \), which are determined from the Geant MC. The \( \Delta t \) PDFs defined above are also used for the MC generation.

For a fit to obtain \( S_{\pi^+ \pi^-} \), a likelihood value of the \( i \)-th event is defined as \( P_i = \sum_k n_k P_k(s_i) P_k(\Delta t_i) \), where \( n_k \) is the fraction of component \( k \) indicating either signal, continuum or \( B^+ \rightarrow \rho^+ \pi^0 \), \( P_k(s) \) is the event-by-event probability for the component \( k \) as a function of \( s = (\Delta E, M_{bc}, \mathcal{R}) \), and \( P_k(\Delta t) \) is the \( \Delta t \) PDF of component \( k \). We obtain \( S_{\pi^+ \pi^-} \) error \( \sigma_{S_{\pi^+ \pi^-}} \) simultaneously by maximizing the likelihood function \( \mathcal{P} = \prod P_i \) in each pseudo experiment. The expected \( S_{\pi^+ \pi^-} \) error \( \sigma_{S_{\pi^+ \pi^-}} \) is determined from a root mean square value of the \( S_{\pi^+ \pi^-} \) distribution; we measure \( \sigma_{S_{\pi^+ \pi^-}} = 0.23 \).

To constrain \( \phi_2 \), we perform an isospin analysis using the obtained \( \sigma_{S_{\pi^+ \pi^-}} \) value and the values in Table I with the statistical approach described in [21]. The \( S_{\pi^+ \pi^-} \) central value is obtained from the isospin relations by assuming \( \phi_2 = 90^\circ \). The statistical errors in Table I are estimated by multiplying 0.1 to the errors in Ref. [17] assuming that statistics are 100 times as large as those in Ref. [17]. The systematic errors of the branching fractions are assumed to arise from uncertainties in the detection efficiency for a \( \pi^0 \) (2%) and a charged particle (1%) [22]. We assume 1% systematic errors for the CP-violation parameters, which originate from the asymmetry of charged particle detection efficiency [22] and the irreducible vertex reconstruction uncertainty of SVD misalignment [23]. Figure 1 shows the obtained confidence levels (C.L.) as a function of \( \phi_2 \) with and without the \( S_{\pi^0 \pi^0} \) constraint. While eight-fold discrete ambiguity is seen in the case without \( S_{\pi^0 \pi^0} \), it reduces to two by including the \( S_{\pi^0 \pi^0} \) constraint.

We now turn to the photon polarization measurement with PC. The SM predicts that the helicity of an emitted
photon in the radiative transition \( b \to s\gamma \) is dominantly left-handed. Therefore the detection of a right handed photon is unambiguous evidence for NP. The external PC in \( B^0 \to K^{*0}\gamma \) followed by \( K^{*0} \to K^+\pi^- \) enables us to measure the amplitude of the right-handed photon emission by making use of the photon polarization information obtained from the angle \( \phi \) between the event planes of \( K^+\pi^- \) and \( \gamma \to e^+e^- \).

The amplitude for the emission of a left- (right-) handed photon is expressed as \( F_L = M e^{i\phi_L} \cos \psi \) (\( F_R = M e^{i\phi_R} \sin \psi \)), where \( \phi_L \) (\( \phi_R \)) is a CP-violating phase, \( \psi \) is \( \mathcal{O}(m_u/m_b) \) in the SM, \( s \) (\( b \)) is the \( s \) (\( b \)) quark mass, and \( M \) is an amplitude that determines the overall decay rate. The distribution for the angle \( \phi \) satisfies

\[
\frac{d\sigma}{d\phi} \propto 1 + \xi R \cos(2\phi + \delta),
\]

where \( \xi = \sqrt{X^2 + Y^2} \), \( \tan \delta = (X \tan \phi_+ - Y)/(X + Y \tan \phi_-) \), \( \phi_- = \phi_R - \phi_L \), \( X = 2(\sigma_{ll} - \sigma_{lll})/\sigma_{ll} + \sigma_{lll} \) and \( Y = 4\sigma_{ll}/\sigma_{ll} + \sigma_{lll} \). Here \( \sigma_{ll} \) (\( \sigma_{lll} \)) is the PC cross section parallel (perpendicular) to the polarization of a polarized photon, and \( \sigma_{IV} \) measures the acoplanarity of the photon, electron and positron vectors. We ignore the contribution from \( \sigma_{IV} \) following Ref. [25], hence assume \( \delta = \phi_- \). The dilution parameter \( \xi \) depends on both photon energy and an opening angle of the \( e^+e^- \) pair, and is approximately 0.1 when integrated over the electron energy and the opening angle [25]. From the \( \phi \) distribution, we can measure \( \delta \) and \( R \) with \( B^0 \to K^{*0}(\to K^+\pi^-)\gamma \) decays.

In addition, the time-dependent CP asymmetry measurements in \( B^0 \to K^{*0}\gamma \) followed by \( K^{*0} \to K^0\pi^0 \) [27] yield the mixing-induced CP-violation parameter

\[
S_{K^{*}\gamma} = -2R \sin(2\phi_1 - \phi_+),
\]

determine \( R \), \( \phi_L \) and \( \phi_R \) separately by combining the polarization and CP asymmetry measurements. Within the SM, we expect \( \phi_L = \phi_R = 0 \) to a good approximation [28]. Observation of the CP-violating phases would thus be a clear evidence for NP.

We generate a large number of \( \Upsilon(4S) \to B^0\bar{B}^0 \to (K^{*0}\gamma)(f_{\text{tag}}) \) events, where \( K^{*0} \) decays into \( K^+\pi^- \) in the Geant MC simulation. The photon emitted is converted at the beampipe or the SVD with a probability of 2.8%. The \( B^0 \) reconstruction efficiency is 0.36% including the branching fraction of \( K^{*0} \to K^+\pi^- \); we expect 7200 \( B^0 \to K^{*0}\gamma \) events having converted photons with the branching fraction of \( 4 \times 10^{-5} \) [17]. Because of the small opening angle of the \( e^+e^- \) pair, typically 10 mrad, we find the \( \phi \) resolution is \( 23^\circ \) and the \( \phi \) reconstruction efficiency is 35%: the remaining 65% of events have no information on \( \phi \) and produce a flat \( \phi \) distribution.

We estimate the expected measurement precision of \( R \) and \( \phi_- \). In this study we ignore the possible background contributions of about 5%, which is estimated using a large Geant MC sample. We generate 1000 pseudo experiments for five \( R \) values from 0.1 to 0.5, while \( \phi_- \) is fixed to 0. Each pseudo experiment contains 7200 signal events generated according to Eq. (2) modified to take into account the \( \phi \) reconstruction efficiency and resolution. We choose \( x = R \cos(\phi_-) \) and \( y = R \sin(\phi_-) \) as fit parameters, and find the \( x \) and \( y \) distributions have the same Gaussian sigma \( \sigma_x \) = 0.52. The result is independent of \( R \) values, and neither bias nor correlation is found. The same procedure is performed with 72000 signal events per pseudo experiment, corresponding to a data sample containing \( 500 \times 10^3 \) \( B\bar{B} \) pairs (500 ab\(^{-1} \) data). We obtain \( \sigma_x = 0.16 \), consistent with the expectation 0.52/\( \sqrt{10} \).

To further constrain \( R \) and the phases, we make use of Eq. (4). Since \( F_L \) is dominated by the SM contribution, we fix \( \phi_L \) to 0; hence \( \phi_- = \phi_+ = \phi_R \). We have two independent constraints on \( x \) and \( y \) from the polarization of the \( K^{*} \gamma \) measurement and \( S_{K\gamma} = -2x \sin \phi_1 + 2y \cos \phi_1 \). The measurement precision of \( S_{K\gamma} \) is expected to be 0.04 (0.02) for the 50 (500) ab\(^{-1} \) data [5]. For the sensitivity estimation, we employ a frequentist statistical approach in Ref. [29]. We examine two cases: the SM expectation \( (R, \phi_R) = (0.02, 0^\circ) \) and the left-right symmetric model assumption \((0.34, 90^\circ) \) [27, 30]. Figure 2 shows the obtained confidence regions in \( \phi_R \) vs. \( R \) plane. With the 50 ab\(^{-1} \) data, the constraint is mostly determined by the \( S_{K\gamma} \) measurement precision because of the large \( \sigma_x \) value. On the other hand, with the 500 ab\(^{-1} \) data the \( \phi \) measurement becomes important for the \( R \) and \( \phi_R \) constraints.

We emphasize the vertex reconstruction using PC can also be applied to the time-dependent CP violation analysis in \( B^0 \to K^0\pi^0 \) decays, which are sensitive to a new CP-violating phase in the \( b \to s\gamma \) transition; we can increase the vertex efficiency by about 10% for \( B^0 \to K^0\pi^0 \).
and can reconstruct the vertex position of $B^0 \to K^0 \pi^0$. The energy resolution of a converted photon is three times better than that of a photon without conversion. This feature improves the signal-to-noise ratio in the exclusive $\bar{b} \to \gamma \tau \nu_\tau$ measurements, and in the search for the lepton number violating process $\tau \to \mu \nu_\mu \nu_\tau$.

Finally, we note that the PC probability increases by 50% if we use a six-layer SVD proposed in [4]. Even a higher PC probability is possible by choosing high-Z material, such as CdTe, for the SVD. Dedicated studies are needed in this case to guarantee good momentum resolution for charged particles.

In summary, we have made two proposals of new measurements using PC at a future high luminosity $B$ factory experiment. The PC enables us to determine the vertex position of $B^0 \to \pi^0 \pi^0$ decays. With the 50 ab$^{-1}$ data, we find that the measurement precision of $S_{\phi_3}$ is 0.23, and that it reduces the discrete ambiguity of the $\phi_3$ solutions. The photon polarization measured using PC combined with the $S_{K^\ast \gamma}$ measurement in $B^0 \to K^{\ast 0} \gamma$ decays allows us to constrain the phase and amplitude of the right-handed current beyond the SM. We find that with the 500 ab$^{-1}$ data sample the polarization measurement becomes important for constraining $R$ and $\phi_R$.

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