Photon polarisation in $b \rightarrow s \gamma$ transition at LHCb

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(On behalf of LHCb Collaboration)
Photon polarisation in $b \rightarrow s\gamma$ transition

- Transitions driven by FCNC represent pure quantum effects within the SM.

- Loop-driven B decays are more sensitive to the presence of New Physics beyond SM.

- The SM photon in $b \rightarrow s\gamma$ is predominantly left-handed.

$$\bar{s}\Gamma_{\mu}^{\gamma}b = \frac{e}{(4\pi)^2} \frac{g^2}{2M_W^2} V^*_{ts}V_{tb} F_2 \bar{s}i\sigma_{\mu\nu} q^\nu \left( m_b \frac{1 + \gamma_5}{2} + m_s \frac{1 - \gamma_5}{2} \right) b$$

- The right-handed contribution can be significantly enlarged due to new physics.

$$b_R \rightarrow s_L\gamma_L \quad b_L \rightarrow s_R\gamma_R$$
Measuring the photon polarisation

- The time-dependent CP-asymmetry in $B(s) \rightarrow f^{CP}: B_s^0 \rightarrow \phi \gamma, B^0 \rightarrow K_S^0 \pi^0 \gamma$
- **Angular correlations among the three-body decay products of the excited kaons in** $B \rightarrow K_{\text{res}}(P_1 P_2 P_3) \gamma$: $B \rightarrow K_1(K\pi\pi)\gamma, B \rightarrow \phi K \gamma$
- Transverse asymmetry in $B^0 \rightarrow K^*(892)^0 l^+ l^-$
- Direct measurement of the photon polarisation in baryons decays: $\Lambda_b \rightarrow \Lambda^{(*)} \gamma$, $\Xi_b \rightarrow \Xi^{(*)} \gamma$

This talk shows measuring the photon polarisation in $B \rightarrow K \pi \pi \gamma$ which has been extensively studied theoretically by M. Gronau, E. Kou et al
The photon polarisation parameter in $B \rightarrow K_{\text{res}}\gamma$ is given by

$$\lambda_{\gamma}^{(i)} = \frac{|c_{R}^{(i)}|^2 - |c_{L}^{(i)}|^2}{|c_{R}^{(i)}|^2 + |c_{L}^{(i)}|^2}$$

where $c_{L(R)}^{(i)}$ are the weak radiative amplitudes $c_{L(R)}^{(i)} \equiv A(\bar{B}(B) \rightarrow K_{\text{res}}\gamma_{L(R)})$

The photon polarisation parameter in $B \rightarrow K_{\text{res}}\gamma$ is common to all $K_{\text{res}}$-states

$$\lambda_{\gamma}^{(i)} = \lambda_{\gamma} \equiv \frac{|C_{7R}|^2 - |C_{7L}|^2}{|C_{7R}|^2 + |C_{7L}|^2}$$

where $C_{7L(R)}$ are Wilson coefficients

- $C_{7R}/C_{7L} \simeq m_s/m_b$ in SM, i.e. +1 for $\bar{b}$ and -1 for $b$

- Much larger $C_{7R}/C_{7L}$ ratios permitted in LR\(^1\) and MSSM\(^2\) extensions of the SM

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\(^1\)left-right symmetric model
\(^2\)the unconstrained minimal supersymmetric standard model
Three-body decay of $K_{\text{res}}$ needed to build a P-odd triple product, 
$\vec{p}_\gamma \cdot (\vec{p}_\pi \times \vec{p}_K)$, which changes sign for left- and right-handed photons.

The decay amplitude is required to have a non trivial phase due to final state interactions in order to preserve $T$.

The strong phase originates from the interference of at least two amplitudes leading to a common three-body final states.
Angular distributions in $B \to K_{\text{res}}(K\pi\pi)\gamma$

- $K_{\text{res}}$-resonance strong decay amplitude can be described by the helicity amplitude $J_\mu$

$$A^{(i)}_{L(R)}(s, s_{13}, s_{23}, \cos \theta) = \epsilon^K_{\mu, L(R)} J_\mu$$

- Experimentally, we measure the sum of the left- and right-handed current contribution:

$$\Gamma(B \to K_{\text{res}}\gamma) = \Gamma(B \to K_{\text{res}}\gamma_L) + \Gamma(B \to K_{\text{res}}\gamma_R)$$

- Isolated single $1^+$ resonance:

$$d\Gamma(B \to K_{\text{res}}(1^+; P_1P_2P_3)\gamma) \propto \frac{1}{4} |\vec{J}|^2 (1 + \cos^2 \theta) + \frac{1}{2} \cos \theta \text{Im}[\vec{n} \cdot (\vec{J} \times \vec{J}^*)]$$

- To determine $\lambda_\gamma$

  - $\text{Im}[\vec{n} \cdot (\vec{J} \times \vec{J}^*)]$ cannot be zero, i.e. $\vec{J}$ contains more than one amplitude and a non-vanishing relative phase.

  - A precise information on the helicity amplitude $\vec{J}$ is needed.
Angular distributions in $B \to K_{\text{res}}(K\pi\pi)\gamma$

Considering the interference between different $J^P$ $K_{\text{res}}$-resonances:

$$d\Gamma(\sum B \to K_{\text{res}}(P_1P_2P_3)\gamma) \propto \sum_{j=\text{even}} a_j(s_{13}, s_{23}) \cos^j \theta + \lambda_\gamma \sum_{j=\text{odd}} a_j(s_{13}, s_{23}) \cos^j \theta$$

where functions $a_j(s_{13}, s_{23})$ depend on the resonances present in the $P_1P_2P_3$ system and their interferences.

- $\lambda_\gamma$ goes with odd powers of $\cos \theta$
- $J$ changes sign under the exchange of $s_{13}$ and $s_{23}$. 
Up-down asymmetry

- Up-down asymmetry: the asymmetry between the measured number of signal events with the photons emitted above and below the $P_1 P_2 P_3$ decay plane in the $K_{res}$ reference plane

$$\cos \theta = \text{sgn}(s_{13} - s_{23}) \cos \theta$$

$$\mathcal{A}_{\text{up-down}} \equiv \frac{\int_0^1 d \cos \theta \frac{d\Gamma}{d \cos \theta} - \int_{-1}^0 d \cos \theta \frac{d\Gamma}{d \cos \theta}}{\int_{-1}^1 d \cos \theta \frac{d\Gamma}{d \cos \theta}}$$

$$= \frac{3}{4} \lambda_\gamma \frac{\int ds ds_{13} ds_{23} \text{Im}[\vec{n} \cdot (\vec{J} \times \vec{J}^*)]}{\int ds ds_{13} ds_{23} |\vec{J}|^2}$$

- The up-down asymmetry is proportional to the photon polarisation $\lambda_\gamma$

- In case of $K_1(1400)^3$: $\mathcal{A}_{\text{up-down}} \sim 0.3 \lambda_\gamma$ for neutral $K_1(1400)$ decays (SM: $-0.3$ with $\lambda_\gamma = -1$) and $\sim 0.1 \lambda_\gamma$ in charged ones.

$^3$PRD 66 (2002) 054008
The LHCb experiment

**Tracking:**

\[ \Delta p/p \sim 0.4\% \text{ at } 5\text{GeV} \]

\[ \sigma_{IP} \sim 20\mu m \text{ for high-}p_T \text{ tracks and } \sigma_T \sim 45\text{fs} \]

**Particle identification:**

\[ \pi/K \text{ separation over } 2-100\text{GeV} \ (\epsilon_K \sim 90\% \text{ for } \sim 5\% \pi \rightarrow K \text{ mid-id}) \]

**Calorimeter system:**

\[ \sigma_{E/E} \sim 10\%/\sqrt{E} \pm 1\% \]
Data collected in 2011 and 2012, corresponding to an integrated luminosity of 3 fb$^{-1}$

A total signal yield of $13876\pm153$ events from the fit of the mass distribution of the selected $B^\pm \to K^\pm\pi^\mp\pi^\pm\gamma$ candidates

The $K\pi\pi$ mass region of [1.1,1.9] GeV/c$^2$ is studied

- [1100, 1300] MeV/c$^2$: the leading contribution from $K_1(1270)^+$ resonance
- [1300, 1400] MeV/c$^2$: the $K_1(1270)^+$ and $K_1(1400)^+$ interfere
- [1400, 1600] MeV/c$^2$: the $K_1(1400)^+$ and $K_2^*(1430)^+$ dominate
- [1600, 1900] MeV/c$^2$: higher spin resonances contributions are expected
Angular distribution

\[ f(\cos \hat{\theta}; c_0 = 0.5, c_1, c_2, c_3, c_4) = \sum_{i=0}^{4} c_i L_i(\cos \hat{\theta}) \ (c_i: \text{Legendre coefficients}) \]

No odd components, i.e. \( A_{ud} = 0 \)

\[ \text{[PRL 112, 161801 (2014)]} \]

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\(^4\)The background-subtracted \( \cos \hat{\theta} \) (\( \cos \hat{\theta} \equiv \text{charge}(B) \cos \theta \)) distribution is corrected for the selection acceptance and normalized to the inverse of the bin width.
Up-down asymmetry

\[ A_{ud} = \frac{c_1 - c_3/4}{2c_0} \times 10^{-2} \]

<table>
<thead>
<tr>
<th>Mass Region</th>
<th>(c_1)</th>
<th>(c_2)</th>
<th>(c_3)</th>
<th>(c_4)</th>
<th>(A_{ud})</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1.1,1.3]</td>
<td>6.3 ± 1.7</td>
<td>5.4 ± 2.0</td>
<td>4.3 ± 1.9</td>
<td>-4.6 ± 1.8</td>
<td>6.9 ± 1.7</td>
</tr>
<tr>
<td>[1.3,1.4]</td>
<td>31.6 ± 2.2</td>
<td>27.0 ± 2.6</td>
<td>43.1 ± 2.3</td>
<td>28.0 ± 2.3</td>
<td>4.9 ± 2.0</td>
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<tr>
<td>[1.4,1.6]</td>
<td>-2.1 ± 2.6</td>
<td>2.0 ± 3.1</td>
<td>-5.2 ± 2.8</td>
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<td>[1.6,1.9]</td>
<td>3.0 ± 3.0</td>
<td>6.8 ± 3.6</td>
<td>8.1 ± 3.1</td>
<td>-6.2 ± 3.2</td>
<td>-4.5 ± 1.9</td>
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[PRL 112, 161801 (2014)]

- A combined significance with respect to the non-polarisation scenario is extracted with \( A_{ud} \) different from zero at 5.2\( \sigma \)
- **First observation of photon polarisation in \( b \rightarrow s\gamma \) transition!**
- Detailed knowledge of the strong interactions of the \( K_{res} \) decay required to extract the photon polarisation
- The coefficients of the angular fit as well as correlation matrices obtained for each of the four \( K\pi\pi \) mass regions prove to be a useful input for theorists
Summary and future

Summary
- A study of $B^\pm \to K^{\pm} \pi^{\mp} \pi^{\pm} \gamma$ decay performed on 3 fb$^{-1}$ data sample
- Photon polarisation has been observed for the first time in $b \to s\gamma$ transitions

Future
- Perform a full amplitude analysis of the $B^\pm \to K^{\pm} \pi^{\mp} \pi^{\pm} \gamma$ decay
  - A precise information on the helicity amplitude $J$ is needed
  - Several possible $K_{\text{res}}$-resonances are existed
  - The pattern of decays of $K_{\text{res}}$ resonance is also complex
  - The full amplitude analysis is dedicated to isolate single $K_{\text{res}}$-resonance
- The measurement of the photon polarisation at LHCb can also be done (is doing) with
  - Proper time distribution of $B^0_s \to \phi \gamma$
  - Transverse asymmetry in $B^0 \to K^* e^+ e^-$
  - Angular distribution in $B^+ \to \phi K^+ \gamma$
  - Radiative b-baryon decays: $\Lambda_b \to \Lambda^{(*)} \gamma$, $\Xi_b \to \Xi^{(*)} \gamma$
- More results are coming soon!
Constraints on $C_{7\gamma}^{(1)}$ in the NP scenario

- $B \to K_S\pi^0\gamma$
- $B \to K_1\gamma$
- $B \to K^{*}\ell^+\ell^-$

Graphical representations showing constraints on $C_{7\gamma}^{(1)}$ for different decay modes.
The radiative differential decay rate:

\[ d\Gamma(B \to K\pi\pi\gamma) = \left| \sum_i \frac{c_R^{(i)} A_R^{(i)}}{s - M_i^2 - iM_i\Gamma_i} \right|^2 + \left| \sum_i \frac{c_L^{(i)} A_L^{(i)}}{s - M_i^2 - iM_i\Gamma_i} \right|^2 \]

\[ \propto (|A_R|^2 + |A_L|^2) + \lambda_\gamma (|A_R|^2 - |A_L|^2) \]

The photon polarisation in \( B \to K\pi\pi\gamma \) is defined by

\[ P_\gamma = \frac{\Gamma(B \to K\pi\pi\gamma_R) - \Gamma(\bar{B} \to K\pi\pi\gamma_L)}{\Gamma(B \to K\pi\pi\gamma_R) + \Gamma(\bar{B} \to K\pi\pi\gamma_L)} \]

\[ = \frac{\int dPS(|A_R|^2 - |A_L|^2) + \lambda_\gamma \int dPS(|A_R|^2 + |A_L|^2)}{\int dPS(|A_R|^2 + |A_L|^2) + \lambda_\gamma \int dPS(|A_R|^2 - |A_L|^2)} \]

Only with single resonance, \( P_\gamma = \lambda_\gamma \)
Up-down asymmetry with a counting method

The counting method gives compatible results
An alternative definition of the photon angle 

\[ \vec{n} = \vec{p}_{\pi^-} \times \vec{p}_{\pi^+} \text{ instead of } \vec{n} = \vec{p}_{\pi,\text{slow}} \times \vec{p}_{\pi,\text{fast}} \]

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