Radiative electroweak penguin decays at LHCb

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On behalf of the LHCb Collaboration

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Outline

Rare and radiative B decays, photon polarisation in $b \to s \gamma$ transitions

Photon reconstruction with the LHCb detector, branching ratio measurements, searches for $B^{(s)}_0 \to J/\psi \gamma$

Measuring the photon polarisation:
- Angular analysis of $B^+ \to K^+ \pi^+ \pi^+ \gamma$ decays [PRL 112, 161801 (2014)]
- Analysis of $B^0 \to K^* e^+ e^-$ decays [JHEP04(2015)064]
- Prospects in $B_s \to \phi \gamma$ decays
Photon polarisation in $b \rightarrow s\gamma$ transitions

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Rare B decays

- **Flavour changing neutral currents** with $\Delta F = 1$ are forbidden at tree level in the SM.
- Occur through loops (boxes, penguin loops) which may receive contributions from new physics (NP).
- For e.g., for $B_s^0 \to \mu^+\mu^-:

\begin{align*}
\text{SM process} & \quad \begin{array}{c}
\bar{b} \\
W^+ \\
Z^0 \\
W^- \\
s \\
\mu^+ \\
\mu^- \\
\end{array} \\
B_s^0 \\
st \\

\text{NP process} & \quad \begin{array}{c}
\bar{b} \\
X^+ \\
X^0 \\
W^- \\
s \\
\mu^+ \\
\mu^- \\
\end{array}
\end{align*}

- Rare decays are used for indirect searches of NP:
  - Suppressed in the SM
  - Sensitive to NP

[Nature 522, 68–72 (04 June 2015)]
Radiative B decays

- FCNC with a final state photon
- The $b \rightarrow s \gamma$ transition occurs through a penguin loop

- Exclusive decays difficult from a theoretical point of view due to form factors

- Sensitive to NP but need observables independent from form factors:
  - CP and isospin asymmetries
  - Photon polarisation
Photon polarisation in SM $b \rightarrow s\gamma$ transitions

- In the SM, the photon in $b \rightarrow s\gamma$ transitions is mostly left-handed because the $W$ couples left-handedly.
Photon polarization in SM $b \rightarrow s \gamma$ transitions

- The decay amplitude for $b \rightarrow s \gamma$ transitions is proportional to:

$$\langle f | H_{\text{eff}} | i \rangle = -4 \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[ C_7^{\text{eff}}(m_b) \langle f | O_7(m_b) | i \rangle + C_7'^{\text{eff}}(m_b) \langle f | O'_7(m_b) | i \rangle \right]$$

- In SM, Wilson coefficients $C_7$ and $C_7'$ are such that:

$$\frac{C_7'}{C_7} \approx m_s/m_b \approx 0.02$$

- The photon polarization parameter $\lambda_\gamma$ is defined as the asymmetry between the right and left components:

$$\lambda_\gamma = \frac{|C_7'|^2 - |C_7|^2}{|C_7'|^2 + |C_7|^2}$$

In SM, $\lambda_\gamma \approx -1$ (with corrections of $O(m_s^2/m_b^2)$) for decays of a $b$ quark.

[arXiv:1206.1502]
Photon polarisation: a probe for NP

• NP processes could introduce right handed currents, hence modifying the photon polarisation

• The photon polarisation is a test for SM but it has never been measured

• Maybe some new penguins around!
Photon reconstruction with the LHCb detector

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The LHCb detector

- Forward spectrometer dedicated to **heavy flavour physics** at LHC

**Tracking:**
- $\Delta p/p \approx 0.5-1\%$ in the full momentum range
- $\sigma_t \approx 45$ fs and $\sigma_{ip} \approx 20$ μm for high-$p_T$ tracks

**Particle identification:** $K/\pi$ separation over 2-100 GeV/c ($\varepsilon_K \approx 90\%$ and $p_{\text{mis-id } \pi \rightarrow K} \approx 5\%$)

**Calorimeter system:** $\sigma_E/E \approx 10%/\sqrt{E} + 1\%$
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Operations

- Data taking: 2009 – 2012 (Run 1, integrated luminosity of 3fb⁻¹)
- Now in Run 2: 2015 – 2018
Main challenges for radiative decays

- High level of **background in pp collisions**
- For energies above 4 GeV the two clusters from $\pi^0 \rightarrow \gamma\gamma$ are reconstructed as a single cluster in the calorimeter
- Mass **resolution dominated by photon reconstruction**

\[ \sigma \approx 25 \text{ MeV}/c^2 \]

\[ \sigma \approx 95 \text{ MeV}/c^2 \]
Branching ratio measurements

- Ratio of branching fractions $\text{BR}(B^0 \rightarrow K^{*0}\gamma)/\text{BR}(B_s^0 \rightarrow \phi\gamma)$ on 0.37 fb\(^{-1}\) of LHCb data (first half of 2011) [Phys. Rev. D 85 (2012) 112013]

\[
\frac{\mathcal{B}(B^0 \rightarrow K^{*}\gamma)}{\mathcal{B}(B_s^0 \rightarrow \phi\gamma)} = 1.12 \pm 0.08 \text{ (stat)} \pm 0.06 \text{ (syst)} \pm 0.09 (f_s/f_d)
\]

- In agreement with theory prediction of $1.0 \pm 0.2$ [Eur.Phys.J.C55:577-595,2008]
Searches for $B_{(s)}^0 \rightarrow J/\psi\gamma$

- Searches with converted photons to suppress background from decays like $B^0 \rightarrow J/\psi\pi^0$ [Phys. Rev. D 92, 112002 (2015)]

In agreement with BABAR limit: $1.6 \times 10^{-6}$ @ 90% C.L. [Phys. Rev. D 70, 091104(2004)]

$\mathcal{B}(B_{s}^0 \rightarrow J/\psi\gamma) < 7.3(8.7) \times 10^{-6}$ @ 90(95)% C.L.

$\mathcal{B}(B^0 \rightarrow J/\psi\gamma) < 1.5(2.0) \times 10^{-6}$ @ 90(95)% C.L.
Measuring the photon polarisation

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How to measure the photon polarisation?

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

• Transverse asymmetry in \(B^0 \to K^* e^+ e^-\)

• Time-dependent analyses of \(B_{(s)} \to f^{CP} \gamma\)
  \((e.g. \, B^0 \to K_S \pi^0 \gamma, \, B_s \to \phi \gamma)\)

• Angular distributions in \(b\)-baryon decays
  \((e.g. \, \Lambda_b \to \Lambda \gamma)\)
How to measure the photon polarisation?

• Angular distribution of radiative decays with three charged particles in the final state (e.g. $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$)
  [PRL 112, 161801 (2014)]

• Transverse asymmetry in $B^0 \rightarrow K^* e^+ e^-$

• Time-dependent analyses of $B_{(s)} \rightarrow f^{CP} \gamma$
  (e.g. $B^0 \rightarrow K_S \pi^0 \gamma$, $B_s \rightarrow \phi \gamma$)

• Angular distributions in b-baryon decays
  (e.g. $\Lambda_b \rightarrow \Lambda \gamma$)
Why do we need a 3 body decay?

Minimum number of tracks needed to build a $P$-odd quantity proportional to the photon polarisation using the final state momenta

$$\vec{p}_\gamma \cdot (\vec{p}_1 \times \vec{p}_2)$$
• Decay rate for the $B^+ \rightarrow K^+_{\text{res}} (K\pi\pi)\gamma$ decay:

$$
\text{d}\Gamma(B \rightarrow K\pi\pi\gamma) = \left| \sum_k \frac{c_{k,R}^{\text{weak}} \times A_{k,R}^{\text{strong}}}{m_{K\pi\pi}^2 - m_k^2 - i m_k \Gamma_k} \right|^2 + \left| \sum_k \frac{c_{k,L}^{\text{weak}} \times A_{k,L}^{\text{strong}}}{m_{K\pi\pi}^2 - m_k^2 - i m_k \Gamma_k} \right|^2
$$

• Decay rate for the $B^+ \rightarrow K^+_\text{res} (K\pi\pi)\gamma$ decay:

$$d\Gamma(B \rightarrow K\pi\pi\gamma) = \left| \sum_k c_{k,R}^{\text{weak}} \times A_{k,R}^{\text{strong}} \frac{m_{K\pi\pi}^2 - m_k^2 - im_k\Gamma_k}{m_{K\pi\pi}^2 - m_k^2 - im_k\Gamma_k} \right|^2 + \left| \sum_k c_{k,L}^{\text{weak}} \times A_{k,L}^{\text{strong}} \frac{m_{K\pi\pi}^2 - m_k^2 - im_k\Gamma_k}{m_{K\pi\pi}^2 - m_k^2 - im_k\Gamma_k} \right|^2$$

\[
\lambda_\gamma = \frac{|c_R^{\text{weak}}|^2 - |c_L^{\text{weak}}|^2}{|c_R^{\text{weak}}|^2 + |c_L^{\text{weak}}|^2}
\]

\[
\lambda_\gamma = \frac{|C_7'|^2 - |C_7|^2}{|C_7'|^2 + |C_7|^2}
\]

How to access $\lambda_\gamma$ in $B^+ \rightarrow K^+_{\text{res}}(K\pi\pi)\gamma$ decays?

In the case of a single $1^+$ resonance:

$$\frac{d\Gamma(B \rightarrow K\pi\pi\gamma)}{ds\,ds_{13}\,ds_{23}\,d\cos \theta} \propto \frac{1}{2} |\vec{J}|^2 (1 + \cos^2 \theta) + \lambda_\gamma \cos \theta \Im[\vec{n} \cdot (\vec{J} \times \vec{J}^*)]$$

where $s$ stands for $m^2(K\pi\pi)$, $s_{13}$ for $m^2(K\pi)$ and $s_{23}$ for $m^2(\pi\pi)$
Adding more resonances ($1^+, 2^+, 1^-$), the formula gets complex:

$$\frac{d\Gamma}{ds_{13}ds_{23}d\cos \theta} = |A|^2 \left\{ \frac{1}{4}|\vec{J}|^2(1 + \cos^2 \theta) + \frac{1}{2}\lambda \gamma \text{Im}[\vec{n} \cdot (\vec{J} \times \vec{J}^*)] \cos \theta \right\}$$

$$+ \quad |B|^2 \left\{ \frac{1}{4}|\vec{K}|^2(\cos^2 \theta + \cos^2 2\theta) + \frac{1}{2}\lambda \gamma \text{Im}[\vec{n} \cdot (\vec{K} \times \vec{K}^*)] \cos \theta \cos 2\theta \right\} + |C|^2 \frac{1}{2} \sin^2 \theta$$

$$+ \quad \left\{ \frac{1}{2}(3 \cos^2 \theta - 1)\text{Im}[AB^*\vec{n} \cdot (\vec{J} \times \vec{K}^*)] + \lambda \gamma \text{Re}[AB^*(\vec{J} \cdot \vec{K}^*)] \cos^3 \theta \right\} \right.$$


As the $K^+\pi^-\pi^+$ system is not known, **simplification is needed**!
How to access $\lambda_\gamma$ in $B^+ \rightarrow K^+_{\text{res}}(K\pi\pi)\gamma$ decays?

The idea is to **integrate over the Dalitz plot and the angular distribution** to obtain the up-down asymmetry:

$$A_{ud} \equiv \frac{\int_0^1 \mathrm{d} \cos \theta \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos \theta} - \int_{-1}^0 \mathrm{d} \cos \theta \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos \theta}}{\int_{-1}^1 \mathrm{d} \cos \theta \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos \theta}} = C \lambda_\gamma$$

Where $C$ takes into account the integrations and depends on the $K\pi\pi$ system content.
Almost 14,000 signal events are reconstructed and selected in the full 3 fb$^{-1}$ LHCb Run 1 data sample.

The background-subtracted $K\pi\pi\gamma$ mass spectrum is obtained.

[PLR 112, 161801 (2014)]
Red: Signal
Green: Combinatorial background
Black: Missing pion background
Purple: Partially reconstructed background
The $K\pi\pi$ mass spectrum is obtained and divided in bins of $m(K\pi\pi)$.

In each bin, the $\cos \theta$ distribution is fitted.

Observation of $\lambda_\gamma$

[PRL 112, 161801 (2014)]
Observation of $\lambda_\gamma$

- Up-down asymmetry expected to be proportional to $\lambda_\gamma$

- Observation of a non-zero photon polarisation with $A_{ud}$ different from 0 at 5.2$\sigma$. 

[PRL 112, 161801 (2014)]
Towards a measurement of $\lambda_\gamma$

- To measure the value of $\lambda_\gamma$, we need to know the proportionnality coefficient $C$ between $A_{ud}$ and $\lambda_\gamma$.
- This coefficient depends on the content of the $K\pi\pi$ system.

- Missing knowledge of the $K\pi\pi$ system to make a measurement: A 5D analysis (using three invariant masses and two angular variables) is ongoing to determine the value of $\lambda_\gamma$.
How to measure the photon polarisation?

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

- **Transverse asymmetry in $B^0 \rightarrow K^* e^+ e^-$**
  
  [JHEP04(2015)064]

- Time-dependent analyses of $B_{(s)} \rightarrow f^{CP} \gamma$
  (e.g. $B^0 \rightarrow K_s \pi^0 \gamma$, $B_s \rightarrow \phi \gamma$)

- Angular distributions in $b$-baryon decays
  (e.g. $\Lambda_b \rightarrow \Lambda \gamma$)
In the very low $q^2$ region, theoretical uncertainties from long distance interaction are reduced. Couplings between a virtual photon and the lepton pair dominate:

$$B^0 \rightarrow K^* \text{ee} \text{ in the low } q^2 \text{ region}$$
Observables sensitive to the photon polarisation

Simplified decay rate of $B^0 \rightarrow K^* (892)e^+e^-$:

$$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2 dq^2 dc \cos \theta \bar{c} \cos \theta_K dq} = \frac{9}{16\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \left( \frac{1}{4} (1 - F_L) \sin^2 \theta_K - F_L \cos^2 \theta_K \right) \cos 2\theta_L + \frac{1}{2} (1 - F_L) A_T^{(2)} \sin^2 \theta_K \sin^2 \theta_L \cos 2\phi + (1 - F_L) A_T^{Re} \sin^2 \theta_K \cos \theta_L + \frac{1}{2} (1 - F_L) A_T^{Im} \sin^2 \theta_K \sin^2 \theta_L \sin 2\phi \right].$$

4 observables:

- $F_L$: the longitudinal asymmetry
- $A_T^{Re}$: proportional to the forward-backward asymmetry
- $A_T^{(2)}$ and $A_T^{Im}$: related to the photon polarization for low $q^2$:

$$A_T^{(2)}(q^2 \rightarrow 0) = \frac{2 \text{Re}(C_7 C_7'^\ast)}{|C_7|^2 + |C_7'|^2}$$

$$A_T^{Im}(q^2 \rightarrow 0) = \frac{2 \text{Im}(C_7 C_7'^\ast)}{|C_7|^2 + |C_7'|^2}$$
Experimental challenges

The low $q^2$ limit is experimentally challenging:

- **Bad resolution of the angle between leptons** due to multiple scattering
- Bremsstrahlung radiation affects the resolution
- $m(e^+e^-) > 20$ MeV$/c^2$ ($q^2_{\text{min}} = 0.0004$ GeV$/c^4$) to veto $B^0 \rightarrow K^* (892)\gamma$ with $\gamma$ conversion
Mass fit

Fit to the $K^+\pi^-e^+e^-$ invariant mass distribution in a wide range from 4300 to 6300 MeV/c$^2$, with $q^2$ in the range [0.002, 1.120] GeV$^2$/c$^2$

Narrower mass range used for the angular analysis
4D fit and results

4D fit of $m(K^+\pi^-e^+e^-)$, $\cos\theta_L$, $\cos\theta_K$ and $\phi$ to extract the 4 observables on 124 events with $q^2$ in the range $[0.002, 1.120]$ GeV$^2$/c$^2$

- Best constraints on $C_7'$
- In agreement with SM predictions

<table>
<thead>
<tr>
<th>Analysis result</th>
<th>Theoretical expectation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_L$</td>
<td>$0.16 \pm 0.06 \pm 0.03$</td>
</tr>
<tr>
<td>$A_T^{(2)}$</td>
<td>$-0.23 \pm 0.23 \pm 0.05$</td>
</tr>
<tr>
<td>$A_T^{Im}$</td>
<td>$0.14 \pm 0.22 \pm 0.05$</td>
</tr>
<tr>
<td>$A_T^{Re}$</td>
<td>$0.10 \pm 0.18 \pm 0.05$</td>
</tr>
</tbody>
</table>

SM prediction adapted from arXiv:1412.3183
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- Angular distribution of radiative decays with three charged particles in the final state (e.g. $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$)

- Transverse asymmetry in $B^0 \rightarrow K^* e^+ e^-$

- Time-dependent analyses of $B_{(s)} \rightarrow f^{CP} \gamma$
  (e.g. $B^0 \rightarrow K_S \pi^0 \gamma$, $B_s \rightarrow \phi \gamma$)

- Angular distributions in $b$-baryon decays
  (e.g. $\Lambda_b \rightarrow \Lambda \gamma$)
Prospects: Photon polarisation in $B^0_s \rightarrow \phi \gamma$

➤ The time-dependent decay rates of $B^0_s$ and $\bar{B}^0_s$ decaying to $\phi \gamma$ are:

$$
\Gamma(t)(B^0_s \rightarrow \phi \gamma) \propto e^{-\Gamma(s)t}[\cosh\left(\frac{\Delta\Gamma(s)}{2}t\right) - A^\Delta \sinh\left(\frac{\Delta\Gamma(s)}{2}t\right)] + C \cos \Delta m_s t - S \sin \Delta m_s t
$$

$$
\Gamma(t)(\bar{B}^0_s \rightarrow \phi \gamma) \propto e^{-\Gamma(s)t}[\cosh\left(\frac{\Delta\Gamma(s)}{2}t\right) - A^\Delta \sinh\left(\frac{\Delta\Gamma(s)}{2}t\right)] - C \cos \Delta m_s t + S \sin \Delta m_s t
$$

where $C$ is the direct $CP$ asymmetry, $S$ is the asymmetry associated with $B^0_s - \bar{B}^0_s$ mixing, $\Delta\Gamma(s)$ and $\Delta m_s$ are the decay width and mass differences between the $B^0_s$ $CP$ eigenstates.


Untagged decay-time analysis for $B^0_s \rightarrow \phi \gamma$:

$$
\Gamma(t) \propto e^{-\Gamma(s)t}[\cosh\left(\frac{\Delta\Gamma(s)}{2}t\right) - A^\Delta \sinh\left(\frac{\Delta\Gamma(s)}{2}t\right)]
$$

➤ With $A^\Delta$ sensitive to the photon polarisation:

$$
A^\Delta = \frac{2 \Re(\overline{C}_7 C_7^* + \overline{C}_7' C_7'^*)}{|C_7|^2 + |\overline{C}_7|^2 + |C_7'|^2 + |\overline{C}_7'|^2}
$$

Results expected soon!
Conclusion

Ø Despite a very challenging environment, the LHCb Collaboration has performed competitive measurements with Run 1 data:

Ø First limit on the branching ratio of $B_s^0 \rightarrow J/\psi \gamma$ and competitive limit for $B^0 \rightarrow J/\psi \gamma$ decays

Ø First observation of a non-zero photon polarisation in $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$ decays using the full 3 fb$^{-1}$ of Run 1 [PRL 112, 161801 (2014)]

Ø First measurement of angular observables sensitive to the photon polarisation in $B^0 \rightarrow K^* e^+ e^-$ decays (in an effective $q^2$ range [0.0020, 1.120] GeV$^2$/c$^4$) [JHEP04(2015)064]

Ø Results of the decay-time analysis of $B^0_s \rightarrow \phi \gamma$ are coming soon
Prospects

- Run 2 will bring more statistics, along with an improved trigger

- **New data set**: Room for improvement in statistically limited analyses

- **New methods**: A 5D analysis is ongoing to achieve the first measurement of photon polarisation in $B^+ \rightarrow K^+\pi^-\pi^+\gamma$ decays

- **New decays**: Searches for baryonic radiative decays such as $\Lambda_b \rightarrow \Lambda\gamma$
Thanks for your attention
Photon polarisation in $b \rightarrow s \gamma$ transitions

- In the SM, the photon in $b \rightarrow s \gamma$ transitions is mostly left handed because the W couples left-handedly.

**Leading contribution**

$$m_b \bar{s}_L \sigma_{\mu\nu} q^\nu b_R$$

**Contribution with chirality flip**

$$m_s \bar{s}_R \sigma_{\mu\nu} q^\nu b_L$$
The ratio of partially reconstructed events over signal events is expected to be the same for $B^0 \rightarrow K^* e^+ e^-$ and $B^0 \rightarrow K^* \gamma$.

The cut on di-electron mass is released to obtain the mass spectrum dominated by $B^0 \rightarrow K^* \gamma$.

![Mass fit](JHEP04(2015)064)
Photon reconstruction in LHCb

- Energy measured in Preshower (PS) and Electromagnetic CALOrimeter
- Direction: derived from the assumed production vertex and the 3D barycentre of the energy deposits in the PS and CALO
Adding resonances is not so simple

The amplitude for a system containing \((1^+, 2^+, 1^-)\) is:

\[
A_{R,L}(\bar{B} \rightarrow K\pi\pi\gamma_{R,L}) = A(\vec{e}_\pm \cdot \vec{J}) \pm B \left((\vec{e}_\pm \cdot \vec{n})(\vec{e}_0 \cdot \vec{K}) + (\vec{e}_\pm \cdot \vec{K})(\vec{e}_0 \cdot \vec{n})\right) \pm C(\vec{e}_\pm \cdot \vec{n})
\]

where A, B and C are constant obtained after factorizing out the terms depending on the polarisation and the final state momenta in the respective expressions of the amplitudes of the 1+, 2+ and 1- resonances.

The vectors are defined using the final state momenta:

\[
\vec{J} = C_1\vec{p}_1 - C_2\vec{p}_2, \\
\vec{K} = |\vec{p}_1 \times \vec{p}_2| \left\{\vec{p}_1[B_{K^*}(s_{23}) + \kappa_\rho B_\rho(s_{12})] + \vec{p}_2[B_{K^*}(s_{13}) + \kappa_\rho B_\rho(s_{12})]\right\}
\]
Constraints on \( C_7 \) and \( C_7' \).

[arXiv: 1510.04239]
q^2 distributions in B^0 \rightarrow K^*ee background subtracted plot

Data B^0 \rightarrow K^{*0}e^+e^− sPlot
MC B^0 \rightarrow K^{*0}e^+e^−
MC B^0 \rightarrow K^{*0}γe^+e^−
Sum of the above

[JHEP04(2015)064]