Rare penguin decays at LHCb

Beyond the 3SM generation at the LHC era
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NIKHEF
Introduction

Loop induced rare decays are sensitive to **New Physics**. **New Particles** (such as 4\textsuperscript{th} gen quarks) can modify the SM Wilson coefficients or introduce **new CPV phases**.

\begin{itemize}
  \item - \((B_s^0 \rightarrow \Phi \Phi)\)
  \item - \(B_s^0 \rightarrow \Phi \gamma, B_d^0 \rightarrow K^{*0}\gamma\)
  \item - \(B_d^0 \rightarrow K^{*0}\mu\mu\)
  \item - \(B_s \rightarrow \mu\mu\)
\end{itemize}

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CP Violation in B system

The mixing between the B-CP eigenstates is described by:

\[ |B_{H,L}\rangle = p|B^0\rangle \mp q|\bar{B}^0\rangle \]

\[ \lambda_f = \frac{q}{p} \frac{\tilde{A}_f}{A_f} \]

When the $B_s$ decays in a CP-eigenstate (or a superposition of CP-eigenstates), CPV can arise in the interference between mixing and decay:

\[ \frac{|q|}{p} = 1, \quad \frac{\tilde{A}_f}{A_f} = 1, \quad \text{arg} \, \lambda_f \neq 0 \]

The CPV weak phase is given by:

\[ \phi_s(B_s^0 \to f) \equiv \Phi_M(B_s^0) - \Phi_D(B_s^0 \to f) \]
CPV in the $B_s \to \Phi\Phi$ decay

For the $B_s \to \Phi\Phi$, the dependence on $V_{ts}$ and $V_{tb}$ in both the $B_s$ mixing and the decay amplitude leads to a complete weak phase cancellation

$$\Phi_{s}^{SM}(B_s \to \Phi\Phi) \sim 0$$

N.B.: $\Phi_{s}^{SM}(B_s \to J/\psi\Phi) = 2 \cdot \arg[V_{tb} \cdot V_{ts}] = -2 \cdot \beta_s$

NP can enter in both the mixing and the decay contributing with new CPV phases (sensitive to the 4x4 CKM elements $V_{ts}$ and $V_{tb}$).

Comparison between the $B_s \to J/\psi \Phi$ allows us to disentangle the two NP contributions.

CDF observation:
$$\text{BR}(B_s^0 \to \phi\phi) = (14^{+6}_{-5} \text{(stat.)} \pm 6 \text{(syst.)}) \times 10^{-6}$$

LHCb expectation for $B_s^0 \to \Phi(\to K^+K^-) \Phi(\to K^+K^-)$
$$N_{\text{sig}} = 3092 \pm 105 \text{ (in 2fb}^{-1})$$
$$N_{\text{bg}} < 2.4 \cdot 10^3 \text{ (in 2fb}^{-1})$$

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We can measure the weak CPV phase by measuring the time dependent CP asymmetry:

\[ A(t) \equiv \frac{\Gamma [B_s^0(t) \to f] - \Gamma [B_s^0(t) \to \bar{f}]}{\Gamma [B_s^0(t) \to f] + \Gamma [B_s^0(t) \to \bar{f}]} = \frac{A^{\text{dir}} \cos(\Delta m_s t) + A^{\text{mix}} \sin(\Delta m_s t)}{\cosh(\Delta \Gamma_s t/2) - A^{\Delta \Gamma} \sinh(\Delta \Gamma_s t/2)} \]

Angular analysis needed to disentangle the different CP components:

\[ \frac{d\Gamma(t)}{d\cos \theta_1 d\cos \theta_2 d\varphi} \propto \sum_{j=0}^{6} K_j(t) f_j(\theta_1, \theta_2, \varphi) \]

SM prediction:

\[ A_{\text{dir}}^{\text{SM}} \approx 0, \]
\[ A_{\text{mix}}^{\text{SM}} = \eta \sin(\phi_s^{\text{SM}}) \approx 0, \]
\[ A_{\Delta \Gamma}^{\Delta \Gamma} = \cos(\phi_s^{\text{SM}}) \approx 1. \]

LHCb sensitivity to the angle $\Phi_s$ (LHCb-2007-047)

$\sigma(\Phi) = 0.12$ with $2\text{fb}^{-1}$ (1 year of LHCb)

$\sigma(\Phi) = 0.05$ with $10\text{fb}^{-1}$ (5 years of LHCb)
Radiative penguins $B \to V\gamma$

Photon polarization is sensitive to $V$-$A$ structure
Photon polarization can be measured by time dependent CP asymmetry

$$\begin{align*}
&\text{Dominated by the } C_7 \text{ Wilson coefficient.}
\end{align*}$$

Interesting channels:
$B_s \to \Phi \gamma$ and $B_d \to K^* \gamma$

SM prediction:
$$\begin{align*}
\text{Br}(B_s \to \Phi \gamma) &= (39.4 \pm 10.7 \pm 5.4) \cdot 10^{-6} \\
\text{Br}(B_s \to \Phi \gamma) &= 57^{+18}_{-15} \text{ (stat)}^{+12}_{-11} \text{ (syst)} \cdot 10^{-6} \\
\end{align*}$$

Observed by BELLE at the $Y(5s)$
(Phys. Rev. Lett. 100, 121801 (2008)):
$$\begin{align*}
\text{Br}(B_s \to \Phi \gamma) &= 57^{+18}_{-15} \text{ (stat)}^{+12}_{-11} \text{ (syst)} \cdot 10^{-6} \\
\end{align*}$$

Br($B_d \to K^* \gamma$) = $(4.01 \pm 0.20) \cdot 10^{-5}$
observed by CLEO
(Phys. Rev. Lett. 84 5283),
Babar (Phys. Rev. D 70 112006)
and Belle (Phys. Rev. D 69 112001)
B_s \rightarrow \Phi \gamma \text{ at LHCb}

Signal yield (B_s \rightarrow \Phi (\rightarrow K^+ K^-) \gamma) : 7700 in 2fb^{-1} (1 year of LHCb)

Time dependent CP asymmetry (for |p/q|=1):

\[ A_{CP}(B_s \rightarrow \phi \gamma)[t] = \frac{S \sin(\Delta m_s t) - C \cos(\Delta m_s t)}{\cosh(\frac{\Delta \Gamma_s}{2} t) - H \sinh(\frac{\Delta \Gamma_s}{2} t)} \]

Free parameters: C, S and H

H and S sensitive to right-handed currents
C sensitive to new CPV phases (proportional to \( \beta_s \))

To measure the parameters C and S the knowledge of the initial B-flavor is needed.
For the measurement of H (possible thanks to \( \Delta \Gamma_s \neq 0 \))
no-flavor tagging is needed (arXiv:0802.0876).
A similar analysis is also possible in the B_s \rightarrow \Phi \mu\mu (under study)

Requires the measurement of \( \Delta \Gamma_s \) elsewhere (i.e. B_s \rightarrow J/\psi \Phi)
**B_s \rightarrow \Phi \gamma** at LHCb

Right-handed currents contribution more detectable in H (proportional to cos of the total weak phase) rather than S (proportional to sine of the total weak phase).

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>\sigma_S</td>
<td>0.11 (2 fb^{-1})</td>
</tr>
<tr>
<td>\sigma_C</td>
<td>0.11 (2 fb^{-1})</td>
</tr>
<tr>
<td>\sigma_H</td>
<td>0.16 (2 fb^{-1})</td>
</tr>
</tbody>
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Resolution for the S, C and H parameters in 1 year of data taking at LHCb

**B_d \rightarrow K^* \gamma** at LHCb

The parameter S was already measured by the B-factories in the \( B_d \rightarrow K^* \gamma \) decay.

The average is \( S_{K^*\gamma} = -0.19 \pm 0.23 \) (arXiv:0704.3575v1).

Direct CP asymmetry in

\( B_d \rightarrow K^{*0} (\rightarrow K^+ \pi^-) \gamma \) under study.

Annual yield: 68K events (2fb^{-1})

Bg events < 41K @ 90% CL (LHCb-2007-030)

\[
A_{CP} = \frac{N_{B^0 \rightarrow K^{*0} \gamma} - N_{\bar{B}^0 \rightarrow \bar{K}^{*0} \gamma}}{N_{B^0 \rightarrow K^{*0} \gamma} + N_{\bar{B}^0 \rightarrow \bar{K}^{*0} \gamma}}.
\]
AFB in the $B_d \rightarrow K^{*0} \mu^+\mu^-$

This decay is completely described by the differential decay rate:

$$\frac{d^4\Gamma_{\bar{B}\rightarrow K\mu^+\mu^-}}{dq^2 \ d\theta_\ell \ d\theta_K \ d\phi} = \frac{9}{32\pi} I(q^2, \theta_\ell, \theta_K, \phi) \sin \theta_\ell \sin \theta_K$$

The AFB is the asymmetry between the forward going ($\cos \theta_\ell > 0$) and the backward going ($\cos \theta_\ell < 0$) $\mu^+$ wrt the B flight direction in the $\mu\mu$-rest frame.

The $q^2$ point ($S_0$) in which the AFB($q^2$)=0 is very sensitive to NP and theoretically predicted (for the SM and several NP models).

The visible branching ratio is $Br(B \rightarrow K^{*0} (\rightarrow K^+\pi^-) \mu^+\mu^-) = 1.22_{-0.32}^{+0.38} \cdot 0.67 \cdot 10^{-6}$

Signal yield: $7200 \pm 180$ events (2fb$^{-1}$),

Expected background events: 1770 events (2fb$^{-1}$)

(Bg from non-resonant $B_d^0 \rightarrow K^+ \pi^- \mu\mu$ not considered). LHCb-2007-038
NP in the $B_d \rightarrow K^* \mu \mu$

SM diagrams for the $B_d \rightarrow K^* \mu \mu$ decay:

NP particles in the loops such as t' (4th generation) changes the AFB.

Number of events:
Belle $\sim$ 230 events
LHCb $\sim$ 1800 events (end 2009)

Most recent BaBar measurement
arxiv:0804.4412v1

Belle Results from ICHEP 2008

For Beyond the 3SM gen. see for instance Phys. Rev. D 77, 014016 (2008)

This process is dominated by the $C_7$, $C_9$ and $C_{10}$ Wilson coefficients.
The simplest method to extract the AFB is a counting experiment, subtracting $q^2$-histograms for forward and backward events.

AFB distribution for one $2\text{fb}^{-1}$ experiment (below the $J/\psi$ resonance)

Straight line fit to extract $S_0$ (LHCb-2007-039):

$$\sigma(S_0)=0.46\text{GeV}^2 \text{ in } 2\text{fb}^{-1}.$$ 

We can do an unbinned likelihood fit of the $q^2$ distributions for forward and backward events

With this method we do not rely anymore on the straight-line-shape near $S_0$. 

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Another possibility is to extract the AFB fitting simultaneously the two distributions (see LHCb-2007-057):

\[
\frac{d \Gamma}{d q^2 d \theta_l} = \frac{3}{4} \frac{d \Gamma}{d q^2} \frac{3}{4} F_L \sin^2 \theta_l + \frac{3}{8} (1 - F_L) (1 + \cos^2 \theta_l) + A_{FB} \cos \theta_l \sin \theta_l
\]

\[
\frac{d \Gamma}{d q^2 d \theta_k} = \frac{3}{4} \frac{d \Gamma}{d q^2} \sin \theta_k (2 F_L \cos^2 \theta_k + (1 - F_L) \sin^2 \theta_k)
\]

1 year of LHCb

AFB

An improvement of 40% on \( \sigma(S_0) \) expected wrt the unbinned \( q^2 \) fit.

No bg and acceptance considered!
**B_d \rightarrow K^* \mu \mu**: 4D unbinned likelihood fit

\[
\frac{d^4 \Gamma_{B_d}}{dq^2 \, d\theta_l \, d\theta_K \, d\phi} = \frac{9}{32\pi} I(q^2, \theta_l, \theta_K, \phi) \sin \theta_l \sin \theta_K
\]

\[I = I_1 + I_2 \cos 2\theta_l + I_3 \sin^2 \theta_l \cos 2\phi + I_4 \sin 2\theta_l \cos \phi + I_5 \sin \theta_l \cos \phi + I_6 \cos \theta_l + I_7 \sin \theta_l \sin \phi + I_8 \sin 2\theta_l \sin \phi + I_9 \sin^2 \theta_l \sin 2\phi.\]

The \(I_i\) terms are functions of the amplitudes \(A_{LL}^{L,R}, A_{\perp}^{L,R}\) and \(A_0^{L,R}\) (6 complex numbers, which depend on \(q^2\)).

We can probe more angular asymmetries which are a function of these amplitudes.

See arXiv:0807.2589

LHCb expectation for the AFB (10fb\(^{-1}\))

Improvement of the order of (20-30%) on \(\sigma(S0)\) wrt the projection fit is expected.

Systematics more difficult to control (under study)

More asymmetries in $B_d \rightarrow K^*\mu\mu$

More asymmetries in $B_d \rightarrow K^*\mu\mu$

Theoretical prediction for the SM

LHCb expectation for SUSY-b (5 years)

Theoretical prediction for the SM

LHCb expectation for SUSY-b (5 years)

$A_T^3$

$A_T^4$

$A_T^2$

SUSY-b:
SUSY model with $C_7'$
non-SM contributions.
For details see:
arXiv:0807.2589

Similar for $B_s$ analogy
$B_s \rightarrow \Phi \mu\mu$ under study (LHCb-2007-154).
**B_s → μ μ : Branching Ratio**

The branching ratio for the channel $B_s \rightarrow ll$ is sensitive to many NP theories. For theories beyond 3SM generations the branching ratio depends on the $t'$ mass and on the 4x4 CKM parameter $V_{tb} V_{ts}^*$ (see Eur.Phys.J. C27 (2003) 405-410).

**ATLAS/CMS** (arXiv:0801.1833v1)

Assuming SM Branching ratio (LHCb):
- 2 fb⁻¹ ⇒ 3σ evidence (1year)
- 6 fb⁻¹ ⇒ 5σ observation (5years)

Assuming SM Branching ratio (ATLAS/CMS):
- 30 fb⁻¹ ⇒ 3σ evidence (3years)

LHCb can exclude the BR above the SM with only 0.5 fb⁻¹ of data (end of 2009)

The $B_s \rightarrow μ μ γ$ is under study within the LHCb collaboration.
Conclusions

• Rare penguin decays are very sensitive to NP: test of CKM and the V-A structure of the SM.

• LHCb can strongly constrain or discover NP in the following channels:
  - \( B_s^0 \rightarrow \Phi\Phi \): Weak CPV phase;
  - \( B_{s/d} \rightarrow \Phi/K^* \gamma \): Time dependent CP asymmetry;
  - \( B_d^0 \rightarrow K^0 \mu\mu \): AFB and more angular asymmetries;
  - \( B_s \rightarrow \mu\mu \): Branching ratio.
We hope to find some non-SM penguins
Back-up SLIDES