

# Probing photon helicity in radiative $B$ decays via charmonium resonance interference

Mathias Knecht and Thomas Schietinger

Laboratory for High-Energy Physics, Ecole Polytechnique Fédérale, CH-1015 Lausanne, Switzerland

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We investigate a new method to probe the helicity of the photon emitted in the  $b \rightarrow s\gamma$  transition. The method relies on the observation of interference effects between two resonance contributions,  $B \rightarrow K^*(K\gamma)\gamma$  and  $B \rightarrow \eta_c(\gamma\gamma)K$  or  $B \rightarrow \chi_{c0}(\gamma\gamma)K$  to the same final state  $K\gamma\gamma$ . Decays of the type  $B \rightarrow K_{\text{res}}(K\gamma)\gamma$  dominate the  $B \rightarrow K\gamma\gamma$  yield throughout most of the phase space, and may be accessible at current  $B$  meson facilities already.

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Flavor-changing neutral currents are an important testing ground for the Standard Model (SM) of elementary particles. The quark transition  $b \rightarrow s\gamma$  has played an outstanding role in this respect by providing direct experimental evidence for the penguin diagram process, which is expected to be particularly sensitive to contributions from physics beyond the SM. Recent measurements of the  $b \rightarrow s\gamma$  rate [1], however, agree very well with theoretical predictions [2], leaving little hope for observing hints of new physics via the decay rate only. Consequently, recent efforts have focused on finding additional observable degrees of freedom related to  $b \rightarrow s\gamma$ , such as CP asymmetries or the helicity of the emitted photon, in order to subject the SM to ever more stringent tests. In a similar vein, the decay  $B \rightarrow X_s\gamma\gamma$  and its exclusive manifestation  $B \rightarrow K\gamma\gamma$  have been studied in this context [3, 4, 5]. In analogy to  $b \rightarrow sl^+l^-$ , the diphoton invariant mass spectrum and forward-backward asymmetries have been suggested as probes for new physics beyond the SM [6].

In this Letter, we point out the significance of contributions via radiatively decaying kaon resonances:  $B \rightarrow K_{\text{res}}\gamma$ , with  $K_{\text{res}}$  being any kaon resonance, such as  $K^*(892)$  or higher, that can decay to  $K\gamma$ . We will further show how these decays may be used to extract information on the helicity of the emitted photon in the  $b \rightarrow s\gamma$  amplitude at future high-statistics  $B$ -meson facilities.

It was first noted by Atwood, Gronau, and Soni [7] that the photon helicity in  $b \rightarrow s\gamma$  carries information on the underlying interaction. While the SM amplitude for  $b \rightarrow s\gamma$  results in a predominantly left-handed photon (right-handed for  $\bar{b} \rightarrow \bar{s}\gamma$ ), there are extensions of the SM that could alter the helicity of the photon without affecting much the rate of the decay. Thus several methods for an indirect determination of the photon helicity in radiative  $B$  decays have been devised: 1) study of the *interference between  $b \rightarrow s\gamma$  and  $\bar{b} \rightarrow \bar{s}\gamma$* , made possible by the phenomenon of  $B^0$ - $\bar{B}^0$  mixing [7]; 2) analysis of the *decay photon by means of its conversion to  $e^+e^-$*  [8] (see also [9] for the case of off-shell photons); 3) analysis of the *recoil system arising from the hadronization of the  $s$ -quark in  $b \rightarrow s\gamma$*  [10]; 4) use of a *polarized initial state*, *i.e.*  $b$ -baryon decay, to infer the photon polarization from

angular correlations with the final state [11, 12]. Yet another way to analyze the decay photon is provided by the interference with another photon in a well-known state arising from the *same decay*. For example  $B \rightarrow K^*(K\gamma)\gamma$  can interfere with  $B \rightarrow Kc\bar{c}(\gamma\gamma)$ , where  $c\bar{c}$  is a charmonium state such as  $\eta_c$  or  $\chi_{c0}$ .

Photon pairs arising from  $\eta_c$  ( $J^P = 0^-$ ) decay are known to be in an exact state of perpendicular polarization [13], *i.e.* a state with photon spin orientation given by  $\mathbf{k}_1 \cdot [\boldsymbol{\epsilon}_1(\mathbf{k}_1) \times \boldsymbol{\epsilon}_2(\mathbf{k}_2)]$ , where  $\boldsymbol{\epsilon}_1$  and  $\boldsymbol{\epsilon}_2$  ( $\mathbf{k}_1$  and  $\mathbf{k}_2$ ) are the transverse polarization (momentum) vectors of the two photons. Similarly, photons from  $\chi_{c0}$  ( $J^P = 0^+$ ) decay are in a state of parallel polarization ( $\boldsymbol{\epsilon}_1 \cdot \boldsymbol{\epsilon}_2$ ). Thus we may use  $\eta_c$  and  $\chi_{c0}$  as probes to analyze the polarization state of the photons from  $B \rightarrow K^*(K\gamma)\gamma$ , since photons from  $\eta_c$  ( $\chi_{c0}$ ) will only interfere with the perpendicular (parallel) polarization component.

The SM amplitude for  $B \rightarrow K^*(K\gamma)\gamma$  as given in Ref. [4] is based on a description of  $b \rightarrow s\gamma$  in the framework of a leading-order effective Hamiltonian,

$$\mathcal{H}_{\text{eff}} = -4 \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* C_7 O_7 \quad (1)$$

with  $G_F$  the Fermi constant,  $C_7$  the Wilson coefficient of the local operator  $O_7 = (em_b)/(16\pi^2) \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$ ,  $e$  the electric charge,  $m_b$  the mass of the  $b$ -quark,  $F^{\mu\nu}$  the electromagnetic field tensor and  $\sigma_{\mu\nu} = \frac{i}{2}(\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu)$ .  $V_{tb}$  and  $V_{ts}$  are the usual Cabibbo-Kobayashi-Maskawa matrix elements. The full amplitude is then given as  $\mathcal{M}_{K^*} = [T^{\mu\nu}(k_1, k_2) + T^{\nu\mu}(k_2, k_1)] \epsilon_\mu^*(k_1) \epsilon_\nu^*(k_2)$  with

$$\begin{aligned} T^{\mu\nu}(k_1, k_2) = & \left( \frac{em_b g F}{16\pi^2} \right) 4 \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* C_7 \epsilon^{\alpha\nu\gamma\delta} k_{2\alpha} (p_B - k_1)_\gamma k_{1\beta'} \\ & \times \frac{\left( g_{\delta\sigma'} - \frac{(p_B - k_1)_\delta (p_B - k_1)_{\sigma'}}{m_{K^*}^2} \right)}{(p_B - k_1)^2 - m_{K^*}^2 + im_{K^*} \Gamma_{K^*}} \\ & \times \left[ i \epsilon^{\mu\beta'\sigma'\tau'} (p_B - k_1)_{\tau'} - \left( g^{\mu\sigma'} (p_B - k_1)^{\beta'} - g^{\beta'\sigma'} (p_B - k_1)^\mu \right) \right] \quad (2) \end{aligned}$$

where  $k_i$  are the 4-vectors ( $E, \mathbf{p}$ ) of the photons, and  $p_B$ ,  $p_K$  the 4-vectors of the  $B$  and  $K$  mesons. The constants  $g$

and  $F$  are related to the coupling strengths for  $K^* \rightarrow K\gamma$  and  $B \rightarrow K^*\gamma$ , respectively, and are different for neutral ( $B^0$ ) and charged decays ( $B^+$ ).

The decay distribution in the plane of the two photon energies (Dalitz plot) is shown in Fig. 1. It exhibits the typical  $(1 + \cos^2\theta)$  shape along the resonance lines, as expected for the decay of a pseudoscalar particle into a pseudoscalar and two vectors via an intermediate vector resonance state. It also features a non-negligible fraction of decays in the central region of the Dalitz plot, outside the two resonance lines. This region is populated by decays receiving contributions from *both* amplitudes,  $B \rightarrow K^*\gamma \rightarrow (K\gamma')\gamma$  and  $B \rightarrow K^*\gamma' \rightarrow (K\gamma)\gamma'$ . Despite the suppression from the Breit-Wigner resonance shape the effect of this interference amplitude results in a substantial enhancement of the over-all branching fraction of the decay. Indeed, from the distribution of events we find that  $\mathcal{B}(B \rightarrow K^*(K\gamma)\gamma) \approx 3.85 \times \mathcal{B}(B \rightarrow K^*\gamma) \times \mathcal{B}(K^* \rightarrow K\gamma)$ . Combining this estimate with recent experimental data on  $B \rightarrow K^*\gamma$  [14] and  $K^* \rightarrow K\gamma$  [15] we obtain branching fractions of  $(3.54 \pm 0.35)$  for  $B^0$  and  $(1.54 \pm 0.15)$  for  $B^+$  in units of  $10^{-7}$ , well accessible with the next generation of  $B$  factories [16] and perhaps also at hadron colliders [17] if backgrounds can be controlled.

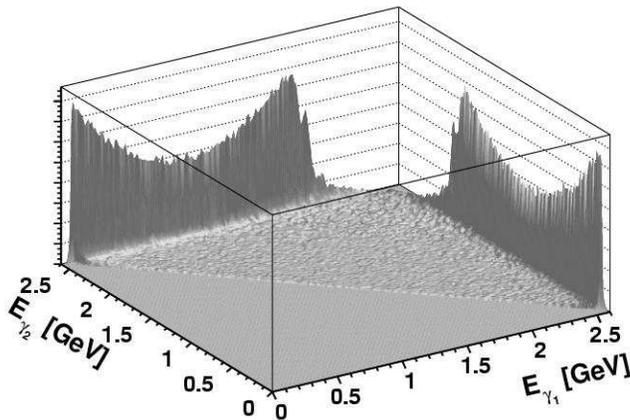


FIG. 1: Decay distribution for  $B \rightarrow K^*\gamma \rightarrow K\gamma\gamma$  in the plane of the two photon energies (Dalitz plot).

Other transitions yielding the  $K\gamma\gamma$  final state include a non-resonant (short-distance) contribution,  $b \rightarrow s\gamma$  contributions via higher kaon resonances decaying to  $K\gamma$ , contributions from  $\eta(\gamma\gamma)K$  and  $\eta'(\gamma\gamma)K$ , as well as the analog contributions from charmonium resonances ( $\eta_c$  and  $\chi_c$  states).

The non-resonant contribution is negligible with respect to the  $K^*$  contribution everywhere in phase space. Our evaluation of the amplitude given in [4] confirms the small non-resonant branching fraction of order  $10^{-9}$  first reported by Hiller and Safir [5] in contradiction to the value given in [4]. Choudhury *et al.* have recently ac-

TABLE I: Branching fractions for the cascade decays  $B \rightarrow K(c\bar{c}) \rightarrow K\gamma\gamma$ , where  $(c\bar{c}) = \eta_c, \eta'_c, \chi_{c0}, \chi_{c2}$ , as far as they have been measured [15, 21].

Resonance	$\mathcal{B}_{(c\bar{c}) \rightarrow \gamma\gamma}$ ( $10^{-4}$ )	$\mathcal{B}_{B^0} \times \mathcal{B}_{(c\bar{c})}$ ( $10^{-7}$ )	$\mathcal{B}_{B^+} \times \mathcal{B}_{(c\bar{c})}$ ( $10^{-7}$ )
$\eta_c(2986)$	$4.3 \pm 1.5$	$5.2 \pm 2.5$	$3.9 \pm 1.8$
$\chi_{c0}(3415)$	$2.6 \pm 0.5$	$< 1.3$	$0.8 \pm 0.2$
$\chi_{c2}(3556)$	$2.46 \pm 0.23$	$< 0.10$	$< 0.07$
$\eta'_c(3638)$	-	-	-

knowledged a numerical error in their computations and published updated values [18] in accordance with [5].

The contributions from higher kaon resonances decaying to  $K\gamma$  are difficult to assess with current experimental information. Recent measurements of  $B \rightarrow K_1(1270)\gamma$  and  $K_2^*(1430)\gamma$  [19] and corresponding radiative width determinations for these resonances [20] indicate that the effective  $K\gamma\gamma$  branching fractions from these higher resonances are in the same range as for  $K^*(892)$ . Since a number of other kaon resonances may contribute to this final state, the overall  $B \rightarrow K\gamma\gamma$  branching fraction due to kaon resonances could be an order of magnitude larger than our estimate for  $K^*$  only, bringing it to a level that may be accessible at currently running  $B$  factories. In view of the coarse experimental information available we leave these contributions to future investigations and assume here that their effects can be subtracted or isolated for the purpose of this study.

While the contributions from  $\eta$  and  $\eta'$  are sizable, giving effective branching fractions of up to  $1.5 \times 10^{-6}$ , they result in photons of relatively low energy. This will render the observation of interference effects with the  $B \rightarrow K^*(K\gamma)\gamma$  amplitude experimentally difficult. We will therefore focus on the more promising charmonium resonances occurring at higher energies. Table I summarizes the relevant experimental data for these resonances. Among the charmonium resonances, only  $\eta_c$  and  $\chi_{c0}$  are known both to decay into two photons and to be produced in  $B$  decays with an associated kaon, so that we will restrict our analysis to these two resonances.

To model the amplitudes  $\mathcal{M}_{\eta_c, \chi_{c0}}$  for the  $B$  decays to  $\eta_c(\gamma\gamma)K$  and  $\chi_{c0}(\gamma\gamma)K$  we use a general Breit-Wigner Ansatz along the lines described in Ref. [5]. Thus we neglect variations in the amplitudes beyond the Breit-Wigner form. For  $B \rightarrow \eta_c K$  we follow the factorization approach employed in Ref. [4]. The full amplitude for  $B \rightarrow K\gamma\gamma$ , including the three resonance contributions, is then given by  $\mathcal{M}_{K^*} + \xi_{\eta_c} \mathcal{M}_{\eta_c} + \xi_{\chi_{c0}} \mathcal{M}_{\chi_{c0}}$ , where  $\xi_{\eta_c, \chi_{c0}} = \pm 1$  denote unknown relative interference signs.

To study the role of the interference terms as photon polarization analyzers, we generalize the SM amplitude for  $B \rightarrow K^*(K\gamma)\gamma$  to include an amplitude for the emission of a right-handed photon from the  $b$ -quark. Follow-

ing Ref. [12], we add a right-handed component to the operator  $O_7$  from Eq. 1, *i.e.*  $C_7 O_7 \rightarrow C_7 O_7 + C_7' O_7'$ , with  $O_7' = (em_b)/(16\pi^2) \bar{s}_R \sigma_{\mu\nu} b_L F^{\mu\nu}$ , describing the emission of a right-handed photon. In this picture, the probability  $f_R$  for the emission of a right-handed photon from the  $b$ -quark is given by the corresponding Wilson coefficient,  $f_R = |C_7'|^2/(|C_7|^2 + |C_7'|^2)$ . The naive SM estimate for this fraction is  $f_R \approx 0.1\%$  based on  $C_7'/C_7 \approx m_s/m_b$  from the chiral structure of the  $W$ -boson couplings to quarks [7]. A recent study including other operators that contribute to  $b \rightarrow s\gamma_R$  finds that  $f_R$  may be as large as 1% within the SM [22]. In the following we assume the Wilson coefficients to be real, *i.e.* we do not consider additional sources of CP violation beyond the SM.

Taking account of the symmetry properties of the amplitude (2) it is straightforward to incorporate the emission of a right-handed photon by adding a parity-inverted term proportional to  $C_7'$ . Evaluation of the full amplitude then shows explicitly that the  $\eta_c$ - $K^*$  interference term is proportional to  $(C_7 - C_7')$  while the  $\chi_{c0}$ - $K^*$  interference term is proportional to  $(C_7 + C_7')$ . These interference terms are accessible to experiment: they manifest themselves as enhancements or reductions in the diphoton mass spectrum of  $B \rightarrow K\gamma\gamma$  decays near the resonance peaks, depending on the signs involved. The Wilson coefficients  $C_7$  and  $C_7'$  may thus be cleanly extracted from the observed diphoton mass spectrum, if the signs of the interference terms are known. Unfortunately, neither of the two interference signs is known model-independently today, such that only values for  $|C_7 - C_7'|$  and  $|C_7 + C_7'|$  can be derived from a measured spectrum, leading to a four-fold ambiguity in the solution for  $(C_7, C_7')$ , see Fig. 2. In spite of the four-fold ambiguity, a measurement of these interference terms still represents a valuable test of the SM. Recall that the overall normalization  $|C_7|^2 + |C_7'|^2$  is given by the inclusive  $b \rightarrow s\gamma$  rate and hence already known from experiment. In Fig. 3 we show diphoton mass spectra for various values of  $c_7^{(\prime)} = C_7^{(\prime)}/\sqrt{C_7^2 + C_7'^2}$  for  $B^-$  decay, with positive interference signs assumed throughout.

Experimentally, the interference terms are most readily isolated by means of asymmetries. An observable that is particularly convenient to extract the  $\eta_c$  interference is the charge asymmetry  $A_C$ , defined as

$$A_C(m_{\gamma\gamma}) = \frac{d\Gamma^-/dm_{\gamma\gamma} - d\Gamma^+/dm_{\gamma\gamma}}{d\Gamma^-/dm_{\gamma\gamma} + d\Gamma^+/dm_{\gamma\gamma}}, \quad (3)$$

with  $\Gamma^\pm = \Gamma(B^\pm \rightarrow K^\pm\gamma\gamma)$ . An analog asymmetry may be defined for neutral  $B$  decays, where experimental difficulties arise from flavor tagging, compensated in part by the larger statistics available. Here we only consider the charged decay. In Fig. 4 (a) we show the expected  $A_C$  for various combinations of  $c_7$  and  $c_7'$ . It exhibits the typical shape of a Breit-Wigner interference around the position of the  $\eta_c$  resonance, with a distortion at higher energies due to the presence of the  $\chi_{c0}$  resonance, which forces the

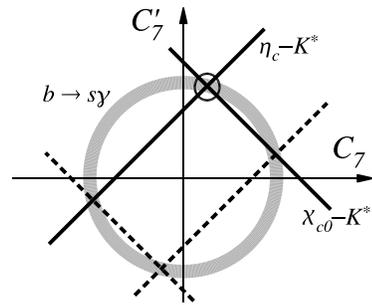


FIG. 2: Schematic illustration of the constraints in the  $C_7$ - $C_7'$  plane obtained from a spectrum measurement of  $B \rightarrow K\gamma\gamma$ . The gray circle depicts the region allowed from inclusive  $b \rightarrow s\gamma$  measurements, the solid diagonal lines represent the solutions corresponding to the  $\eta_c$ - $K^*$  and  $\chi_{c0}$ - $K^*$  interferences, with dashed lines indicating mirror solutions in the case where the interference signs are unknown.

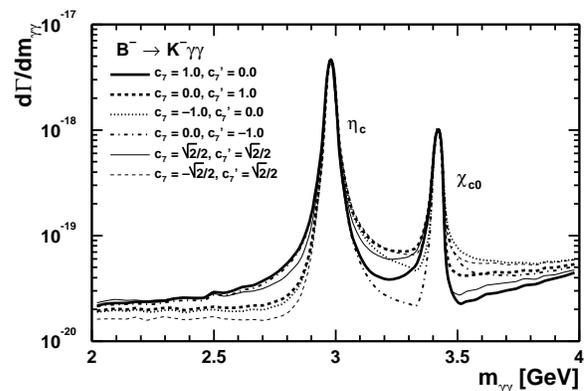


FIG. 3: Diphoton mass spectra for  $B^- \rightarrow K^- \gamma\gamma$  for various values of the normalized Wilson coefficients  $c_7$  and  $c_7'$ .

charge asymmetry to zero in its vicinity. The value of the maximum asymmetry below the  $\eta_c$  peak is a direct measure of  $(c_7 - c_7')$ , we find  $A_C^{\max} \approx (0.37 \pm 0.02) \times (c_7 - c_7')$  for positive interference sign. The error is dominated by the uncertainty in the  $\eta_c$  branching fraction, see Table I.

The  $\chi_{c0}$  interference, being CP-even, cannot be extracted in the same manner. Instead we define a charge-averaged peak asymmetry around the  $\chi_{c0}$ ,

$$A_{\chi_{c0}}(\Delta m_{\gamma\gamma}) = \frac{d\bar{\Gamma}(m^-)/dm_{\gamma\gamma} - d\bar{\Gamma}(m^+)/dm_{\gamma\gamma}}{d\bar{\Gamma}(m^-)/dm_{\gamma\gamma} + d\bar{\Gamma}(m^+)/dm_{\gamma\gamma}}, \quad (4)$$

where  $m^\pm = m_{\chi_{c0}} \pm \Delta m_{\gamma\gamma}$ , and  $\bar{\Gamma} = (\Gamma^+ + \Gamma^-)/2$ . The expected peak asymmetry is shown in Fig. 4 (b), again for various combinations of  $c_7$  and  $c_7'$ . It is dominated by the sought-after interference effect, since the distribution of  $B \rightarrow K^*(K\gamma)\gamma$  events is rather flat in that region. For values of  $\Delta m_{\gamma\gamma}$  well below  $m_{\chi_{c0}} - m_{\eta_c}$  (at which point  $A_{\chi_{c0}} = 1$  due to the  $\eta_c$  peak) we find  $A_{\chi_{c0}}^{\max} \approx (0.40 \pm 0.01) \times (c_7 + c_7')$  for positive interference sign. In this case the error mainly originates from the uncertainty

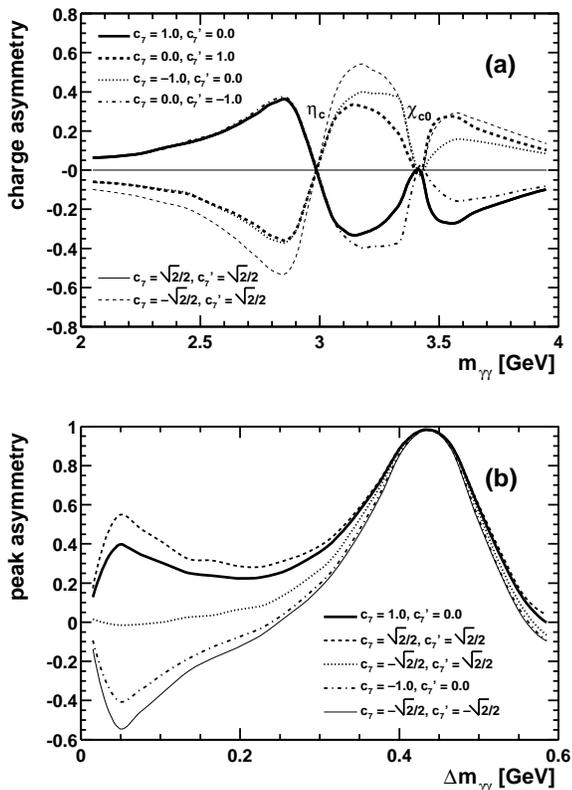


FIG. 4: (a) Charge asymmetry  $A_C(m_{\gamma\gamma})$  and (b) peak asymmetry  $A_{\chi_{c0}}(\Delta m_{\gamma\gamma})$  for various values of  $c_7$  and  $c'_7$ . All interference terms are assumed to have positive sign.

in the  $\chi_{c0}$  branching fraction (Table I).

The principal experimental limitation for such a measurement will be the required statistics of  $B$  decays. To arrive at a rough estimate of the required order of magnitude of  $B$  mesons, we note that some  $10^3$  clean  $B \rightarrow K^*(K\gamma)\gamma$  decays would be necessary for a measurement distinguishing between the case of a fully polarized and that of an unpolarized photon emitted in  $b \rightarrow s\gamma$ . Factoring in branching fractions and typical reconstruction efficiencies for radiative decays at  $e^+e^- B$  factories ( $\approx 10\%$ ) and hadron colliders ( $\approx 0.1\%$ ) we find that several  $10^{10}$  ( $10^{12}$ ) neutral or charged  $B$  mesons would be needed in the case of an  $e^+e^-$  (hadron) collider. These numbers are compatible with expected annual production rates at future facilities being proposed [16] or built [17]. Of course, many experimental issues remain to be addressed within the context of a specific experimental setup and as more knowledge on the amplitudes involved in  $B \rightarrow K\gamma\gamma$  decay becomes available.

Our conclusion is that contributions to  $B \rightarrow K\gamma\gamma$  from kaon resonances are sizable and may be very useful for probing the  $b \rightarrow s\gamma$  transition beyond the SM. While our method to determine the photon polarization in this transition requires more statistics than the more conven-

tional ones, it has the advantage that it yields additional information on the Wilson coefficients  $C_7$  and  $C'_7$ .

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