Radiative B-decays at LHCb

Ivan Belyaev (Syracuse)
Outline

• Radiative decays, observables (asymmetries, polarization,...)
  
  • $b \rightarrow s \gamma$:
    • $B \rightarrow K^{*0} \gamma$, $B_s \rightarrow \phi \gamma$
    • $\Lambda_b \rightarrow \Lambda^0 \gamma$, $\Lambda_b \rightarrow \Lambda(X) \gamma$
  
  • $b \rightarrow d \gamma$

• Event selection at LHCb
  
  • Annual Event yields
  • Background estimates

• Summary
Radiative penguin decays

- Loop-induced decays are the perfect place to search for New Physics hints
- In SM model loops are suppressed
  - GIM cancellation
  - "rare decays"
- Heavy particles are suppressed in trees
  - could appear in the loops
- New particles in loops:
  - Enhancements in decay rates: even the minor absolute enhancement could result in large relative enhancement
  - New phases
  - New asymmetries
  - ... ?
- Ideal laboratory for New Physics search
  - But also some QCD tests
Radiative penguin decays

- No so rare decays
  - PDG
    \[ \text{Br}(B \rightarrow K^* \gamma) = (4.3 \pm 0.4) \times 10^{-5} \]
    \[ \text{Br}(B^- \rightarrow K^\ast \gamma) = (3.8 \pm 0.5) \times 10^{-5} \]
  - 1-amplitude dominance
  - strong phase appears at order of \( \alpha_s \) or \( 1/m_b \)

→ “Direct” asymmetries are small (0.6%) for \( b \rightarrow s \gamma \) & a bit larger (-16%) for \( b \rightarrow d \gamma \)

\[ A_{B^0 \rightarrow K^* \gamma}^{\text{dir}} = \frac{\Gamma_{B^0 \rightarrow K^0 \gamma} \Gamma_{B^0 \rightarrow \bar{K}^0 \gamma} - \Gamma_{B^0 \rightarrow \bar{K}^0 \gamma} \Gamma_{B^0 \rightarrow K^0 \gamma}}{\Gamma_{B^0 \rightarrow K^0 \gamma} + \Gamma_{B^0 \rightarrow \bar{K}^0 \gamma}} \]
\textbf{b} \rightarrow \text{s(d)} \gamma \, : \, \text{CP-asymmetries}

- \boldsymbol{B_s} \rightarrow \phi \gamma :
  \begin{itemize}
  \item not \text{CP}-eigenstate!
  \item V-A: \gamma \, \text{is left-handed}
  \item "Wrong polarization": \( \sim m_s (m_d)/m_b \)
\end{itemize}

Both \( A^{\text{mix}} \) and \( A^{\text{dir}} \) are small

- \text{Mix: product of small } \phi_s \text{ and small fraction of } \gamma_R
- \text{Better sensitivity for relatively small } \Delta m_s
  - \text{space resolution for } \phi \rightarrow K^+K^- \text{ vertex } \leftrightarrow \text{ } B_s \text{ proper time resolution}

\[ A_{B^0(s) \rightarrow f_{CP}\gamma} (t) = \frac{\Gamma_{B^0_{(s)} \rightarrow f_{CP}\gamma} (t) - \Gamma_{B^0_{(s)} \rightarrow f_{CP}\gamma} (t)}{\Gamma_{B^0_{(s)} \rightarrow f_{CP}\gamma} (t) + \Gamma_{\bar{B}^0_{(s)} \rightarrow f_{CP}\gamma} (t)} \approx A^{\text{dir}}_{B^0(s) \rightarrow f_{CP}\gamma} \cos \Delta m (s) t + A^{\text{mix}}_{B^0(s) \rightarrow f_{CP}\gamma} \sin \Delta m (s) t \]
Photon Polarisation

- Naive:
- Left-handed photon (to conserve the angular momentum)
  - right handed components of the order of $m_s/m_b$

- true only for 2 body decays
- cannot be applied to $b \to s\gamma + \text{gluons}$
  - other operators could contribute
  - explicit calculations for $B \to K^*\gamma, B \to \rho\gamma$
  - right handed components may be up to $10\div15\%$

How to measure $\gamma$-polarization?

**“Photon-side”**
- measure the polarization
- virtual photon $(b\rightarrow s l^+ l^-)$
- real photon
- conversion $\gamma\rightarrow e^+ e^-$

*Melikov, Nikitin, Simula, PLB 442, 381 (1998)*

*Grossman, Pirjol, JHEP06, 029 (2000)*

**Hadron side**
- Exploit $K^{**} (K\pi\pi)$ system

- Polarized $b$-baryon decays
  - exploit the angular correlations between initial and final state
  - Good to try at LHCb!


*Mannel, Recksiegel, JPG: NPP 24, 979 (1998)*

*I.Belyaev "Radiative B-decays at LHCb" 7*
$\Lambda_b \rightarrow \Lambda^0 \gamma \quad \Lambda_b \rightarrow \Lambda(X)\gamma$

- one can apply to higher resonances $\Lambda(X) \rightarrow p K$
- spin 5/2 is useless (lack of observables) $\text{BR} \sim 10^{-5} \div 10^{-6}$
- spin 1/2 need to be separated from 3/2
- The measurement both photon and proton distributions are required


I.Belyaev "Radiative B-decays at LHCb"
**$\gamma$ polarization**

- $\Lambda_b \rightarrow \Lambda^0 \gamma$
  \[
  \frac{d\Gamma}{d\cos\theta_\gamma} \propto 1 - \alpha_\gamma P_B \cos\theta_\gamma
  \]
  \[
  \frac{d\Gamma}{d\cos\theta_p} \propto 1 - \alpha_\gamma \alpha_p \cos\theta_p
  \]

- $\Lambda_b \rightarrow \Lambda(3/2) \gamma$
  \[
  \frac{d\Gamma}{d\cos\theta_\gamma} \propto 1 - \alpha_{\gamma,3/2} P_B \cos\theta_\gamma
  \]
  \[
  \alpha_{\gamma,3/2} = \frac{1 - \eta}{1 + \eta} \alpha_\gamma
  \]
  \[
  \frac{d\Gamma}{d\cos\theta_p} \propto 1 - \alpha_{p,3/2} \cos^2\theta_p
  \]
  \[
  \alpha_{p,3/2} = \frac{\eta - 1}{\eta + \frac{1}{3}}
  \]

- $\Lambda_b \rightarrow \Lambda(1/2) \gamma$
  - Distribution for $\gamma$ is the same
  - Distribution for proton is flat

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The LHCb experiment

- Single arm spectrometer
- $b$ physics and rare decays
- $L = 2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
Analysis & Background suppression

• Beauty particles:
  • $m_b \sim 5$ GeV/c$^2$
  • $\beta\gamma\tau \sim O(1\text{cm})$

• Particles from $B$-decays:
  • Large $p_T$
    • L0 (hardware) trigger:
      • leptons ($e^\pm, \mu^\pm, \mu\mu$),
      • photons
      • hadrons
  • Large impact parameters
    • (software) trigger

• Background:
  • $b\bar{b}$-production with at least one $B$ within 400mrad cone

• High Level Trigger and Off-line background suppression continues to utilize these properties
  • $B$-decay products do not point to reconstructed primary vertices
  • Exclusively reconstructed $B$-candidate does point to primary vertex
  • $B$-candidate is associated with primary vertex with minimal impact parameter (significance)
Selection of $B_d \rightarrow K^{*0}\gamma$ and $B_s \rightarrow \phi\gamma$

- Realistic simulation and reconstruction!
  - $\pi^\pm, K^\pm$:
    - Charged tracks consistent with PID
    - Inconsistent with any PV  
      - $\chi^2_{IP} > 16(4)$
  - Two prong vertex
    - $\chi^2_{VX} < 49$
  - $K^{*0}$:
    - $|\Delta M| < 60$ MeV/c$^2$
  - $\phi$:
    - $|\Delta M| < 10$ MeV/c$^2$
  - $\gamma$:
    - Clusters in Ecal not associated with any reconstructed track
    - $E_T > 2.8$ GeV
    - $2.2(2.0) < E_T^* < 2.7$ GeV
Selection of $B_d \rightarrow K^{*0}\gamma$ and $B_s \rightarrow \phi\gamma$ (II)

- **B**: 
  - Angle between the momentum and the flight direction from production to decay vertex 
    \[ |\theta_B| < 6 \, (15) \text{ mrad} \]
  - Correlated feeddown with merged $\pi^0$, wrongly reconstructed as single photon 
    $B \rightarrow K^{*0} \, \pi^0, \, B_s \rightarrow \phi\pi^0$
  - Opposite $K^{*0}(\phi)$ polarization 
    \[ |\cos \theta| < 0.75 \]
\[ B_d \rightarrow K^{*0}\gamma \quad B_s \rightarrow \phi\gamma \quad (III) \]

- B-mass window is defined as \( \pm 200 \text{ MeV}/c^2 \)
- \( \sigma(M_B) = 65 \text{ MeV}/c^2 \)
- The correlated feeddown is well under the control

**Annual yield (using \(10^{12} \text{ b}\overline{b}\) events/\(10^7\) second)**

<table>
<thead>
<tr>
<th>Event</th>
<th>( B_d \rightarrow K^{*0}\gamma )</th>
<th>( B_s \rightarrow \phi\gamma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varepsilon_{\text{REC}} [%] )</td>
<td>4.5</td>
<td>4.3</td>
</tr>
<tr>
<td>( \varepsilon_{\text{TRIG/REC}} [%] )</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>( \varepsilon_{\text{SEL/TRIG}} [%] )</td>
<td>18</td>
<td>27</td>
</tr>
<tr>
<td>( \varepsilon_{\text{TOT}} [%] )</td>
<td>0.16</td>
<td>0.22</td>
</tr>
<tr>
<td>N/year</td>
<td>35k</td>
<td>9.3k</td>
</tr>
</tbody>
</table>

15.05.2k+6 “Heavy Flavours”

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Selection of $\Lambda_b \rightarrow \Lambda^0 \gamma$  $\Lambda_b \rightarrow \Lambda(X) \gamma$

- Basically on the same principles
  - Different for $\Lambda^0$, since $\Lambda^0$ decay vertex does not define $\Lambda_b$ decay vertex
  - The special topology selection need to be used

- $\Lambda_b \rightarrow \Lambda(1520) \gamma$  4200
- $\Lambda_b \rightarrow \Lambda(1670) \gamma$  2200
- $\Lambda_b \rightarrow \Lambda(1690) \gamma$  2200
- $\Lambda_b \rightarrow \Lambda^0 \gamma$  750

15.05.2k+6  “Heavy Flavours”

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Background

Background estimation is limited by the size of available sample of $O(10^7)$ forward $b\bar{b}$ events and $3 \times 10^7$ minimum bias events.

No background events are found in "wide" mass interval 4.5-6.0 GeV/c$^2$.

90%CL upper limits are set for the background from $b\bar{b}$-production:

- $K^*g$: <0.7
- $\phi\gamma$: <2.4
- $\Lambda^0\gamma$: <42
- $\Lambda(X)\gamma$: <10
- $B/S$: <18

We consider now forward $b\bar{b}$ production as a major source of background:

- Large $p_T$, large impact parameters, secondary vertices, ...
- (This assumption needs to be properly validated and proved)
**First look at $B_d \rightarrow \omega \gamma$**

- $b \rightarrow d \gamma$ transition
- $|V_{td}/V_{ts}|$ can be extracted with moderate theoretical uncertainty
  - also for large $\Delta m_s$
  - Or formfactor calculations could be checked
- $\text{Br} (B \rightarrow K^*\gamma)/\text{Br} (B \rightarrow \omega \gamma) \sim 65$
- Reconstruction efficiency is low:
  - $\pi^0$ need to be reconstructed
  - Background condition is difficult
  - 3 neutral particles in final state

$\sigma = (63 \pm 9) \text{ MeV}/c^2$

<table>
<thead>
<tr>
<th>$\varepsilon_{\text{TOT}}$ [%]</th>
<th>N/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.012</td>
<td>40</td>
</tr>
</tbody>
</table>

$B/S < 3.5$ @ 90 % CL

$\text{Br} (B^0 \rightarrow \omega \gamma) = 0.5 \times 10^{-6}$
Next steps

• **Look at $B \to \rho^0 \gamma$ events**
  - expected to be better than $B \to \omega \gamma$ but not so nice as $B \to K^{*0} \gamma$

• **Exploit the decays $B \to (K\pi\pi)\gamma$ to study the photon polarisation**

• **Probe the sensitivity for $A_{\text{dir}}(B_s \to \phi\gamma)$ and $A_{\text{mix}}(B_s \to \phi\gamma)$**
  - Now we know that $\Delta m_s$ is not very large

• Study for systematic effects and uncertainties
## Summary

- **LHCb** has a good physics potential for study of radiative B-decays

<table>
<thead>
<tr>
<th>Process</th>
<th>N/year</th>
<th>B/S @90%CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_d \rightarrow K^*0\gamma )</td>
<td>35k</td>
<td>&lt;0.7</td>
</tr>
<tr>
<td>( B_s \rightarrow \phi\gamma )</td>
<td>9.3k</td>
<td>&lt;2.4</td>
</tr>
<tr>
<td>( B_d \rightarrow \omega\gamma )</td>
<td>40</td>
<td>&lt;3.5</td>
</tr>
<tr>
<td>( \Lambda_b \rightarrow \Lambda^0\gamma )</td>
<td>750</td>
<td>&lt;42</td>
</tr>
<tr>
<td>( \Lambda_b \rightarrow \Lambda(1520)\gamma )</td>
<td>4.2k</td>
<td>&lt;10</td>
</tr>
<tr>
<td>( \Lambda_b \rightarrow \Lambda(1670)\gamma )</td>
<td>2.2k</td>
<td>&lt;18</td>
</tr>
<tr>
<td>( \Lambda_b \rightarrow \Lambda(1690)\gamma )</td>
<td>2.2k</td>
<td>&lt;18</td>
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The statistical error on \( A_{\text{dir}}(B\rightarrow K^*0\gamma) \) is well below 1%.

The statistical error on \( V_{td}/V_{ts} \) from \( B\rightarrow K^*0\gamma \) and \( B\rightarrow \omega\gamma \) of about \( O(0.1\sqrt{(1+B/S)/N}) \).

15% sensitivity to \( \gamma_R \) after 5 years.