Rare decays at LHCb

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Outline

• Loop-induced rare decays
• Event Simulation
• Event selection at LHCb
  • Annual Event yields
  • Background estimates
• Summary

Loop induced rare decays

• Radiative penguins
  • $B \rightarrow K^*\gamma$, $B_s \rightarrow \phi\gamma$, $B \rightarrow \omega\gamma$
• EW-penguins
  • $B \rightarrow K^0\mu^+\mu^-$
• Gluonic penguins
  • $B_s \rightarrow \phi\phi$, $B \rightarrow \phi K_S$
• “Very rare”
  • $B \rightarrow \mu^+\mu^-$

LHCb detector and its status is presented in detail in plenary talk by T.Nakada
Rare (=“loop-induced”) decays

- Loop-induced decays are the perfect place to search for New Physics hints
- SM model loops are suppressed
  - GIM cancellation
  - “rare decays”
- Penguins
  - $b \rightarrow s(d) \gamma,Z^0,g$
- Boxes

- Heavy particles are suppressed in trees
  - could appear in the loops
- New particles in loops:
  - Enhancement in decay rates
  - New phases
  - New asymmetries
  - ... ?
- Ideal laboratory for New Physics search
- But also some QCD tests
Radiative penguin decays

- No so rare decays
  - PDG
    \[ \text{Br}(B \to K^{*0}\gamma) = (4.3 \pm 0.4) \times 10^{-5} \]
    \[ \text{Br}(B^- \to K^{*-}\gamma) = (3.8 \pm 0.5) \times 10^{-5} \]

- Isotopic asymmetries
  \[
  A_{B \to K^{*}\gamma}^I = \frac{\Gamma_{B^0 \to K^{*0}\gamma} - \Gamma_{B^- \to K^{*-}\gamma}}{\Gamma_{B^0 \to K^{*0}\gamma} + \Gamma_{B^- \to K^{*-}\gamma}}
  \]
  - \( \sim C_6 + C_5/N_C \)
  - \( \sim O(1\%) \)

\[ \text{Suppressed by: } \alpha_s, 1/m_b \text{ or } |V_{CKM}| \]
\( b \to s(d)\gamma \) : \( CP \)-asymmetries

- 1-amplitude dominance
- strong phase appears at order of \( \alpha_s \) or \( 1/m_b \)
  
  “Direct” asymmetries are small (\( \leq 1\% \))

\[
A_{B^0 \to K^{*0}\gamma}^{\text{dir}} = \frac{\Gamma_{B^0 \to K^{*0}\gamma} - \Gamma_{B^0 \to \bar{K}^{*0}\gamma}}{\Gamma_{B^0 \to K^{*0}\gamma} + \Gamma_{B^0 \to \bar{K}^{*0}\gamma}}
\]

\( B_s \to \phi\gamma \):
- not \( CP \)-eigenstate!
- \( V-A \): \( \gamma \) is circular polarized
  
  “Wrong polarization”:
  \( \sim m_s(m_d)/m_b \)

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

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

- **PYTHIA** as pp-event generator as $\sqrt{s} = 14$ TeV
- **QQ** for weak-decays
- **GEANT 3.21**
  - Realistic geometry & material description
- The pile-up is included
- "Realistic" digitization, reconstruction algorithms & L0/L1 trigger simulation
- Background: "forward" $b\bar{b}$-production in 400mrad cone
  - $10^7$ available events
Background suppression

- **Beauty particles:**
  - $m_b \sim 5 \text{ GeV/c}^2$
  - $\beta\gamma\tau \sim 0(1\text{ cm})$

- **Particles from $B$-decays:**
  - Large $p_T$
    - $L_0$ (hardware) trigger:
      - leptons ($e^{\pm}, \mu^{\pm}, \mu\mu$),
      - photons
      - hadrons
  - Large impact parameters
    - $L_1$ (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 $B_s \rightarrow \phi\gamma$

- $\pi^\pm, K^\pm$:
  - 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 $B_d \rightarrow K^* \gamma$ and $B_s \rightarrow \phi \gamma$ (II)

- **$B$**:  
  - $|\theta_B| < 6$ (15) mrad

- Correlated feeddown with merged $\pi^0$, wrongly reconstructed as single photon
  - $B \rightarrow K^* \pi^0$, $B_s \rightarrow \phi \pi^0$
  - opposite $K^* (\phi)$ polarization
  - $|\cos \theta| < 0.75$
B_d → K^*0γ  B_s → φγ  (III)

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

<table>
<thead>
<tr>
<th></th>
<th>B_d → K^*0γ</th>
<th>B_s → φγ</th>
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</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>
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</table>

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

<table>
<thead>
<tr>
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<th>B_d → K^*0γ</th>
<th>B_s → φγ</th>
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<tbody>
<tr>
<td>N/year</td>
<td>35k</td>
<td>9.3k</td>
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</table>
Background

Background estimation is limited by the size of available sample of $10^7$ 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$^2$.

Only 90%CL upper limits can be set now from $b\bar{b}$-background.

- We consider now forward $b\bar{b}$ production as a major source of background.
  - Large $p_T$, large impact parameters, secondary vertices, ...
  - (This assumption need to be properly validated and proved)

<table>
<thead>
<tr>
<th>$B_d \rightarrow K^{*0} \gamma$</th>
<th>$B_s \rightarrow \phi \gamma$</th>
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<tr>
<td>$B/S$</td>
<td>$&lt;0.7$</td>
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</table>
First look at $B_d \rightarrow \omega \gamma$

- $b \rightarrow d \gamma$ transition
- $|V_{td}|$ can be extracted without large theoretical uncertainty
  - also for large $\Delta m_s$
- $\text{Br} (B \rightarrow K^*\gamma) / \text{Br} (B \rightarrow \omega \gamma) \sim 65$

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

$B / S < 3.5$ @ 90 % CL

$\text{Br} (B^0 \rightarrow \omega \gamma) = 0.5 \times 10^{-6}$
**EW penguins:** \( B_d \rightarrow K^*\mu^+\mu^- \)

- Combination of \( b \rightarrow sZ, \) \( b \rightarrow s\gamma \) penguins with the box diagram
- Both \( \Gamma \) and \( d\Gamma/ds \) is very sensitive to New Physics as well as the forward-Backward \( A_{FB}(s) \) asymmetry

\[
A_{FB}(s) = \left( \int_0^1 d\cos\theta - \int_{-1}^0 d\cos\theta \right) \frac{d^2\Gamma}{dsd\cos\theta}
\]

\( \theta \) is angle between \( \mu^+ \) and \( K^*0 \) in dimuon restframe
Selection of $B_d \rightarrow K^{*0} \mu \mu$

- $\mu^{\pm}$:
  - charged tracks consistent with PID
  - $p_T > 500$ MeV/c²
- Two prong $\mu \mu$-vertex:
  - $\chi^2_{VX} < 8$
- $J/\psi, \psi(2S)$ veto:
  - $2.9-3.2, 3.65-3.75$ GeV/c²
- $K, \pi$:
  - charged tracks consistent with PID
  - $p_T(\pi) > 200$ MeV/c²
- $K^{*0}$:
  - $\chi^2_{VX} < 8$
  - $p_T > 900$ MeV/c²
  - $|\Delta M| < 100$ MeV/c²
Efficiencies, Event yields and B/S

- $\varepsilon_{\text{TOT}} = 0.7\%$, $\varepsilon_{\text{TRIG}} = 74\%$
- Annual yield: 4400 events

B/S for forward $b\bar{b}$ events
- $[0.2-2.0]$ at 90% CL

Various $b \rightarrow \mu X, \mu \mu X, J/\psi X$ channels were studied as sources of potential feeddown

<table>
<thead>
<tr>
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<th>B/S at 90% CL</th>
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</thead>
<tbody>
<tr>
<td>$b \rightarrow \mu (c \rightarrow \mu X) X$</td>
<td>$&lt;1.1$</td>
</tr>
<tr>
<td>$b \rightarrow \mu X + c.c$</td>
<td>$0.5 \pm 0.2$</td>
</tr>
<tr>
<td>$B \rightarrow J/\psi K^*$</td>
<td>$&lt;0.04$</td>
</tr>
<tr>
<td>$B \rightarrow J/\psi K_S$</td>
<td>$&lt;0.04$</td>
</tr>
<tr>
<td>$B_s \rightarrow J/\psi \phi$</td>
<td>$&lt;0.05$</td>
</tr>
</tbody>
</table>
Gluonic penguins:

- **SM**: Channels with domination of 1-gluonic penguin amplitude
  - The contributions from EW-penguin amplitudes $O(10\%)$
- **$CP$-violation for $B_d \rightarrow \phi K_S$**
  
  $A_{CP}(B_d \rightarrow \phi K_S) = A_{CP}(B_d \rightarrow J/\psi K_S)$
  
  The accuracy: $O(5\%) \rightarrow 30\%$

$B_d \rightarrow \phi K_S \quad B_s \rightarrow \phi \phi$

- **Last summer Belle reports the value** $A_{CP}(B_d \rightarrow \phi K_S)$ **inconsistent with**
  
  $A_{CP}(B_d \rightarrow J/\psi K_S) = -\sin(2\beta)$
  
  - Hints for New Physics in $b \rightarrow sg$ transitions ?
  - The probe for FSI ?
Selection of $B_d \to \phi K_S$ and $B_s \to \phi \phi$

- **$K^\pm$**:
  - Charged tracks consistent with PID
  - Inconsistent with any PV
    - $\chi^2_{IP} > 4$
- **Two prong vertex**
  - $\chi^2_{VX} < 10(100)$
- **$\phi$**
  - $|\Delta M| < 17(12) \text{ MeV}/c^2$
- **$B_s \to \phi \phi$**
  - $\chi^2_{VX} < 100$
  - $\theta_B < 10 \text{ mrad}$
  - Decay angle: $|\cos \theta| < 0.75$
  - $|\Delta M| < 24 \text{ MeV}/c^2$
Selection of $K_S$ for $B_d \rightarrow \phi K_S$

- $K_S$:
  - Secondary vertex from $\pi^+\pi^-$ pair consistent with PID
    - $\chi^2_{VX} < 20$
  - Different track categories:
    - With and without track fragments measured in precise silicon vertex detector
  - $|\Delta M| < 15(25)\text{ MeV}/c^2$
Selection of $B_d \rightarrow \phi K_S$

- **B:**
  - Impact parameter to the primary vertex
    - $IP < (250,200,100) \mu m$
  - $p_T(K_S) > 1100(500) \text{ MeV}/c^2$
  - $p_T(\phi) > 1350 \text{ MeV}/c^2$
  - $\theta_B < 10 \text{ mrad}$
  - $|\Delta M| < 55 \text{ MeV}/c^2$
  - $\sigma(M_B) = 16 \text{ MeV}/c^2$
Efficiencies, Event Yields and B/S

- Enlarged mass window
- $B_s \rightarrow \phi \phi$
  - 4-7 GeV/c$^2$
- $B_d \rightarrow \phi K_s$
  - 4-6.6 GeV/c$^2$
- No background events from $10^7$ forward $b\bar{b}$ events
- 1 event from $10^6 b \rightarrow \phi X$ sample (for $B_d \rightarrow \phi K_s$)
  - effectively $\times 3.5$ statistics as forward $b\bar{b}$

<table>
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<th>$B_d \rightarrow \phi K_s$</th>
<th>$B_s \rightarrow \phi \phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_{TRIG} [%]$</td>
<td>19</td>
<td>23</td>
</tr>
<tr>
<td>$\varepsilon_{TOT} [%]$</td>
<td>0.074</td>
<td>0.45</td>
</tr>
<tr>
<td>N/year</td>
<td>800</td>
<td>1200</td>
</tr>
<tr>
<td>$B/S$</td>
<td>&lt;1.1 (b\bar{b})</td>
<td>&lt;0.2 (b\rightarrow \phi X)</td>
</tr>
</tbody>
</table>
Real rear decay: $B_s \rightarrow \mu^+\mu^-$

- **SM**: $Br \sim 3 \times 10^{-9}$
- Many New Physics models predict enhancement
  - $10^1$-$10^3$
- $\mu^\pm$
  - Compatible with $\mu$ PID
  - $p_T > 1.3$ GeV/c
- $\mu\mu$
  - $\chi^2_{VX} < 4$
  - $\Delta Z/\sigma Z > 29$
  - $p_T > 3$ GeV/c
  - $|\Delta M| < 600$ MeV/c$^2$
Efficiencies, Event Yield and B/S

- $\varepsilon_{\text{TOT}} = 2.5\%$, $\varepsilon_{\text{TRIG}} = 80\%$
- $N/\text{year} = 17$ events

No background events
neither from $10^7$ forward
$b\bar{b}$ sample
no from $10^7$
$b\rightarrow\mu X, \bar{b}\rightarrow\mu X$ sample

<table>
<thead>
<tr>
<th></th>
<th>B/S at 90%</th>
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<tbody>
<tr>
<td>Forward $b\bar{b}$</td>
<td>$&lt;440$</td>
</tr>
<tr>
<td>$b\rightarrow\mu X, \bar{b}\rightarrow\mu X$</td>
<td>$&lt;6$</td>
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</tbody>
</table>
**Summary**

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

<table>
<thead>
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<th>Decay</th>
<th>N/year</th>
<th>B/S @90%CL</th>
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<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>$B_d \rightarrow K^{*0}\mu^+\mu^-$</td>
<td>4.4k</td>
<td>[0.2, 2.0]</td>
</tr>
<tr>
<td>$B_s \rightarrow \phi K_S$</td>
<td>800</td>
<td>&lt;1.1 ($b\bar{b}$)</td>
</tr>
<tr>
<td>$B_s \rightarrow \phi\phi$</td>
<td>1.2k</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>$B_s \rightarrow \mu\mu$</td>
<td>17</td>
<td>&lt;440 ($b\bar{b}$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;6 ($b\rightarrow\mu X$)</td>
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