Radiative decays at LHCb

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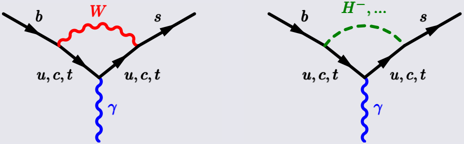
CKM 2014
Vienna, Austria
8-12 September 2014

Introduction

- Radiative decays $b \to s\gamma$ proceed through FCNC
- These electromagnetic penguin loops are **sensitive to new physics**, via new particles in the loop



- **In the SM** the quark level $b \to s\gamma$ vertex is given as (without QCD correction):

$$\bar{s}\Gamma_\mu^{b\to s\gamma} b = \frac{e}{(4\pi)^2}\frac{g^2}{2M_W^2} V_{ts}^* V_{tb} F_2 \bar{s} i\sigma_{\mu\nu} q^\nu \left(\underbrace{m_b \frac{1+\gamma_5}{2}}_{\substack{\text{Describes}\\ b_R \to s_L\gamma_L}} + \underbrace{m_s \frac{1-\gamma_5}{2}}_{\substack{\text{Describes}\\ b_L \to s_R\gamma_R}} \right) b$$

  - **Maximal parity violation** up to small corrections $\propto \dfrac{m_s}{m_b} \approx 0.02$
  - **Emitted photon predominantly left-handed**
- **Several SM extensions predict an enhancement of the right-handed compenent**

Outline

$\Rightarrow$ This presentation focuses on the latest results on photon polarization in radiative B decays

- Photon polarization in radiative B decays
- Photon polarization in $B \to K\pi\pi\gamma$: Effect of the different K_{res} and SM expectations
- Angular distribution in $B \to K\pi\pi\gamma$: how to extract the polarization
- $B \to K\pi\pi\gamma$ in LHCb: Event selection and results of the angular analysis
- Conclusions and next steps

Photon polarization in radiative B decays

- **Indirect measurements**:
  - Measurement of the time-dependent decay rate of the radiative neutral B-mesons decays $B_s^0 \to \phi\gamma$
  - Transverse asymmetries in the semileptonic $B \to K^*(\to K\pi)\ell^+\ell^-$ decay

- **Direct measurements**:
  - b-baryons radiative decays: $\Lambda_b \to \Lambda^*\gamma$, $\Xi_b \to \Xi^*\gamma$
  - Study of the angular distribution of the three-body hadronic final state $K\pi\pi$, from $B \to K_{res}(\to K\pi\pi)\gamma$

$\Rightarrow$ **This presentation**

Photon polarization in $B \to K\pi\pi\gamma$

- The photon polarization in $\bar{B} \to \bar{K}^{(i)}_{res}\gamma$ is given by:

$$\lambda_\gamma^{(i)} = \frac{\left|c_R^{(i)}\right|^2 - \left|c_L^{(i)}\right|^2}{\left|c_R^{(i)}\right|^2 + \left|c_L^{(i)}\right|^2}$$

  where $c_L^{(i)} \equiv A(\bar{B} \to \bar{K}^{(i)}_{res}\gamma_L)$ and $c_R^{(i)} \equiv A(\bar{B} \to \bar{K}^{(i)}_{res}\gamma_R)$ are the weak amplitudes

- For a given resonance, the weak amplitude $c_R^{(i)}$ and $c_L^{(i)}$ are proportional to the Wilson coefficients C_{7R} and C_{7L} up to a sign (*Gronau and Pirjol, PRD 66, 054008 (2002)*)
  (C_{7R} and C_{7L} describe the amplitude of $b \to s\gamma$ for right- and left- handed photons in the effective weak radiative Hamiltonian)

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

$\Rightarrow$ **The photon polarization is independent from the K_{res}**

- In the SM: $\left|\frac{C_{7R}}{C_{7L}}\right| \approx \frac{m_s}{m_b} \Rightarrow \lambda_\gamma = -1\ (+1)\ + \mathcal{O}\left(\frac{m_s^2}{m_b^2}\right)$ for $\bar{B}$ (B) decays

Angular distribution in $B \to K_1(1^+)(\to K\pi\pi)\gamma$

- Experimentally, we measure the decay width (sum of left and right-handed contributions):

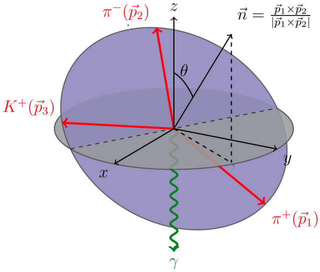
$$\frac{d\Gamma(\bar{B} \to \bar{K}_1\gamma \to (P_1P_2P_3)\gamma)}{ds\, ds_{13}\, ds_{23}\, dcos\theta} \propto \sum_{L,R} \Gamma(\bar{B} \to \bar{K}_{1\,L,R}\gamma_{L,R}) \left|\mathcal{M}(\bar{K}_{1\,L,R} \to P_1P_2P_3)\right|^2$$

- The differential decay width of $\bar{K}_{1\,L,R}$ decay can be described by the helicity amplitude $\mathcal{J}_\mu$ and the left- and right-handed circular-polarization vector $\epsilon^{\mu}_{K_1\,L,R}$

$$\mathcal{M}(\bar{K}_{1\,L,R} \to P_1P_2P_3) = \epsilon^{\mu}_{K_1\,L,R}\, \mathcal{J}_\mu$$

- Decay width for the isolated single 1^+ resonance:

$$\frac{d\Gamma(\bar{B} \to \bar{K}_1\gamma \to (P_1P_2P_3)\gamma)}{ds\, ds_{13}\, ds_{23}\, dcos\theta} \propto \frac{1}{4}|\vec{\mathcal{J}}|^2(1 + cos^2\theta) + \lambda_\gamma \frac{1}{2}\mathrm{Im}\left(\vec{n} \cdot (\vec{\mathcal{J}} \times \vec{\mathcal{J}}^*)\right)cos\theta$$



- Difference between the left- and right-handed polarization amplitudes comes from $\mathrm{Im}(\vec{n} \cdot (\vec{\mathcal{J}} \times \vec{\mathcal{J}}^*))$
- To be nonvanishing: requires the amplitude $\mathcal{J}$ to contain more than one amplitude with a nonvanishing relative phase
- Condition realized for $K_1 \to K\pi\pi$ (nonvanishing relative phase originating from Breit-Wigner forms)

Kou et al. PRD 83, 094007 (2011), Gronau, Pirjol, PRD 66, 054008 (2002), Gronau et al., PRL 88, 051802 (2002)

Angular distribution in $B \to K\pi\pi\gamma$

- Considering the interference between the different J^P contributions 1^+, 1^-, 2^+ ($K_1(1400)$, $K^*(1410)$ and $K_2^*(1430)$), the decay width is:

$$\frac{d\Gamma(\bar{B} \to \bar{K}\pi\pi\gamma)}{ds\, ds_{13}\, ds_{23}\, dcos\theta} \propto \sum_{j=0,2,4} a_j(s, s_{13}, s_{23}) \cos^j\theta + \lambda_\gamma \sum_{j=1,3} a_j(s, s_{13}, s_{23}) \cos^j\theta$$

λ_γ **only in odd** $cos\theta$ **terms ⇒ we can access the polarization via up-down asymmetry (wrt** $K\pi\pi$ **plan)**

- The integrated up-down asymmetry of the photon momentum wrt K_1 decay plane is:

$$\begin{aligned}\mathcal{A}_{up-down} &= \frac{\int_0^1 \frac{\mathrm{d}\Gamma}{\mathrm{d}cos\theta}\mathrm{d}cos\theta - \int_{-1}^0 \frac{\mathrm{d}\Gamma}{\mathrm{d}cos\theta}\mathrm{d}cos\theta}{\int_{-1}^1 \frac{\mathrm{d}\Gamma}{\mathrm{d}cos\theta}\mathrm{d}cos\theta} \\ &= \frac{3}{4}\lambda_\gamma \frac{\int \mathrm{d}s\,\mathrm{d}s_{13}\,\mathrm{d}s_{23}\,\mathrm{Im}\left(\vec{n}\cdot(\vec{\mathcal{J}} \times \vec{\mathcal{J}}^*)\right)}{\int \mathrm{d}s\,\mathrm{d}s_{13}\,\mathrm{d}s_{23}|\vec{\mathcal{J}}|^2}\end{aligned}$$

⇒ **The up-down asymmetry is proportional to the photon polarization** λ_γ

- For example, in case of $K_1(1400)$, integrating over the entire Dalitz plot: $\mathcal{A} = (0.34 \pm 0.05)\lambda_\gamma$

Kou et al. PRD 83, 094007 (2011), Gronau, Pirjol, PRD 66, 054008 (2002), Gronau et al., PRL 88, 051802 (2002)

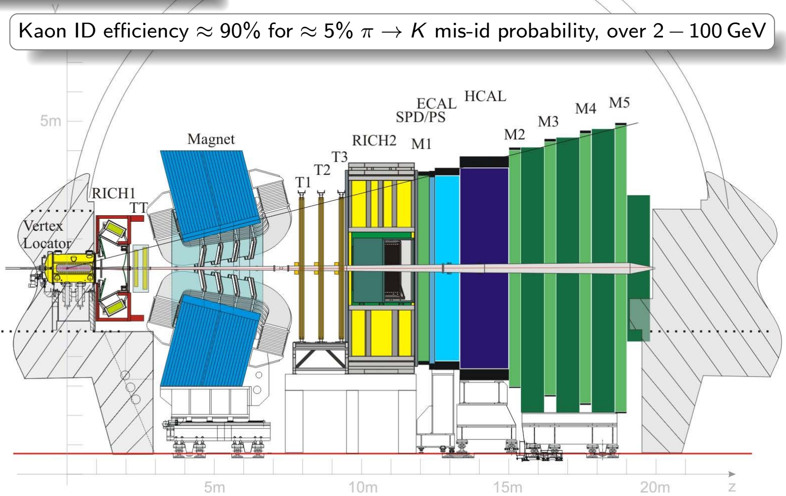
The LHCb detector

Tracking resolution:
$\Delta p/p = 0.4\%$ at 5 GeV
$= 0.6\%$ at 100 GeV

ECAL resolution:
$\sigma_E/E = 1\% \oplus 10\%/\sqrt{E}$

Impact parameter resolution:
20 μm for high-p_T tracks

Kaon ID efficiency $\approx 90\%$ for $\approx 5\%$ $\pi \to K$ mis-id probability, over $2-100$ GeV



Single-arm forward spectrometer ($2 < \eta < 5$)

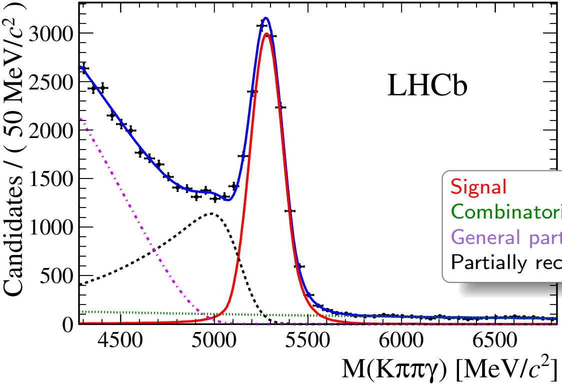
$B^\pm \to K^\pm\pi^\mp\pi^\pm\gamma$ in LHCb - Selection

- Analysis based on data collected from pp collisions in 2011 ($\sqrt{s} = 7\,\text{TeV}$) and 2012 ($\sqrt{s} = 8\,\text{TeV}$), corresponding to an **integrated luminosity of $3\,\text{fb}^{-1}$**

- $\boldsymbol{B^\pm \to K^\pm\pi^\mp\pi^\pm\gamma}$ candidates built using:
  - **Photons:**
    - Built from energy deposit in ECAL, no track pointing to the ECAL cluster
    - MVA based on EM cluster shape to reject ≈ 65% $\pi^0 \to \gamma\gamma$ where 2 photons in the same cluster: $\epsilon_\gamma \approx 95\%$
  - **Hadrons:**
    - Satisfying particle identification requirements
  - **Topology cuts:**
    - $K\pi\pi$ mass required to be in $[1.1, 1.9]\,\text{GeV}$
    - $B^\pm$ candidate mass required to be in $[4.3, 6.9]\,\text{GeV}$
  - **Background cuts:**
    - All candidates consistent with $\bar{D}^0 \to K^+\pi^-\pi^0$ or $\rho^+ \to \pi^+\pi^0$ are removed (to remove peaking background $B^+ \to \bar{D}^0\rho^+$, where π^0 is mis-id as a photon)
    - BDT used to further improve the separation between signal and background

Observation of Photon Polarization in the $b \to s$ Transition [PRL 112, 161801 (2014)]

Mass distribution



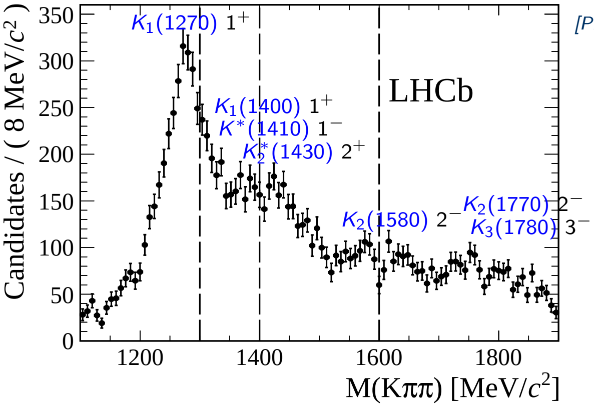
[PRL 112, 161801 (2014)]

Signal yield:
13876 ± 153 events

- Simultaneous unbinned maximum likelihood fit for **2011 and 2012**
- **Signal**: Double sided Crystal Ball, 4 tail parameters fixed from MC
- **Combinatorial background**: Exponential
- Partially reconstructed background:
  - **General partially reconstructed background**
  - **Partially reco bkg with only one pion missing**

  ARGUS convolved with Gaussian - Parameters for missing π background fixed from MC
- Same shape parameters for 2011 and 2012 but the width to account for **differences in calorimeter calibration**

$K\pi\pi$ mass distribution



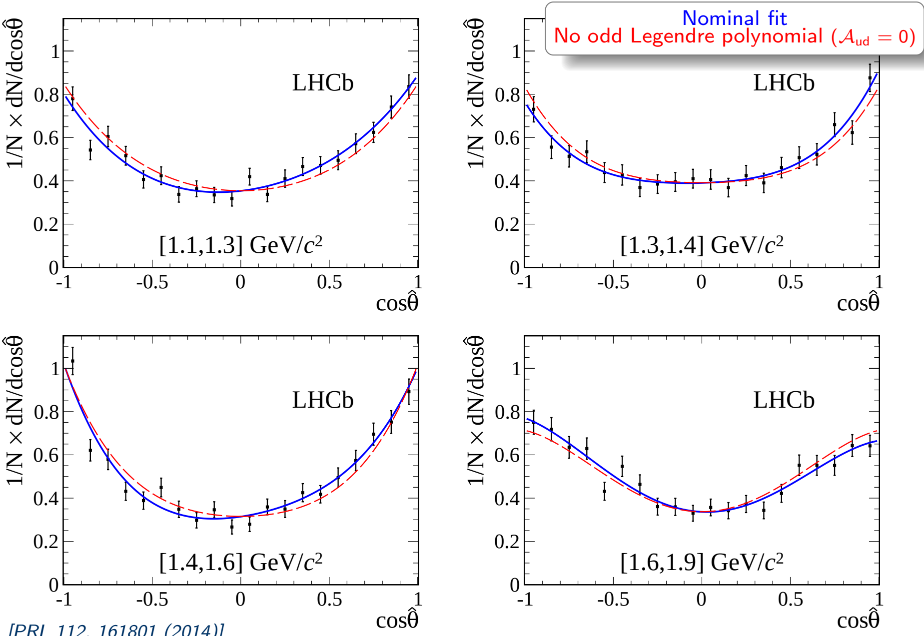
[PRL 112, 161801 (2014)]

- Background substracted $K\pi\pi$ mass spectrum (using sPlot) after constraining the B mass to its nominal value
- Interferences between the different resonances
- **Up-down asymmetry studied inclusively in 4 bins**

Angular analysis

- For each $K\pi\pi$ interval: Simultaneous fit to the B mass in bins of the photon angle to determine the background substracted angular distribution
- Same fit parameters, only yields are free
- As the sign of the photon polarization depends on the sign of the electric charge of B, we use the variable:
$$cos\hat{\theta} \equiv \text{charge}(B)\, cos\theta$$
- Resulting background substracted distributions are corrected for the trigger/selection acceptance
- Fit with a 4^{th}-order polynomial normalized to unit area:
$$f(cos\hat{\theta}, c_0 = 0.5, c_1, c_2, c_3, c_4) = \sum_{i=0}^{4} ci\, L_i(cos\hat{\theta})$$
where L_i are Legendre polynomial of order i
- The **up-down asymmetry** can be expressed by:
$$\mathcal{A}_{\text{up-down}} = \frac{\sum_{i=0}^{4}\left(\int_0^1 c_i L^i(cos\hat{\theta})\mathrm{d}cos\hat{\theta} \;-\; \int_{-1}^{0} c_i L^i(cos\hat{\theta})\mathrm{d}cos\hat{\theta}\right)}{\sum_{i=0}^{4}\int_{-1}^{1} c_i L^i(cos\hat{\theta})\mathrm{d}cos\hat{\theta}}$$
$$\Rightarrow \quad \boldsymbol{\mathcal{A}_{\text{up-down}} = \frac{c_1 - \frac{c_3}{4}}{2c_0}}$$

Angular analysis: Results

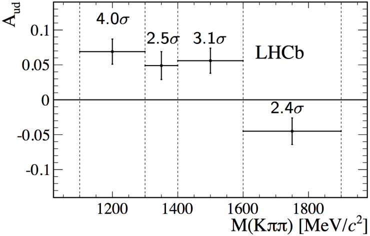


[PRL 112, 161801 (2014)]

Angular analysis: Results and cross-checks

$\times 10^{-2}$	[1.1, 1.3]	[1.3, 1.4]	[1.4, 1.6]	[1.6, 1.9]
c_1	6.3 ± 1.7	5.4 ± 2.0	4.3 ± 1.9	-4.6 ± 1.8
c_2	31.6 ± 2.2	27.0 ± 2.6	43.1 ± 2.3	28.0 ± 2.3
c_3	-2.1 ± 2.6	2.0 ± 3.1	-5.2 ± 2.8	-0.6 ± 2.7
c_4	3.0 ± 3.0	6.8 ± 3.6	8.1 ± 3.1	-6.2 ± 3.2
$\mathcal{A}_{ud}$	6.9 ± 1.7	4.9 ± 2.0	5.6 ± 1.8	-4.5 ± 1.9

[PRL 112, 161801 (2014)]



Results

- Quoted uncertainties contain statistical and systematic contributions
- Combined significance determined from a χ^2 test where the null hypothesis is defined as $\lambda_\gamma = 0$, implying $\mathcal{A}_{up-down} = 0$ in each mass interval
- 5.2σ significance for non-zero up-down asymmetry
- **First observation of a parity-violating photon polarization different from 0**

Cross-checks

- Adding further orders in Legendre polynomials: negligible effect
- Further cross-checks performed with counting experiment and give:
  - Compatible up-down asymmetry
  - Lower significance (5.0σ) but in agreement with expectations from pseudo experiments

Conclusions

- $B^{\pm} \to K^{\pm}\pi^{\mp}\pi^{\pm}\gamma$ decay studied using the full 2011-2012 LHCb data sample ($3\,\mathrm{fb}^{-1}$)
- First observation of the photon polarization in $b \to s\gamma$ transitions
- Next steps (ongoing work):
  - Full amplitude analysis of the $B^{\pm} \to K^{\pm}\pi^{\mp}\pi^{\pm}\gamma$ decay
  - Angular analysis of $B^0 \to K^*\ell^+\ell^-$, $B^+ \to \phi K^+\gamma$
  - Proper time distribution of $B_s^0 \to \phi\gamma$
  - Radiative b-baryons decays: $\Lambda_b \to \Lambda^*\gamma$, $\Xi_b \to \Xi^*\gamma$

Thanks for your attention!

BACKUP

Backgrounds

Combinatorial background		
Partially reconstructed background	Missing π $B^0 \to K^+\pi^-\pi^+\pi^-\gamma$ $B^+ \to K^+\pi^-\pi^+\pi^0\gamma$ Missing γ $B^+ \to K^+\pi^-\pi^+\eta(\to \gamma\gamma)$ General partially reconstructed	 Estimated to be neglected
Contamination from	$B^0 \to K_1^0\gamma \to K^+\pi^-\pi^0\gamma$ (Missing π^0 + random extra π)	Estimated to be neglected
Peaking background	$B^+ \to \bar{D}^0(\to K^+\pi^-\pi^0)\pi^+$ $B^+ \to \bar{D}^0(\to K^+\pi^-\pi^0)\rho^+(\to \pi^+\pi^0)$ $B^+ \to \bar{D}^{*0}(\to \bar{D}^0(\to K^+\pi^-)\gamma)\pi^+$ $B^+ \to K^{*+}(\to K^+\pi^0)\pi^+\pi^-$	Removed by $\bar{D}^0$ cuts Removed by $\bar{D}^0$, ρ^+ cuts Removed by γ cuts Removed by γ cuts
Crossfeed from	$B^+ \to \pi^+\pi^-\pi^+\gamma$	Estimated to be neglected

Systematics

Systematics include

- Effect of bin migration: Evaluated with pseudo-experiments
- Fit model: evaluated by testing alternative models
- Parameters fixed from simulation, including acceptance: Evaluated using pseudo experiments