Radiative B decays at LHCb

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Abstract. Radiative B decays are sensitive probes for new physics. In particular, the measurement parameters sensitive to the photon polarisation could help constrain various models of new physics. We present three methods used by the LHCb collaboration to measure the photon polarisation using $3\,\mathrm{fb}^{-1}$ of integrated luminosity.

1. Introduction

Radiative decays of B mesons are flavour changing neutral current processes which are forbidden at tree level in the Standard Model (SM). These decays predominantly occur via $b \to s\gamma$ loop diagrams and are therefore sensitive to new physics (NP) effects.

Numerous studies of radiative decays have been performed at LHCb since the beginning of the data taking in 2010, two of which provided the first constraints on the photon polarisation parameter. The observation of a non-zero photon polarisation in $B^+ \to K^+\pi^-\pi^+\gamma$ decays[1] at LHCb is presented here [1], along with the measurement of angular observables related to the photon polarisation in $B^0 \to K^{0*}e^+e^-$ decays at low dielectron invariant masses, due to the contribution of the virtual photon [2]. The decay time analysis of $B_0^s \to \phi\gamma$ decays, which also constrains this parameter, will be introduced [3].

2. Photon polarisation in radiative B decays

Photons produced in $b \to s\gamma$ transitions are expected to be predominantly left handed in the SM. However, some NP contributions may introduce a significant right handed component to the photon polarisation. Although the measured inclusive $b \to s\gamma$ rate [4] has already put strong constraints on NP scenarios, there is still room for observation of non-SM effects in the photon polarisation.

The decay amplitude for $b \to s\gamma$ transition is proportional to [5]:

$$< f|H_{\mathrm{eff}}|i> = -4\frac{G_F}{\sqrt{2}}V_{tb}V_{ts}^*[\mathcal{C}_7^{\mathrm{eff}}(m_b) < f|O_7(m_b)|i> + \mathcal{C}_7^{\prime\mathrm{eff}}(m_b) < f|O_7'(m_b)|i>] \qquad (1)$$

where $\mathcal{C}_7^{\mathrm{eff}}$ and $\mathcal{C}_7^{\prime\mathrm{eff}}$ are the Wilson coefficients coupled to the left and right handed photon respectively.

In the SM, those coefficients are such that:

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[1] The charge conjugation is implied throughout the text.

$$\frac{\mathcal{C}_7'^{\text{eff}}}{\mathcal{C}_7^{\text{eff}}} \simeq \frac{m_s}{m_b} \simeq 0.02 \tag{2}$$

The photon polarisation parameter λ_γ is defined as the asymmetry between the right and left components:

$$\lambda_\gamma = \frac{|\mathcal{C}_7'^{\text{eff}}|^2 - |\mathcal{C}_7^{\text{eff}}|^2}{|\mathcal{C}_7'^{\text{eff}}|^2 + |\mathcal{C}_7^{\text{eff}}|^2} \tag{3}$$

In the SM, the value of this parameter is -1 up to corrections of the order of (m_s^2/m_b^2) for decays of a b quark.

3. Studies of Radiative B decays at LHCb

The measurement of radiative B decays at LHCb [6] is allowed by the good quality of the tracking systems with a momentum resolution $\delta p/p$ of 0.5-1% in the full momentum range, a time resolution of 45 fs and a resolution on the impact parameter of 20 μm for high p_T tracks. The Ring Imaging CHerenkov detector (RICH) provides a good particle identification, allowing to separate kaons and protons from pions. Finally, the calorimeter system which is essential to the detection of radiative decays has a resolution of $\sigma_E/E \simeq 10\%/\sqrt{E} + 1\%$.

Studies of radiative decays at LHCb face three main challenges that are the use of pp collisions which generate high levels of background, the misidentification of π^0s due to unresolved photons at transverse energies above 4 GeV, and the mass resolution dominated by the photon reconstruction.

Despite these difficulties, LHCb has managed to perform high precision measurements of radiative B decays. Using the 0.37 fb^{-1} of LHCb data obtained in the first half of 2011, the ratio of branching ratios of $B_0 \to K^*\gamma$ over $B_0^s \to \phi\gamma$ decays has been measured to be $1.12 \pm 0.08(stat)_{0.04}^{0.06}(syst)_{0.08}^{0.09}(f_s/f_d)$ [7], which is in agreement with the theory prediction of 1.0 ± 0.2 [8]. In particular, searches for $B^0 \to J/\psi\gamma$ and $B_s^0 \to J/\psi\gamma$ have been conducted on the 3 fb^{-1} of data collected by LHCb in 2011 and 2012 using converted photons to suppress background from decays like $B^0 \to J/\psi\pi^0$ [9]. For the $B^0 \to J/\psi\gamma$ mode, branching ratios higher than 1.5×10^{-6} are excluded at 90% confidence level, which is in agreement with the BABAR limit [10]. Branching ratio values over 7.3×10^{-6} have been excluded at 90% confidence level for $B_s^0 \to J/\psi\gamma$ decays, which is the first limit ever set on this decay.

4. Measuring the photon polarisation

Several methods have been proposed to measure the photon polarisation in B decays. The four most promising methods respectively use:

⋄ Angular distribution of radiative decays with three charged particles in the final state (e.g. $B^+ \to K^+\pi^-\pi^+\gamma$)

⋄ The transverse asymmetry in $B^0 \to K^{0*}e^+e^-$ decays in the low dielectron invariant mass region

⋄ Time-dependent analyses of B^0 or B_s^0 decaying into a photon and a CP-eigenstate (e.g. $B^0 \to K_S\pi^0\gamma$, $B_s^0 \to \phi\gamma$)

⋄ Angular distributions in $\Lambda_b \to \Lambda\gamma$ and other b baryon decays.

The first two methods have been exploited at LHCb and their results are presented below. The third one is ongoing.
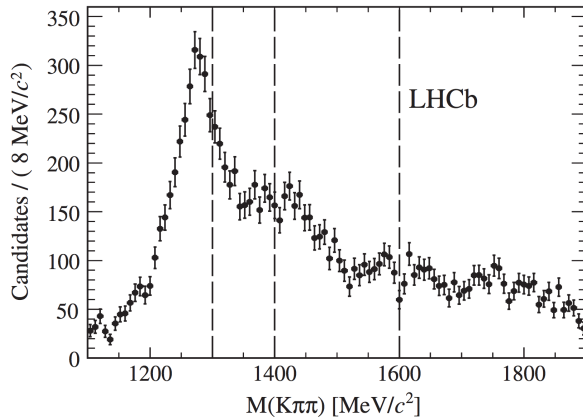
Figure 1: Background-subtracted $K\pi\pi$ mass distribution of the $B^+ \to K^+\pi^-\pi^+\gamma$ signal. The four intervals of interest are shown separated by dashed lines [1].
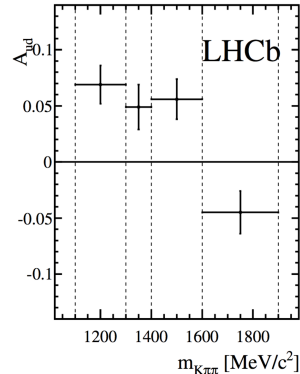

Figure 2: Values obtained for $\mathcal{A}_{\mathrm{ud}}$ from fits to the normalized background substracted $\cos\widehat{\theta}$ distribution in each bin of $K\pi\pi$ mass [1].

4.1. Observation of a non-zero photon polarisation in $B^+ \to K^+\pi^-\pi^+\gamma$ decays

The $B^+ \to K^+\pi^-\pi^+\gamma$ decay is expected to proceed via different K^* resonances so the decay can be written as $B \to K_{\mathrm{res}}(\to P_1P_2P_3)\gamma$ where P_1, P_2 and P_3 refer to the final state hadrons. Using the final-state momenta $\overrightarrow{\mathrm{p}_i}$ (i = 1, 2, 3) and p_γ in the K_{res} rest frame, $\cos\theta$ is defined as [11]:

$$\cos\theta = -\frac{\overrightarrow{\mathrm{p}_\gamma}}{|\overrightarrow{\mathrm{p}_\gamma}|} \cdot \widehat{n}, \text{ with } \widehat{n} \equiv \frac{\overrightarrow{\mathrm{p}_1} \times \overrightarrow{\mathrm{p}_2}}{|\overrightarrow{\mathrm{p}_1} \times \overrightarrow{\mathrm{p}_2}|} \tag{4}$$

As $\cos\theta$ changes sign under the exchange of s_{13} and s_{23}, a new variable $\cos\tilde{\theta} = \mathrm{sign}(\mathrm{s}_{12}-\mathrm{s}_{23})\cos\theta$ is introduced. Then the up-down asymmetry is defined as:

$$\mathcal{A}_{\mathrm{ud}} = \frac{\int_0^1 \mathrm{dcos}\tilde{\theta} \times \frac{\mathrm{d}\Gamma}{\mathrm{dcos}\tilde{\theta}} - \int_{-1}^0 \mathrm{dcos}\tilde{\theta} \times \frac{\mathrm{d}\Gamma}{\mathrm{dcos}\tilde{\theta}}}{\int_{-1}^1 \mathrm{dcos}\tilde{\theta} \times \frac{\mathrm{d}\Gamma}{\mathrm{dcos}\tilde{\theta}}} = C \times \lambda_\gamma \tag{5}$$

where the proportionality coefficient C depends on the content of the $K\pi\pi$ system. Due to missing knowledge of the $K\pi\pi$ system and lack of theoretical predictions, this proportionality coefficient can not be determined yet.

This analysis used a data sample of *pp* collisions recorded by LHCb in 2011 and 2012, corresponding to a total luminosity of $3\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 7$ and 8 TeV [1]. The signal is reconstructed by selecting events with a high $\mathrm{p_t}$ photon and three charged tracks, one of which is associated to a charged kaon and the other two to oppositely charged pions. High transverse energy photons are reconstructed from energy deposits in the calorimeter. The signal events are separated from the background from B decays with π^0s using the shape of the electromagnetic shower in the calorimeter.

A fit to the mass distribution of $B^+ \to K^+\pi^-\pi^+\gamma$ candidates is performed and yields 13876 $\pm$ 153 events. The background-subtracted $K\pi\pi$ spectrum is obtained and shown on Fig. 1. The peak of the $K_1(1270)$ is visible and the rest of the spectrum is populated by many K resonances of different masses and spins. The data set is divided in 4 bins following recommendations from theory [11]. In each of those four bins, the background subtracted angular distribution is fitted with a fourth order Legendre polynomial normalized to the unit area:

$$\text{f}(\cos\widehat{\theta};\, c_0 = 0.5,\, c_1,\, c_2,\, c_3,\, c_4) = \sum_{i=0}^{4} c_i \text{L}_i(\cos\widehat{\theta}) \tag{6}$$

where $\text{L}_i(\text{x})$ is the Legendre Polynomial of order i and $\cos\widehat{\theta}$ is equal to $\cos\widetilde{\theta}$ corrected for the charge of the B meson. The up-down asymmetry can be expressed in terms of the c_i coefficients by:

$$\mathcal{A}_{\text{ud}} = c_1 - \frac{c_3}{4} \tag{7}$$

The results obtained from a χ^2 fit of the normalized binned angular distribution are shown in Fig. 2. The combined observed values translate into a 5.2 σ significance for non zero up-down asymmetry. As the up-down asymmetry is proportional to the photon polarisation, this study also lead to the observation of a non-zero photon polarisation with a significance of 5.2 σ. However, as the proportionality coefficient between these observables is unknown, a partial wave analysis is needed and in progress at LHCb to disentangle the contributions from the different resonances.

4.2. $B^0 \to K^{0*}e^+e^-$ at low dielectron invariant mass

$B^0 \to K^{0*}e^+e^-$ decays occur through penguin diagrams or electroweak box diagrams. The contribution of each of these diagrams varies with the dilepton mass. In the region of low dilepton invariant mass squared (q^2) below 6 GeV$^2/c^4$, couplings from a virtual photon to the dilepton pair dominate, allowing for sensitivity to the helicity of the photon in $b \to s\gamma$ transitions.

The partial decay rate of the $B^0 \to K^{0*}e^+e^-$ decays can be described with four variables [12]: q^2 and three angular variables, θ_l, θ_K and ϕ. θ_l is defined as the angle between the electron and the opposite direction of the B in the dilepton rest frame. θ_K is the angle of the K meson with respect to the opposite direction of the B in the rest frame of the $K\pi$ system. Finally, ϕ is the angle between the plane containing the e^+ and the e^- and the plane containing the kaon and the pion, in the rest frame of the B meson. The ϕ angle is redefined as $\tilde{\phi} = \phi + \pi$ if $\phi < 0$, which cancels out terms proportional to $\cos\phi$ or $\sin\phi$. Neglecting the $K\pi$ S-wave contribution, the angular distributions for $B^0 \to K^{0*}e^+e^-$ decays in the limit of massless leptons reads:

$$\begin{aligned}
\frac{1}{d(\Gamma+\overline{\Gamma})/dq^2} \frac{\text{d}^4(\Gamma+\overline{\Gamma})}{\text{d}q^2\text{dcos}\theta_l\text{dcos}\theta_K\text{d}\tilde{\phi}} = &\frac{9}{16\pi}\Big[\frac{3}{4}(1-\text{F}_L)\sin2\theta_K + \text{F}_L\cos2\theta_K + \\
&(\frac{1}{4}(1-\text{F}_L)\sin^2\theta_K - \text{F}_L\cos^2\theta_K)\cos2\theta_l + \frac{1}{2}(1-\text{F}_L)A_{\text{T}}^{(2)}\sin^2\theta_K\sin^2\theta_l\cos2\tilde{\phi} + \\
&(1-\text{F}_L)A_{\text{T}}^{\text{Re}}\sin^2\theta_K\cos\theta_l + \frac{1}{2}(1-\text{F}_L)A_{\text{T}}^{\text{Im}}\sin^2\theta_K\sin^2\theta_l\sin2\tilde{\phi}
\end{aligned} \tag{8}$$

where A_{T}^{Im} is a CP asymmetry, F_L the longitudinal polarisation of the K^{*0} (which is expected to be small at low q^2), and A_{T}^{Re} is related to the forward-backward asymmetry. In the limit $q^2 \to 0$, the variables $A_{\text{T}}^{(2)}$ and A_{T}^{Im} are sensitive to the photon polarisation. They depend on the Wilson coefficients C_7 and C_7' as:

$$A_{\text{T}}^{(2)}(q^2 \to 0) \to \frac{\mathcal{R}e(\mathcal{C}_7\mathcal{C}_7')}{|\mathcal{C}_7|^2 + |\mathcal{C}_7'|^2} \text{ and } A_{\text{T}}^{\text{Im}}(q^2 \to 0) \to \frac{\mathcal{I}m(\mathcal{C}_7\mathcal{C}_7')}{|\mathcal{C}_7|^2 + |\mathcal{C}_7'|^2}. \tag{9}$$

Using the $3\,\text{fb}^{-1}$ of data collected by LHCb in 2011 and 2012 at 7 and 8 TeV respectively, the $B^0 \to K^{0*}e^+e^-$ signal candidates are reconstructed from candidate dilepton pairs and K* mesons [2]. Oppositely charged tracks with high p_{T} and a good quality vertex are used to select signal candidate dilepton pairs. Bremsstralung radiation is accounted for by adding to
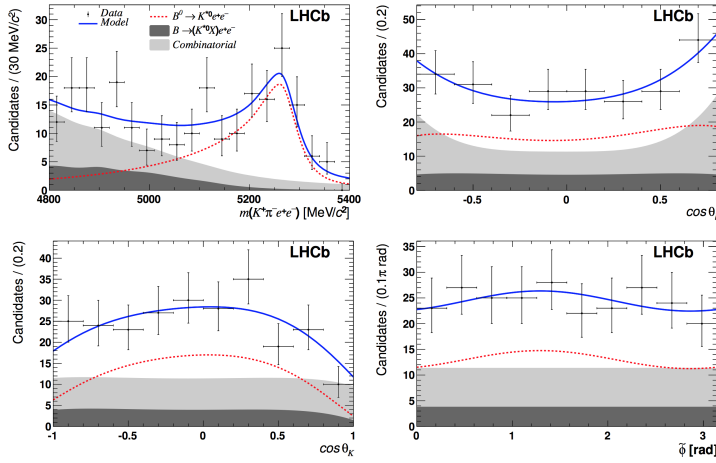
Figure 3: Distributions of the $K^+\pi^-e^+e^-$ invariant mass, $\cos\theta_l$, $\cos\theta_K$ and $\tilde{\phi}$ variables for the $B^0 \to K^{0*}e^+e^-$ decay mode. The dashed line is the signal PDF, the light grey area corresponds to the combinatorial background, the dark grey area is the partially reconstructed background. The solid line is the total PDF [2].

the measured electron momentum the contributions from neutral calorimeter clusters that are close to the extrapolation of the electron track. The reconstructed e^+e^- pair is required to have an invariant mass squared in the range $[0.0004, 1]$GeV/c^2. The choice of the lower bound is a compromise between the gain in sensitivity from measurements at lowest possible q^2 values and the decrease in resolution due to multiple scattering when q^2 decreases.

First, a wide mass window of $K^+\pi^-e^+e^-$ invariant mass between 4300 and 6300 GeV/c^2 is used to obtain the fitted value of the $B^0 \to K^{0*}e^+e^-$ yields. An unbinned maximum likelihood fit is performed. The fit yields 150 ± 17 $B^0 \to K^{0*}e^+e^-$ signal events.

In order to reduce the contribution from combinatorial background, whose angular distribution is difficult to model, the angular fit is performed on a reduced mass window of $4800 - 5400$ MeV/c^2, which contains 124 $B^0 \to K^{0*}e^+e^-$ signal events.

The measurement of A_T^Im, A_T^Re, $A_\mathrm{T}^{(2)}$ and $\mathrm{F_L}$ is performed by fitting simultaneously the m($K^+\pi^-e^+e^-$), $\cos\theta_l$, $\cos\theta_K$ and $\tilde{\phi}$ distributions shown in Fig. 3. The fitted values for these parameters are corrected for the $(3.8 \pm 1.9)\%$ contamination from $B^0 \to K^{0*}\gamma_{e^+e^-}$ decays assuming the physics parameter values are zero for these decays, giving the following results:

$$\mathrm{F_L} = 0.16 \pm 0.06 \pm 0.03 \quad A_\mathrm{T}^{(2)} = -0.23 \pm 0.23 \pm 0.05$$
$$A_\mathrm{T}^\mathrm{Im} = 0.14 \pm 0.22 \pm 0.05 \quad A_\mathrm{T}^\mathrm{Re} = 0.10 \pm 0.18 \pm 0.05 \tag{10}$$

Taking into account the bin migration due to reconstruction effects, the true q^2 effective range for the reported results on A_T^Im, A_T^Re, $A_\mathrm{T}^{(2)}$ and $\mathrm{F_L}$ ranges from 0.0020 ± 0.0008 to 1.120 ± 0.060 GeV^2/c^4.

For this range of q^2 values, the equations relating $A_\mathrm{T}^{(2)}$ and A_T^Im to $\mathcal{C}_7$ and $\mathcal{C}_7'$ are accurate at the 5% level, leading to a $\dfrac{\mathcal{C}_7'}{\mathcal{C}_7}$ ratio compatible with zero, in agreement with the SM.

4.3. Photon polarisation in $B_s^0 \to \phi\gamma$ decays
The time-dependent decay rates of B_s^0 and $\overline{B_s^0}$ decaying to $\phi\gamma$ can be written [13]:

$$\Gamma(t)(B_s^0 \to \phi\gamma) \propto \exp^{-\Gamma_s t}[\cosh(\frac{\Delta\Gamma_s}{2}t) - A^\Delta\sinh(\frac{\Delta\Gamma_s}{2}t) + C\cos\Delta m_s t - S\sin\Delta m_s t]$$
$$\Gamma(t)(\overline{B_s^0} \to \phi\gamma) \propto \exp^{-\Gamma_s t}[\cosh(\frac{\Delta\Gamma_s}{2}t) - A^\Delta\sinh(\frac{\Delta\Gamma_s}{2}t) - C\cos\Delta m_s t + S\sin\Delta m_s t] \tag{11}$$

where C is the direct CP asymmetry, S is the asymmetry associated with $B_0^s - \overline{B_0^s}$ mixing, $\Delta\Gamma_{(s)}$ and Δm_s are the decay width and mass differences between the B_0^s CP eigenstates.

Hence, if an untagged analysis is performed, *i.e.* if the B_0^s and $\overline{B_0^s}$ states can not be disentangled, the total decay rate reads:

$$\Gamma(t) \propto \exp^{-\Gamma_{(s)}t}[\cosh(\frac{\Delta\Gamma_{(s)}}{2}t) - A^\Delta \sinh(\frac{\Delta\Gamma_{(s)}}{2}t)] \tag{12}$$

where A^Δ depends on the Wilson coefficients $\mathcal{C}_7$ and $\mathcal{C}_7'$ as:

$$A^\Delta \sim \frac{2\mathcal{R}e(e^{-i\phi_s}\mathcal{C}_7\mathcal{C}_7')}{(|\mathcal{C}_7|^2 + |\mathcal{C}_7'|^2)} \tag{13}$$

Therefore the decay-time analysis of $B_0^s \to \phi\gamma$ is sensitive to the photon polarisation. This analysis has been conducted in LHCb using $3\,\text{fb}^{-1}$ of 2011 and 2012 data and the results have been made public after the conference.

5. Conclusion

Despite a very challenging environment, the LHCb Collaboration has performed competitive measurements with Run 1 data. A first limit has been set on the branching ratio of $B_s^0 \to J/\psi\gamma$ decays and a competitive limit has been found for $B^0 \to J/\psi\gamma$ decays. The first observation of a non-zero photon polarisation in $B^+ \to K^+\pi^-\pi^+\gamma$ decays has been obtained using the full $3\,\text{fb}^{-1}$ of Run 1. The first measurement of angular observables sensitive to the photon polarisation in $B^0 \to K^{0*}e^+e^-$ decays (in an effective q^2 range [0.0020, 1.120] GeV^2/c^4) has been performed. And the results of the decay-time analysis of $B_0^s \to \phi\gamma$ have just been published.

From 2015 to 2018, LHCb Run 2 will significantly increase statistics with an integrated luminosity of the order of $5\,\text{fb}^{-1}$, along with an improved trigger implementation, offering the possibility of an improvement in statistically limited analyses, as well as new searches for baryonic radiative decays such as $\Lambda_b \to \Lambda\gamma$. New methods are also being developed to enable a first measurement of the photon polarisation using an partial wave analysis of $B^+ \to K^+\pi^-\pi^+\gamma$ decays.

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