Radiative B meson decays at LHCb

Mostafa HOBALLAH on behalf of the LHCb collaboration
Laboratoire de Physique Corpusculaire de Clermont-Ferrand
Université Blaise Pascal & IN2P3/CNRS
Introduction

• Radiative $b \to s\gamma$ decays proceed via an effective FCNC (loop penguin diagrams)
  – Sensitive probe of physics at high mass scales
• Good testing ground in search of new physics
• FCNC processes are described by an effective Hamiltonian in the form of Operator Product Expansion:

$$H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \left[ C_i(\mu) O_i(\mu) + C'_i(\mu) O'_i(\mu) \right] + \sum \frac{C}{\Lambda_{NP}^2} O_{NP}$$

- $i = 1,2$ Tree
- $i = 3 - 6,8$ Gluon penguin
- $i = 7$ Photon penguin
- $i = 9,10$ Electroweak penguin
- $i = S$ Higgs (scalar) penguin
- $i = P$ Pseudoscalar penguin

Pheno 2014
Introduction

- NP can modify the Wilson coefficients ($C_i$) affecting observable quantities as (in case of radiative decays) photon polarization ($C'_\gamma$)
  - Observation of the photon polarization in $B^+ \rightarrow K^+\pi^-\pi^+\gamma$ decays
  - Measurement of the photon polarization in $B_s \rightarrow \phi\gamma$ decays
- The left-handed nature of the weak interactions SU(2)$_L$ predicts:
  - $W$ boson couples to left handed quarks
  - The photon is left handedly polarized
  - $b \rightarrow s \gamma_L$ (left-handed polarization)
  - $\bar{b} \rightarrow \bar{s} \gamma_R$ (right-handed polarization)
  - The opposite polarization is suppressed by $m_S/m_b$
The LHCb detector

- Single-arm forward spectrometer (2<\eta<5)
- Vast program of heavy flavor studies
- Challenge:
  - Precision measurements in a hadronic environment
    - On top of
  - High background level from large multiplicities
    - 30 particles for hard PP collision
  - High statistics from 30 KHz rate
    - Access to all b species:
      - Bd, Bu, Bs, \Lambda b, \Xi b, ..... 
- Excellent performance:
  - \sigma(m)\sim10-25 \text{ MeV/c}^2 \text{ (except for radiative \sim90 \text{ MeV/c}^2)}
  - \Delta p/p\sim0.4-0.6 \%(5-100 \text{ GeV/c})
  - High proper time resolution \sigma(t)=60 \text{ fs}
  - \sigma E/E = 10\%/\sqrt{E} + 1\%
  - \varepsilon(K\rightarrow K)\sim95\% \text{ for } \varepsilon(\pi\rightarrow K)\sim5\%
Rad. Decays at LHCb: $B^0 \to K^* \gamma$ and $B_s \to \phi \gamma$


- Mass resolution $\sim 90$ MeV/c$^2$ dominated by LHCb Electromagnetic CALorimeter (ECAL) resolution.
- Many background contributions
  
  $\text{BR}(B^0 \to K^* \gamma) = (4.33 \pm 0.15) \times 10^{-5}$
  
  $\text{BR}(B_s \to \phi \gamma) = (5.7 \pm 2.1 - 1.8) \times 10^{-5}$

- World best measurement of the ratio of branching fractions

\[
\frac{\mathcal{B}(B^0 \to K^* \gamma)}{\mathcal{B}(B_s^0 \to \phi \gamma)} = 1.23 \pm 0.06 \text{ (stat.)} \pm 0.04 \text{ (syst.)} \pm 0.10 \left( \frac{f_s}{f_d} \right)
\]

Theory predictions:

\[
\frac{\mathcal{B}(B^0 \to K^* \gamma)}{\mathcal{B}(B_s^0 \to \phi \gamma)} = 1.0 \pm 0.2
\]

- And $\text{BR}(B_s \to \phi \gamma)$

\[
\mathcal{B}(B_s^0 \to \phi \gamma) = (3.5 \pm 0.4) \times 10^{-5}
\]

HFAG 2010

Pheno 2014
Rad. Decays at LHCb: $B^0 \rightarrow K^* \gamma$


- $B^0 \rightarrow K^* \gamma$

$$N_{B^0} + N_{\overline{B^0}} = 5300 \pm 100$$

- World best measurement of the direct CP asymmetry in $B_0 \rightarrow K^* \gamma$

$$A_{CP}(B^0 \rightarrow K^{*0} \gamma) = (0.8 \pm 1.7 \text{ (stat.)} \pm 0.9 \text{ (syst.)})\%$$

Theory predictions:

$$A_{CP} = -0.0061 \pm 0.0043$$

Pheno 2014
RD at LHCb: $B^0 \rightarrow K^* \gamma^* (e^+ e^-)$

- The world best measurement of the BR of $B^0 \rightarrow K^* e^+ e^-$

$$B(B^0 \rightarrow K^* e^+ e^-)_{30-1000 \text{MeV}/c^2} = (3.1^{+0.9}_{-0.8}^{+0.2}_{-0.3} \pm 0.2) \times 10^{-7}$$

- An update with 2012 data is ongoing
  - Perform an angular analysis to extract a virtual photon polarization


Pheno 2014
Photon polarization from $B \rightarrow K\pi\pi\gamma$

- The main goal is to extract photon polarization from $B \rightarrow K_{\text{res}}\gamma$ where $K_{\text{res}} \rightarrow K\pi\pi$
- The decay amplitude is given by
  \[
  |A(B \rightarrow K_{\text{res}}\gamma \rightarrow P_1 P_2 P_3\gamma)|^2 = |c_R|^2 |M_R|^2 + |c_L|^2 |M_L|^2
  \]
- The photon polarization
  \[
  \lambda_\gamma \equiv \frac{|c_R|^2 - |c_L|^2}{|c_R|^2 + |c_L|^2}
  \]
- With $\lambda_\gamma = -1$ for $B^-$ decays and $+1$ for $B^+$ decays
- This 3-body decay allow to access the $\gamma$ polarization through the up-down asymmetry defined by the $\gamma$ direction w.r.t the plane defined by the daughters of the kaon resonance
Photon polarization from $B \to K\pi\pi\gamma$

- The differential decay rate, for a given intermediate resonance is given as:

$$\frac{d\Gamma(B \to K_{\text{res}}\gamma \to P_1P_2P_3\gamma)}{dsds_{13}ds_{23}d\cos\theta} \propto |\mathcal{F}|^2 (1 + \cos^2\theta) + \lambda_\gamma 2 \text{Im} \left[ \vec{n} \cdot (\vec{\mathcal{F}} \times \vec{\mathcal{F}}^*) \right] \cos\theta$$

  Helicity amplitude

  Photon direction

- And for multiple intermediate resonances, we have

$$\frac{d\Gamma(\sum B \to K_{\text{res},i}\gamma \to P_1P_2P_3\gamma)}{dsds_{13}ds_{23}d\cos\theta} \propto \sum_{j=0,\text{even}}^{4} a_j(s_{13},s_{23}) \cos\theta + \sum_{j=1,\text{odd}}^{3} \lambda_\gamma a_j(s_{13},s_{23}) \cos\theta$$

  Eq. 1

- To extract an up-down asymmetry, the photon direction should be well defined

Photon polarization

Kou et al, PRD83 (2011) 094007

Gronau et al, PRL88 (2002) 051802
The photon direction

- We define:
  
  \[\cos \theta \equiv -\frac{\vec{p}_y}{|\vec{p}_y|} \cdot \hat{n}\]

- With:
  
  \[\hat{n} \equiv \frac{\vec{p}_1 \times \vec{p}_2}{|\vec{p}_1 \times \vec{p}_2|}\]
The up-down asymmetry: formalism

• The up-down asymmetry:
  – The number of events having the photon above the plane defined by the daughter of the Kaon resonance subtracted from those with the photon below the plane

\[
A_{UD} \equiv \frac{\int_{-1}^{1} d\cos \theta \frac{d\tau}{d\cos \theta} - \int_{-1}^{0} d\cos \theta \frac{d\tau}{d\cos \theta}}{\int_{-1}^{1} d\cos \theta \frac{d\tau}{d\cos \theta}} = \frac{3}{4} \lambda \gamma \frac{1}{\int d\sigma d s_{13} d s_{23} \text{Im} \left[ \vec{n} \cdot (\vec{\mathcal{J}} \times \vec{\mathcal{J}}^*) \right]} 
\]

• \( A_{UD} \) is proportional to \( \lambda \gamma \)

• If \( J \) is known, i.e. \( A_{UD} \) is known for a single resonance, the up-down asymmetry would allow to compute the photon polarization \( \lambda \gamma \)
The $B \rightarrow K \pi \pi \gamma$ invariant mass spectrum


- Fit components:
  - Signal
  - Combinatorial
  - Part' reco' Missing $\pi$
  - Partially reconstructed

$\chi^2/\text{ndf} = 0.84$
The $K\pi\pi$ invariant mass Spectrum

- Can’t isolate individual components without amplitude analysis
  - Asymmetry measurement need to be inclusive
- Up-down asymmetry can’t be converted to photon polarization, only a significance w.r.t no-polarization is extracted (in each mass region)


<table>
<thead>
<tr>
<th>Mass Region</th>
<th>Candidates / (8 MeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200</td>
<td>K1(1270)</td>
</tr>
<tr>
<td>1400</td>
<td>K1(1400), K2*(1430)</td>
</tr>
<tr>
<td>1500</td>
<td>K2(1580)</td>
</tr>
<tr>
<td>1700</td>
<td>K2(1770), K3*(1780)</td>
</tr>
</tbody>
</table>
The up-down asymmetry: measurement

- A background-subtracted $\cos(\theta)$ distribution is extracted from each $K\pi\pi$ invariant mass bin

- $\cos(\theta)$ distribution is fitted (unbinned ML fit) with 4-th order polynomial normalized to unit area

$$f(\cos \theta; c_0 = 0.5, c_1, c_2, c_3, c_4) = \sum_{i=0}^{4} c_i L_i(\cos \theta)$$

Eq. 2
**cos (θ) distribution**


- Odd terms are put to zero: assume no photon polarization
- Fit of odd and even components

5.2 σ significance: taking into account correlations between errors
Up-down asymmetry: results


- The asymmetry is then given by: [from Eq. 1 (slide 9) and Eq. 2 (slide 14)]

\[
A_{UD} = c_1 - \frac{c_3}{4}
\]

<table>
<thead>
<tr>
<th></th>
<th>[1.1, 1.3]</th>
<th>[1.3, 1.4]</th>
<th>[1.4, 1.6]</th>
<th>[1.6, 1.9]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_1$</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>
</tr>
<tr>
<td>$c_2$</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>
</tr>
<tr>
<td>$c_3$</td>
<td>-2.1±2.6</td>
<td>2.0±3.1</td>
<td>-5.2±2.8</td>
<td>-0.6±2.7</td>
</tr>
<tr>
<td>$c_4$</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>
</tr>
<tr>
<td>$A_{ud}$</td>
<td>6.9±1.7</td>
<td>4.9±2.0</td>
<td>5.6±1.8</td>
<td>-4.5±1.9</td>
</tr>
</tbody>
</table>

- The quoted uncertainties contain systematic and statistical contributions
Conclusions I

• Radiative decays at LHCb: many important results
  • Direct CP asymmetry in $B^0 \rightarrow K^*\gamma$
  • Ratio of BR of $B^0 \rightarrow K^*\gamma / B_s \rightarrow \phi\gamma$
  • The BR of $B^0 \rightarrow K^*e^+e^-$

  – Observation of photon polarization in $B \rightarrow K\pi\pi\gamma$
  • Up-down asymmetry

• And more to come..
Conclusions II

• LHCb has, for the first time, an evidence of the polarization of the photon with a 5.2σ significance
  – A dedicated amplitude analysis will help to translate this result to a value for the photon polarization

Or

• Input from theory is needed to translate this result into a value of the photon polarization $\lambda_\gamma$
  – How to derive the polarization over all the mass range

• Constrain effects of physics beyond the SM in $b \to s \gamma$ sector
Perspectives

- Bs→φγ time dependent analysis:
  - In the time dependent decay rate, the photon polarization appears through two parameters, S and A

\[ \Gamma_B(t) \propto |A|^2 e^{-\Gamma t} \left[ \cosh(\Delta \Gamma t / 2) - A^\Delta \sinh(\Delta \Gamma t / 2) \pm C \cos(\Delta m t) \mp S \sin(\Delta m t) \right] \]

- Which channels?
  - Bd→K*(K_sπ^0)γ
    - \( \Delta \Gamma \sim 0 \) → the sinh term cancels and we have only access to S
    - Done at Babar but not possible at LHCb S= 0.9 ± 1.0 ± 0.2 (Babar, 1.1 GeV < m_{K_Sπ^0} < 1.8 GeV)
  - Bs→φ(K+K-)γ
    - \( \Delta \Gamma_s \) is not negligible → the dominant term is the sinh → A^\Delta can be measured
    - Work in progress: untagged time dependent analysis to extract A^\Delta

\[ \tan \psi = \frac{\overline{B} \to f^{CP}_{\gamma R}}{B \to f^{CP}_{\gamma L}} \]

Where \( \phi \) is the B mixing phase.
AM I AN UNCLEAR COMMUNICATOR?

SIX O’CLOCK.
spares
CP asymmetry in $B \rightarrow K \pi \pi \gamma$

2011+2012 Data [LHCb-PAPER-2014-001]

- A CP asymmetry measurement can also be conducted:

$$A_{CP}^{raw} = -0.022 \pm 0.015$$
A CP asymmetry measurement can also be conducted:

\[ A_{CP}^{\text{raw}} = -0.022 \pm 0.015 \]

The raw ACP obtained from the fit is corrected to obtain the physical CP asymmetry:
- Charged B meson production asymmetry
- Particle interaction with matter (cross-section) asymmetry \( (K^+ \text{ vs } K^-) \)
- Geometrical detection asymmetries

Corrections are extracted from control channels and from data corresponding to different magnet polarities.
CP asymmetry in $B \rightarrow K_{\text{res}} \gamma$: results

2011+2012 Data [LHCb-PAPER-2014-001]

• $B \rightarrow K\pi\pi\gamma$ has been observed by LHCb: world largest sample

$$N = 13876 \pm 153$$ events

• CP asymmetry (consistent with 0) has been measured for the first time in $B \rightarrow K\pi\pi\gamma$

$$A_{CP} = -0.007 \pm 0.0155^{+0.012}_{-0.011} \text{(stat.)}^{+0.012}_{-0.011} \text{(syst.)}$$