Determining the photon polarization of the radiative $B \to K_1(1270)\gamma$ decay

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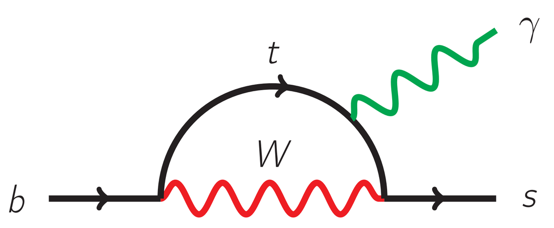
Abstract

Recently, the radiative B-decay to the strange axial-vector mesons, $B \to K_1(1270)\gamma$, was observed. This process is particularly interesting as the subsequent K_1-decay into its three body final state allows us to determine the polarization of the γ, which is mostly left- (right-)handed for $\bar{B}$ (B) in the SM while various new physics models predict additional right- (left-)handed components. In order to obtain a theoretical prediction for this polarization measurement, it is important to understand the hadronic effects to this decay channel. We first revisit the strong decays of the K_1 mesons, namely the partial wave amplitudes as well as their relative phases, in the framework of the $^3P_0$ quark-pair-creation model. Then, we present our result on the sensitivity study of the $B \to K_1(1270)\gamma$ process to the photon polarization. The new method we introduced in this work improves the sensitivity by a factor two compared to the standard angular analysis.

Introduction: why are we interested in photon polarization of $b \to s\gamma$?



The rare radiative decay $b \to s\gamma$ can be described in terms of the effective Hamiltonian:

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{ts}V_{tb}^*(C_{7L}\mathcal{O}_{7L} + C_{7R}\mathcal{O}_{7R})$$

$$\mathcal{O}_{7L,R} = \frac{e}{16\pi^2} m_b \bar{s}\sigma_{\mu\nu}\frac{1 \pm \gamma_5}{2} F^{\mu\nu} b$$

- C_{7L} describes $b_R \to s_L\gamma_L$ (left-handed photon)
- C_{7R} describes $b_L \to s_R\gamma_R$ (right-handed photon)

- In the SM $C_{7R}/C_{7L} \approx m_s/m_b$ * $\Rightarrow$ photons are predominantly left(right)-handed in the $\bar{B}$(B)-decays.
- This property can be not true in some extensions of the SM (LRSM, SUSY, ...) and hence one can have an excess of right(left)-handed photons.

$\Rightarrow$ **The measurement of the photon polarization could provide a test of physics beyond the SM, namely right-handed currents.**

*Here we neglect the QCD corrections and long-distance effects from $\mathcal{O}_2$

How to measure the photon polarization

Why do we use $B \to K_1(1270)\gamma$?

- In [1] it was proposed to use $B \to K_{res}\gamma$ decay where the angular distribution of the three body decay of K_{res} carries the information of the polarization.
- One of the $B \to K_{res}\gamma$ modes is finally measured!

$$\mathcal{B}(B^+ \to K_1^+(1270)\gamma) = (4.3 \pm 1.2) \times 10^{-5}$$

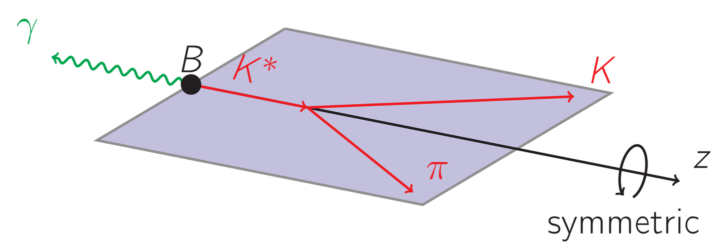
- We study in detail the usefulness of this channel to determine the photon polarization.

There have been attempts to measure the photon polarization by various methods:

- mixing-induced CP-asymmetry in $B^0 \to K^{*0}(\to K_S\pi^0)\gamma$ and $B_s \to \phi\gamma$
- transverse asymmetries in $B^0 \to K^{*0}(\to K^-\pi^+)\ell^+\ell^-$
- Forward-Backward asymmetry in $\Lambda_b \to \Lambda(\to p\pi^-)\gamma$

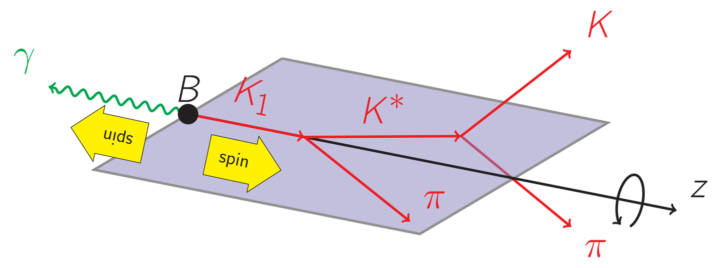
But it has not been seen yet, while LHCb and B-Factories have interesting programs concerning this measurement.

Two-body decay is NOT good

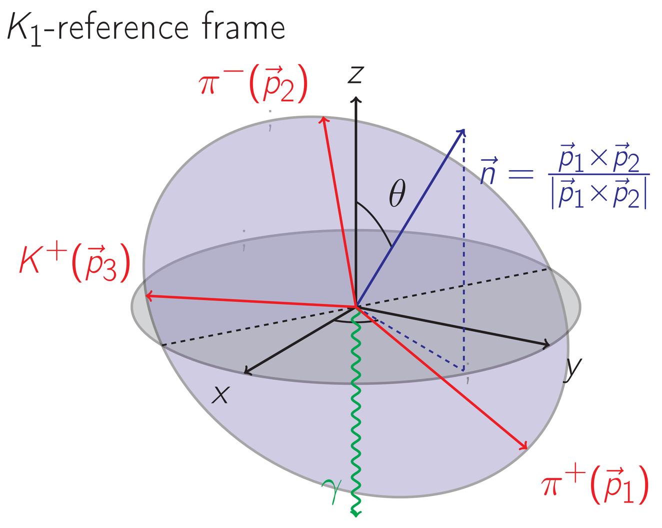


Formalism

B-reference frame



K_1-reference frame



- Helicity is conserved ($\varepsilon_\gamma = \varepsilon_{K_1}$).
- Measurement of the angular θ-distribution of γ with respect to the $K\pi\pi$ decay plane $\Leftrightarrow$ measurement of the photon polarization.

The decay distribution is obtained as a function of the photon polarization parameter λ_γ:

$$\frac{d\Gamma}{ds_{13}ds_{23}d\cos\theta} \propto \frac{1}{4}|\vec{J}|^2(1+\cos^2\theta) + \lambda_\gamma \frac{1}{2} Im[\vec{n}\cdot(\vec{J}\times\vec{J}^*)]\cos\theta, \quad \lambda_\gamma = \frac{|C_{7R}|^2 - |C_{7L}|^2}{|C_{7R}|^2 + |C_{7L}|^2} \quad (*)$$

In the SM the photon polarization parameter $\lambda_\gamma \simeq -1(+1) + O(m_s^2/m_b^2)$ for $\bar{B}(B)$ respectively.

- The helicity amplitudes of $\bar{K}_1 \to \bar{K}\pi\pi$-decay are given by the general form:

$$\mathcal{M}_{L,R}(\bar{K}_1 \to \bar{K}\pi\pi) = \varepsilon^\mu_{L,R}J_\mu, \quad J_\mu = c_1(s_{13},s_{23})p_{1\mu} - c_2(s_{13},s_{23})p_{2\mu}$$

where ε is the polarization vector of K_1, $s_{ij} = (p_i + p_j)^2$.

- The decay $K_1(1270) \to K\pi\pi$ proceeds predominantly via $K^*\pi(16\%)$ and $\rho K(42\%)$ modes. The coefficients $c_{1,2}(s_{13},s_{23})$ can be expressed in terms of the form factors or partial wave amplitudes of the $K_1 \to K^*\pi$, ρK transitions which we calculate using $^3P_0$ quark model [2].

The mixing angle issue

The observed $K_1(1270)$ and $K_1(1400)$ are not pure $1^3P_1(K_{1A})$ or $1^1P_1(K_{1B})$ states:

$$\begin{aligned}|K_1(1270)\rangle &= |K_{1A}\rangle\sin\theta_{K_1} + |K_{1B}\rangle\cos\theta_{K_1}\\ |K_1(1400)\rangle &= |K_{1A}\rangle\cos\theta_{K_1} - |K_{1B}\rangle\sin\theta_{K_1}\end{aligned}$$

- The mixing angle is essential to understand the K_1-decay properties and in particular why $\mathcal{B}(B \to K_1(1400)\gamma) \ll \mathcal{B}(B \to K_1(1270)\gamma)$.
- We find the mixing angle to be $\theta_{K_1} = (60^{+5}_{-13})^\circ$ at 95% C.L. from the fit, combining the ratios of the measured branching fractions of K_1 to $(K^*\pi)_{S,D}$ and ρK channels.

$^3P_0$ Qark-Pair-Creation Model

The partial wave amplitudes for the axial-vector meson (A) decay to the ground states of vector (V) and pseudoscalar (P) mesons are given by

$$\begin{aligned}a_S(K_1(1270) \to K^*\pi/\rho K) &= S(\sqrt{2}\sin\theta_{K_1} \mp \cos\theta_{K_1})\\ a_D(K_1(1270) \to K^*\pi/\rho K) &= D(-\sin\theta_{K_1} \mp \sqrt{2}\cos\theta_{K_1})\\ a_S(K_1(1400) \to K^*\pi/\rho K) &= S(\sqrt{2}\cos\theta_{K_1} \pm \sin\theta_{K_1})\\ a_D(K_1(1400) \to K^*\pi/\rho K) &= D(-\cos\theta_{K_1} \pm \sqrt{2}\sin\theta_{K_1})\end{aligned}$$

$$S = \gamma\sqrt{\tfrac{3}{2}\tfrac{2I_1 - I_0}{18}}, \quad D = \gamma\sqrt{\tfrac{3}{2}\tfrac{I_1 + I_0}{18}}$$

$$I_m = \frac{1}{8}\int d^3\vec{k}\,\mathcal{Y}_1^m(\vec{k}_P - \vec{k})\psi_0^{(P)}(\vec{k})\psi_0^{(V)}(-\vec{k})\psi_1^{-m(A)}(\vec{k}_P + \vec{k})$$

Previous method of Gronau et al.: Up-Down Asymmetry

Gronau et al. [1] defined a very simple observable "Up-Down Asymmetry" which is proportional to the polarization parameter λ_γ:

$$\mathcal{A}_{up-down} = \frac{\int_0^1 d\cos\theta\frac{d\Gamma}{d\cos\theta} - \int_{-1}^0 d\cos\theta\frac{d\Gamma}{d\cos\theta}}{\int_{-1}^1 d\cos\theta\frac{d\Gamma}{d\cos\theta}} = \frac{3}{4}\lambda_\gamma\frac{\int ds_{13}ds_{23}Im[\vec{n}(\vec{J}\times\vec{J}^*)]}{\int ds_{13}ds_{23}|\vec{J}|^2}$$

Count the number of events with photon emitted above/below the $K\pi\pi$-plane and subtract them.

After integrating over the whole Dalitz region one obtains $\mathcal{A}_{up-down} = (0.33 \pm 0.05)\lambda_\gamma$ for $B^+ \to K_1^+(1400)(\to K^0\pi^+\pi^0)\gamma$ and $\mathcal{A}_{up-down} = (0.05 \div 0.10)\lambda_\gamma$ for $B^+ \to K_1^+(1270)(\to K^+\pi^-\pi^+)\gamma$.

DDLR method

In this work we apply the DDLR method [3], which was first proposed to determine the τ-polarization in $\tau \to a_1(\to \pi\pi\pi)\nu_\tau$ decays. The DDLR method can be applied when the PDF has a linear dependence on the polarization parameter λ_γ as is the case in our formula in (*).

- In DDLR [3] it was demonstrated that in this particular case

$$\frac{d\Gamma}{ds_{13}ds_{23}d\cos\theta} \propto \underbrace{\frac{1}{4}|\vec{J}|^2(1+\cos^2\theta)}_{\equiv f(s_{13},s_{23},\cos\theta)} + \lambda_\gamma \underbrace{\frac{1}{2}Im[\vec{n}\cdot(\vec{J}\times\vec{J}^*)]\cos\theta}_{\equiv g(s_{13},s_{23},\cos\theta)}$$

the value of λ_γ can be obtained by the fit to the distribution of the single variable ω

$$\omega(s_{13},s_{23},\cos\theta) \equiv \frac{g(s_{13},s_{23},\cos\theta)}{f(s_{13},s_{23},\cos\theta)}$$

instead of the multidimensional fit of f and g.

- It is also pointed out that the use of the full kinematic information (not only θ but also s_{13}, s_{23}) increases the sensitivity to the polarization (single variable fit is practical for this reason too).

Maximum likelihood method

- Our probability density function can be written as

$$W(\xi) = f(\xi) + \lambda_\gamma g(\xi)$$

where ξ represents the kinematic variables $(s_{13}, s_{23}, \cos\theta)$.

- Then, the log-likelihood function for a sample of N measurements is:

$$\ln\mathcal{L} = \ln\prod_{i=1}^N W(\xi_i) = \sum_{i=1}^N \ln(1 + \lambda_\gamma\omega_i)$$
$$+ \text{ other terms independent of } \lambda_\gamma$$

- Using the maximum likelihood method, we obtain λ_γ as a solution of the following equation:

$$\frac{\partial\ln\mathcal{L}}{\partial\lambda_\gamma} = \sum_{i=1}^N \frac{\omega_i}{1+\lambda_\gamma\omega_i} = N\left\langle\frac{\omega}{1+\lambda_\gamma\omega}\right\rangle = 0$$

Notice: the resulting λ_γ depends only on ω!

Approximate solution for λ_γ

- In particular case $\lambda_\gamma\omega \ll 1$

$$\frac{\partial\ln\mathcal{L}}{\partial\lambda_\gamma} \simeq N(\langle\omega\rangle - \lambda_\gamma\langle\omega^2\rangle) = 0 \Rightarrow$$
$$\lambda_\gamma \simeq \frac{\langle\omega\rangle}{\langle\omega^2\rangle}$$

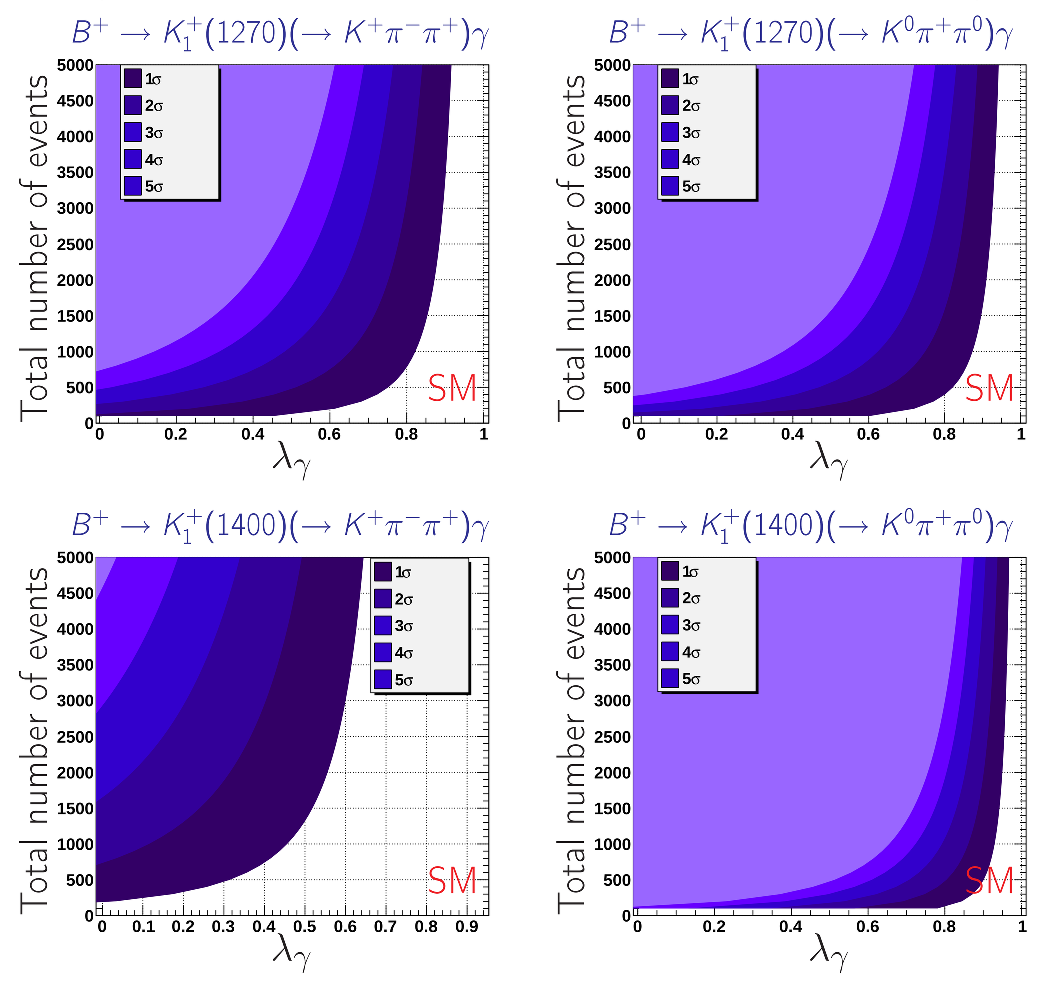
- Furthermore, we obtain the variance from

$$\frac{1}{\sigma_\lambda^2} = -\frac{\partial^2\ln\mathcal{L}}{\partial\lambda_\gamma^2} = N\left\langle\left(\frac{\omega}{1+\lambda_\gamma\omega}\right)^2\right\rangle \Rightarrow$$
$$\sigma_\lambda^2 \simeq \frac{1}{N\left(\langle\omega^2\rangle - 2\frac{\langle\omega\rangle\langle\omega^3\rangle}{\langle\omega^2\rangle}\right)}$$

That means that no fit is needed to extract λ_γ, one only has to sum ω and ω^2 over all the events.

Results

Compatibility plots of exclusion regions for λ_γ in the SM



Expected $\lambda_\gamma^{(SM)}$ from $B \to K_1(1270)\gamma$:

N_{events}	$B^+ \to K^+\pi^-\pi^+\gamma$	$B^+ \to K^0\pi^+\pi^0\gamma$
1k	1.00±0.18	1.00±0.12
10k	1.00±0.06	1.00±0.04

Expected $\lambda_\gamma^{(SM)}$ from $B \to K_1(1400)\gamma$:

N_{events}	$B^+ \to K^+\pi^-\pi^+\gamma$	$B^+ \to K^0\pi^+\pi^0\gamma$
1k	0.93±0.60	1.00±0.07
10k	0.92±0.20	1.00±0.02

- It is ideal to measure $B \to K_1(1270)\gamma$ and $B \to K_1(1400)\gamma$ at the same time, so that we could have a better control for the resonances.
- However, using $B \to K_1$ form factors calculated in [4], we expect about 40 times less $B \to K_1(1400)\gamma$ events compared to $B \to K_1(1270)\gamma$.
- The large error in the $K_1(1400)^+$ channel is originated from the fact that $K_1(1400)^+ \to K^+\pi^-\pi^+$ proceeds only via $K^{*0}\pi^+$ mode $\Rightarrow$ No source for the imaginary part.

Conclusions

1. We investigate the $B \to K_1\gamma$ decay in order to determine the photon polarization of the quark-level $b \to s\gamma$ process.
2. The use of the single variable $\omega(s_{13}, s_{23}, \cos\theta)$, which contains all the information on polarization in each event, avoids the complex multi-dimensional fit and enhances the sensitivity of the measurement.
3. New method gives a gain in accuracy of a factor 2 compared to the fit of pure $\cos\theta$-distribution, integrated over the Dalitz region.
4. In our study we obtain the statistical accuracy of 6% for the SM-prediction for λ_γ for 10k events of $B^+ \to K_1^+(1270)(\to K^+\pi^-\pi^+)\gamma$ decay.
5. Future experiments, LHCb and Super-B factories have good prospectives for the study of this channel. One expects an annual yield of about several dozens thousands of signal events at LHCb and several thousands at Super-B.

References

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