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Measurements of the photon polarization in $b \to s\gamma$ decays

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The possible participation of New Physics candidates as virtual states can be probed through the study of the photon polarization in $b \to s\gamma$ transitions. The latest results of measurements of $b \to s\gamma$ channels obtained at the LHCb detector; specifically the measurement of the photon polarization in $B^+ \to K^+\pi^+\pi^-\gamma$ and the angular analysis of $B^0 \to K^{*0}e^+e^-$, are presented in this contribution.

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1. Introduction

The $b \to s\gamma$ transition is forbidden at tree level in the Standard Model (SM) and occurs via loop diagrams at leading order. These processes can be described by an effective Hamiltonian using a technique called operator product expansion. In the SM, the dominant contribution is from by the so-called electromagnetic penguin, described by $\mathcal{O}_{7\gamma}$. It is explicitly written as

$$\mathcal{O}_{7\gamma}=\frac{e}{16\pi^2}m_b\bar{s}_{\alpha L}\sigma^{\mu\nu}b_{\alpha R}F_{\mu\nu} \quad \text{and} \quad \mathcal{O}'_{7\gamma}=\frac{e}{16\pi^2}m_b\bar{s}_{\alpha R}\sigma^{\mu\nu}b_{\alpha L}F_{\mu\nu},$$

for the left and right handed operators, respectively. The corresponding Wilson coefficients are $\mathscr{C}_{7\gamma}$ and $\mathscr{C}'_{7\gamma}$. The structure of this process constrains the polarization of the photon to be dominantly left-handed in the SM up to a small correction of order m_s/m_b [1]. Nevertheless, yet unobserved particles predicted by different Beyond Standard Model theoretical models could enhance the number of right-handed photons emitted, so precise measurements of the photon polarization are excellent probes for New Physics (NP) effects.

2. Photon polarization in $B^+ \to K^+\pi^+\pi^-\gamma$

The photon polarization can be accessed through decay channels with three bodies and a photon in the final state. The three bodies must come from a resonance since this defines its helicity in correlation to the photon's, and thus the angular study of the products yields information of the latter. In the resonance's rest frame the tracks of the three bodies define a plane from which the direction of photon emission, related to its helicity, can be determined and expressed as function of an angle θ. This angle is defined in the rest frame of the final state hadrons as the angle between the direction opposite to the photon momentum $\vec{p}_\gamma$ and the normal $\vec{p}_{\pi,\mathrm{slow}} \times \vec{p}_{\pi,\mathrm{fast}}$ to the $K^+\pi^+\pi^-$ plane, where $\vec{p}_{\pi,\mathrm{slow}}$ and $\vec{p}_{\pi,\mathrm{fast}}$ correspond to the momenta of the lower and higher momentum pions, respectively. This allows the definition of an up-down asymmetry, A_{ud}, as the difference in the numbers photons emitted to either side of the plane normalized to all the photons emitted,

$$A_{\mathrm{ud}} \equiv \frac{N(K^+\pi^+\pi^-\gamma)_{\cos\theta>0} - N(K^+\pi^+\pi^-\gamma)_{\cos\theta<0}}{N(K^+\pi^+\pi^-\gamma)_{\cos\theta>0} + N(K^+\pi^+\pi^-\gamma)_{\cos\theta<0}} = \frac{\int_0^1 \mathrm{d}\cos\theta \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta} - \int_{-1}^0 \mathrm{d}\cos\theta \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta}}{\int_{-1}^1 \mathrm{d}\cos\theta \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta}}.$$

Following Ref. [2] the differential decay rate of $B^+ \to K^+\pi^+\pi^-\gamma$ is parametrized as a fourth-order polynomial in $\cos\theta$ as

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}s\,\mathrm{d}s_{13}\,\mathrm{d}s_{23}\,\mathrm{d}\cos\theta} \propto \sum_{i=0,2,4} a_i(s,s_{13},s_{23})\cos^i\theta + \lambda_\gamma \sum_{j=1,3} a_j(s,s_{13},s_{23})\cos^j\theta,$$

where $s_{ij} = (p_i + p_j)^2$ and $s = (p_1 + p_2 + p_3)^2$, and p_1, p_2 and p_3 are the four-momenta of the π^-, π^+ and K^+ mesons, respectively. The functions a_k depend on the resonances contributing to the $K^+\pi^+\pi^-$ final state and their interferences. The photon polarization parameter, λ_γ, can be written in terms of the Wilson coefficients $\mathscr{C}_{7\gamma}$ and $\mathscr{C}'_{7\gamma}$, which are related to the left- and right-handed operators, respectively, as [1]

$$\lambda_\gamma \simeq \frac{|\mathscr{C}'_{7\gamma}|^2 - |\mathscr{C}_{7\gamma}|^2}{|\mathscr{C}'_{7\gamma}|^2 + |\mathscr{C}_{7\gamma}|^2}.$$

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Therefore, measuring the extremal values of ± 1 would represent fully polarized photons, with the positive case corresponding to the right handed case and viceversa, and any value in between a mix of polarizations. Given the integral definition of $A_{\rm ud}$, it is easy to see that the dependence on even powers of $\cos\theta$ is lost and it only depends on odd powers, therefore $A_{\rm ud}$ is proportional to λ_γ and any non-zero measurement would indicate polarization of the photon. Since the sign of λ_γ depends on the sign of the electric charge of the $B^\pm$ meson, the variable $\cos\hat{\theta} \equiv {\rm charge}(B)\cdot\cos\theta$ is defined for the analysis.

The LHCb collaboration has published the results of the study of the up-down asymmetry in $B^+ \to K^+\pi^+\pi^-\gamma$ done with 3 fb^{-1} of integrated luminosity, the full Run I dataset [3]. This analysis is performed in four different intervals of the $K^+\pi^+\pi^-$ invariant mass $[1.1, 1.3], [1.3, 1.4], [1.4, 1.6]$, and $[1.6, 1.9]$ GeV$/c^2$, as means to separate contributions from the different resonances. The up-down asymmetry is studied via both an angular fit and a counting experiment in each of these intervals and compared to the null-hypothesis, $\lambda_\gamma = 0$, in order to extract a significance value via a χ^2 test. Both methods yield compatible results. Plots for the angular fit can be seen in Figure 1.

The significance for all the studied mass range is $5.2\,\sigma$, resulting in the first observation of photon polarization in $b \to s\gamma$ transitions. Due to the complex resonance structure of the $K^+\pi^+\pi^-$ mass spectrum, precise determination of the a_k functions requires knowledge of the spin parities of the resonances therein and a full amplitude analysis is needed to extract a concrete value of λ_γ, currently in progress at LHCb.

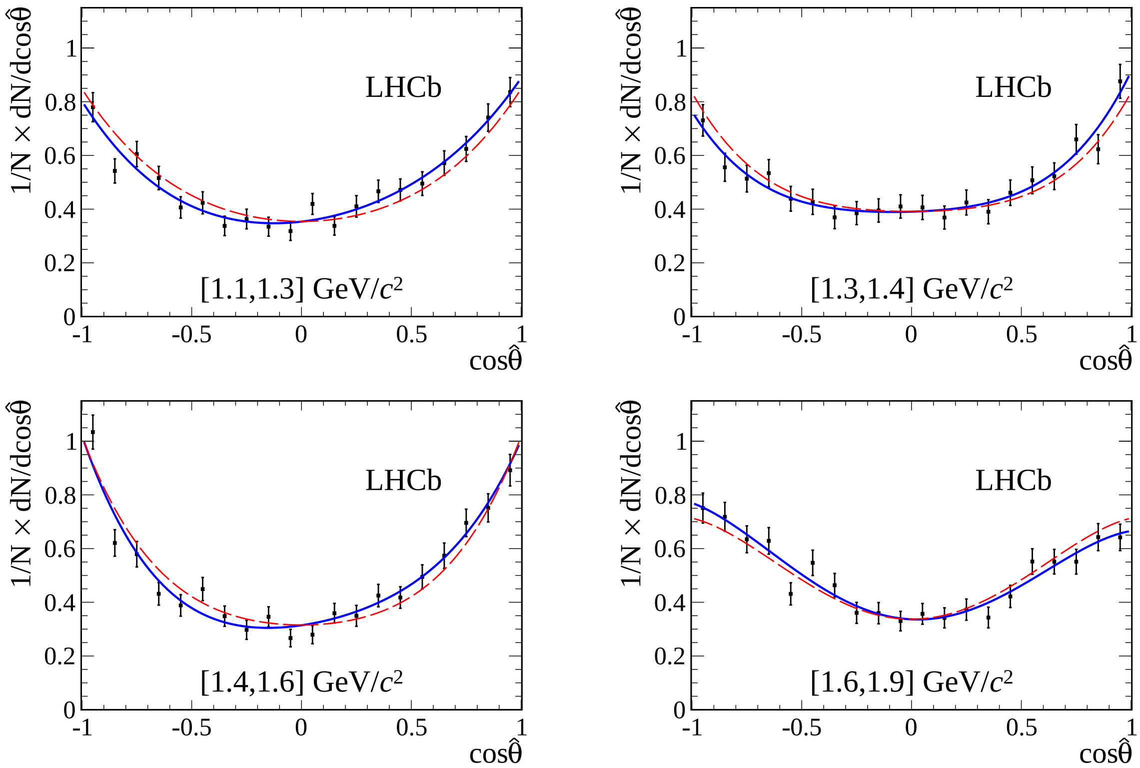

Figure 1: Distributions of $\cos\hat{\theta}$ for $B^+ \to K^+\pi^+\pi^-\gamma$ signal in four intervals of $K^+\pi^+\pi^-$ mass. The solid blue curves are the result of fits allowing all the polynomial components up to the fourth power, while the dashed red correspond to those only allowing even components, corresponding to the null hypothesis.

3. Angular analysis of $B^0 \to K^{*0} e^+ e^-$

The LHCb collaboration has previously published angular studies of $B^0 \to K^{*0}\ell^-\ell^+$ modes in the $B^0 \to K^{*0}\mu^+\mu^-$ mode [4–6]. The dielectron mode's angular parameters are measured with the full LHC Run I dataset [7], corresponding to 3 fb^{-1} of integrated luminosity at LHCb. Due to their small mass, electrons in the final state permit analyses at very low q^2, the dilepton invariant mass squared. For small values of q^2 the virtual photon contribution dominates, giving sensitivity to $\mathscr{C}_{7\gamma}$ and $\mathscr{C}'_{7\gamma.}$ Experimentally, this channel is challenging due to the difficult electron reconstruction owing to bremsstrahlung energy losses which have to be accurately modelled into the mass fit function and corrected by recovering energy clusters associated to the original electron tracks in the electromagnetic calorimeter. Furthermore, the dielectron mode presents a lower trigger efficiency than that of $B^0 \to K^{*0}\mu^+\mu^-$.

The analysis is performed in an effective q^2 range of 0.002 to 1.120 GeV^2/c^4 via a four dimensional unbinned maximum likelihood fit to the invariant mass of the decay products and three decay angles that characterize the relative distribution of the final states. Those angles are the angle between the direction of the e^+ (e^-) and the direction opposite to that of the B^0 ($\bar{B}^0$) meson in the dielectron rest frame, θ_ℓ; the angle between the direction of the kaon of the K^{*0} and the direction opposite to that of the B^0 ($\bar{B}^0$) in the K^{*0} ($\bar{K}^{*0}$) rest frame, θ_K; and the angle between the plane containing the dielectron system and the plane containing the kaon and the pion from the K^{*0} ($\bar{K}^{*0}$) in the B^0 ($\bar{B}^0$) rest frame, ϕ. Without any loss of sensitivity to the parameters of interest one can fold the ϕ angle as $\tilde{\phi} = \phi + \pi$ for $\phi < 0$, which eliminates the sensitivity to other unknown observables not in the scope of this analyses and therefore simplifying the fit function. The $B^0 \to K^{*0}e^+e^-$ angular distribution can be written as

$$
\begin{aligned}
\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\tilde{\phi}} = \frac{9}{16\pi}\Bigg[& \frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \\
& \left(\frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K - F_\mathrm{L}\cos^2\theta_K\right)\cos 2\theta_l \quad + \\
& \frac{1}{2}(1-F_\mathrm{L})A_\mathrm{T}^{(2)}\sin^2\theta_K\sin^2\theta_l\cos 2\tilde{\phi} \quad + \\
& (1-F_\mathrm{L})A_\mathrm{T}^\mathrm{Re}\sin^2\theta_K\cos\theta_l \quad + \\
& \frac{1}{2}(1-F_\mathrm{L})A_\mathrm{T}^\mathrm{Im}\sin^2\theta_K\sin^2\theta_l\sin 2\tilde{\phi}\Bigg].
\end{aligned}
$$

Using this expression, one can extract values for the angular observables F_L, $A_\mathrm{T}^{(2)}$, $A_\mathrm{T}^{\mathrm{Re},}$ and $A_\mathrm{T}^{\mathrm{Im},}$ defined in terms of the transversity amplitudes as [8]

$$
\begin{aligned}
F_\mathrm{L} &= \frac{|A_0|^2}{|A_0|^2+|A_\parallel|^2+|A_\perp|^2}, \\
A_\mathrm{T}^{(2)} &= \frac{|A_\perp|^2-|A_\parallel|^2}{|A_\parallel|^2+|A_\perp|^2}, \\
A_\mathrm{T}^\mathrm{Re} &= \frac{2\mathscr{R}e(A_{\parallel L}A^*_{\perp L}+A_{\parallel R}A^*_{\perp R})}{|A_\parallel|^2+|A_\perp|^2}, \quad \text{and} \\
A_\mathrm{T}^\mathrm{Im} &= \frac{2\mathscr{I}m(A_{\parallel L}A^*_{\perp L}+A_{\parallel R}A^*_{\perp R})}{|A_\parallel|^2+|A_\perp|^2}.
\end{aligned}
$$

The amplitudes A_x correspond to the different polarization states $x = 0, \perp, \|$ of the K^{*0} in the decay, the labels L and R correspond respectively to the left and right chiralities of the dielectron system and $|A_x|^2$ is shorthand for $|A_{xL}|^2 + |A_{xR}|^2$. In the $q^2 \to 0$ limit $A_{\mathrm{T}}^{(2)}$ and $A_{\mathrm{T}}^{\mathrm{Im}}$ can be expressed in terms of the Wilson coefficients $\mathscr{C}_{7\gamma}$ and $\mathscr{C}'_{7\gamma}$ as

$$A_{\mathrm{T}}^{(2)}(q^2 \to 0) = \frac{2\mathscr{R}e(\mathscr{C}_7 \mathscr{C}_7'^*)}{|\mathscr{C}_7|^2 + |\mathscr{C}_7'|^2}, \quad \text{and} \quad A_{\mathrm{T}}^{\mathrm{Im}}(q^2 \to 0) = \frac{2\mathscr{I}m(\mathscr{C}_7 \mathscr{C}_7'^*)}{|\mathscr{C}_7|^2 + |\mathscr{C}_7'|^2}.$$

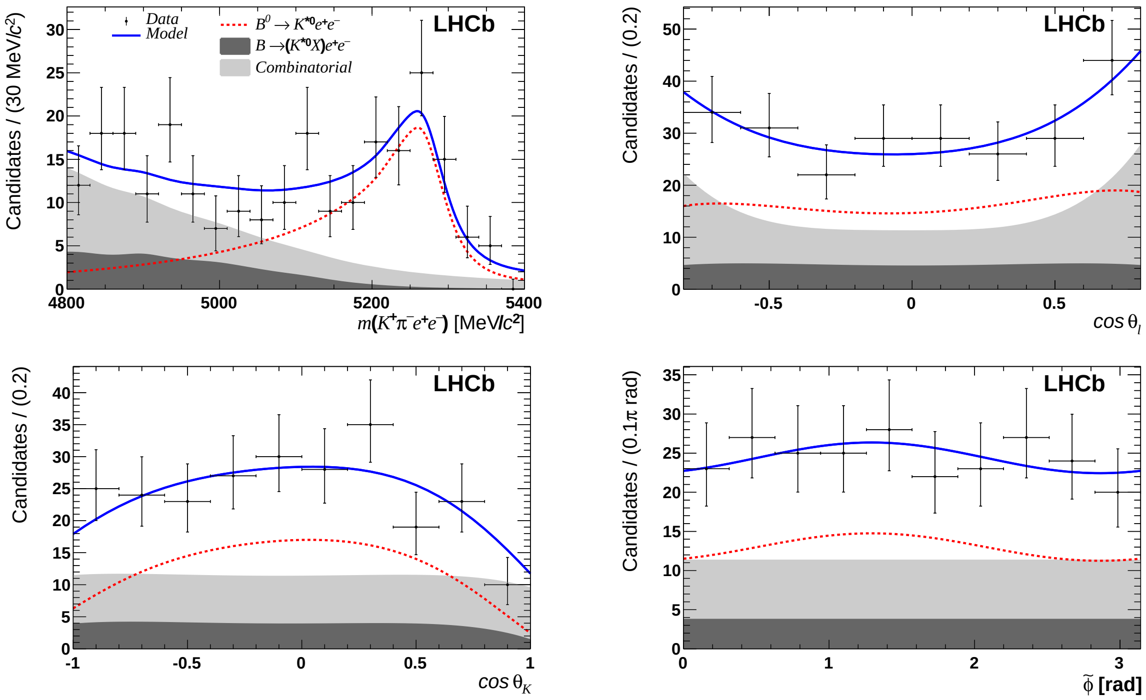

Figure 2: Fitted distributions of the $K^+\pi^-e^+e^-$ invariant mass, $\cos\theta_\ell$, $\cos\theta_K$ and $\tilde{\phi}$ variables for the $B^0 \to K^{*0}e^+e^-$ decay mode. The dashed line is the signal PDF, the light grey area corresponds to the combinatorial background and the dark grey area is the partially reconstructed background. The solid line is the total PDF.

The plots of the fits to the invariant mass and the three angular variables are shown in Figure 2. The angular observables were measured to be

$$\begin{aligned} F_{\mathrm{L}} &= +0.16 \pm 0.06 \pm 0.03, \\ A_{\mathrm{T}}^{(2)} &= -0.23 \pm 0.23 \pm 0.05, \\ A_{\mathrm{T}}^{\mathrm{Re}} &= +0.10 \pm 0.18 \pm 0.05, \\ A_{\mathrm{T}}^{\mathrm{Im}} &= +0.14 \pm 0.22 \pm 0.05, \end{aligned}$$

where the first uncertainty is statistical and the second systematic. These results are in good agreement with the SM predictions of pure left-handed polarization [8, 9].

Conclusions

The photon polarization in $b \to s\gamma$ is a powerful observable to probe for NP effects, and the LHCb collaboration is obtaining leading measurements in this field. At present the results agree with their SM predictions, but future developments and the increase in statistics during the Run II period of the LHC will allow further exploration of this interesting sector.

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