Search for New Physics with Rare Heavy Flavour Decays at LHCb

DISCRETE 2010

T. Blake on behalf of LHCb
Outline

1. **Introduction**
   - Physics with Rare Decays
   - The LHCb detector

2. **Prospects for 2010 - 2011**
Aim to review the state of three of LHCb’s key Rare Decay analyses in light of our experience with the 2010 data from the LHC:

- \(B_d \rightarrow K^{*0} \mu^+ \mu^-\)
- \(B_d \rightarrow K^{*0} \gamma\)
- \(B_s \rightarrow \mu^+ \mu^-\) and \(f_s/(f_u + f_d)\)
**What is a “rare decay”?**

- FCNC process, mediated by electroweak box and penguin diagrams in SM.

- New Physics enters at same (i.e. loop) order and can give rise to comparably large deviations from SM predictions in:
  - Branching ratios.
  - Angular distributions.
  - CP and Isospin asymmetries.
Model independent approach. Are there new heavy degrees of freedom $\rightarrow$ NP?

Form effective Hamiltonian for $b \rightarrow s$ transitions:

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \left[ C_i \mathcal{O}_i + C'_i \mathcal{O}'_i \right]$$

Short range physics (heavy degrees of freedom) are contained in the coefficients, $C_i$, and the operators $\mathcal{O}_i$ contain the long range contributions.
Sensitivity through Rare Decays

Operator $\mathcal{O}_i$

\[
\mathcal{O}_7 \sim m_b (\bar{s}_L \sigma_{\mu\nu} b_R) F_{\mu\nu} \quad b \to s\gamma \text{ & } b \to s\ell\ell
\]

\[
\mathcal{O}_9 \sim (\bar{s} b)_{V-A} (\bar{\ell} \ell)_V \quad b \to s\ell\ell
\]

\[
\mathcal{O}_{10} \sim (\bar{s} b)_{V-A} (\bar{\ell} \ell)_A \quad b \to s\ell\ell
\]

\[
\mathcal{O}_{S,P} \sim (\bar{s} b)_{S+P} (\bar{\ell} \ell)_{S,P} \quad B_s \to \mu^+ \mu^-
\]

In the SM:

- $\mathcal{C}_{S,P} \propto m_\ell m_b/m_W^2 \sim 0$.
- Helicity flipped operators ($\mathcal{C}_i'\mathcal{O}_i'$) suppressed by $m_s/m_b$. 
Sensitivity to New Physics

SM Operators

2 Higgs Doublet Models at low $\tan \beta$
Littlest Higgs without T-Parity,
Universal Extra Dimensions.

+ New Operators

2 Higgs Doublet Models at large $\tan \beta$
Littlest Higgs with T-Parity, MSSM with MFV.

Non-CKM

Littlest Higgs with T-Parity, 4th Generation Models.

Warped Extra Dimensions.

Taken from [Buras]
Introduction
Prospects for 2010 - 2011

Physics with Rare Decays
The LHCb detector

The LHCb detector

Forward arm spectrometer covering $2 < \eta < 5$. $\bar{b}b$ production through gluon fusion

T. Blake
Rare Decays at LHCb
Needle in a haystack?

Challenge is to trigger on, reconstruct and cleanly select the decays . . .

. . . in the busy Hadronic environment
Excellent performance from LHC in 2010.

Results shown by LHCb based on integrated luminosity of up-to 37 pb$^{-1}$.

Detector efficiency $> 90\%$.

Peak luminosity $1 - 2 \times 10^{32}$ cm$^2$s$^{-1}$ with $\mathcal{O}(400)$ colliding bunches.
Outline

1. Introduction
2. Prospects for 2010 - 2011
   - Prospects for Rare Decays in 2010-2011
   - Summary
$B_d \rightarrow K^{*0} \mu^+ \mu^-$: Introduction

- $B_d \rightarrow K^{*0} \mu^+ \mu^-$ is a FCNC mediated by box and penguin diagrams in the SM.
- Sensitive to new physics with contributions from:
  - right-handed currents.
  - new scalar / pseudo-scalar operators.

For first 1 fb$^{-1}$ focus on $A_{FB}$, the forward-backward asymmetry of the muons.
$B_d \rightarrow K^{*0} \mu^+ \mu^-$: MC performance

BaBar, Belle and LHCb with 100 pb$^{-1}$

(Theory Errors, $\frac{A}{m_b}$ corrections at 10% level, average of theory curve)

1.5σ SM exclusion

$\sigma_{bb} = 219 \mu$b

LHCb datapoint uses Belle central value. Statistical error only.
**$B_d \rightarrow K^{*0}\mu^+\mu^-$: Lessons from early data**

- Use $B_d \rightarrow J/\psi K^{*0}$ as a control channel (70x higher BR with same final state) to understand efficiency and angular biases in data.

- Signal region, $m_{\mu^+\mu^-} \neq m_{J/\psi}$ and $m_{\mu^+\mu^-} \neq m_{\psi(2S)}$ is currently blinded.
$B_d \rightarrow K^{*0} \mu^+ \mu^-$: Lessons from early data

$LHCb$
Preliminary
$\sqrt{s} = 7$ TeV Data
$L \sim 17$ pb$^{-1}$

$B_d \rightarrow J/\psi K^{*0}$ background dominated by events with genuine $J/\psi$/$\psi(2S)$. 

$\mu^+ \mu^-$ Invariant Mass / (50 MeV / c$^2$)
**B_d \rightarrow K^{*0} \mu^+ \mu^-**: Lessons from early data

- Signal efficiency is close to MC predictions for \( B_d \rightarrow J/\psi K^{*0} \).
- Biased estimate of background in signal region for \( B_d \rightarrow K^{*0} \mu^+ \mu^- \) is \( B/S < 1 \).
- Expect world best measurement of \( A_{FB} \) with \( \mathcal{O}(200) \text{ pb}^{-1} \).

![Graph showing distribution of events](image)

- Background outside the \( m_B, m_{J/\psi} \) and \( m_{\psi(2S)} \) mass windows.
- Expected \( B_d \rightarrow K^{*0} \mu^+ \mu^- \) signal, scaled from \( B_d \rightarrow J/\psi K^{*0} \) in data.
\[ B_d \rightarrow K^{*0}\gamma \]

- \( \text{BR}(B_d \rightarrow X_s \gamma) \) in agreement with SM predictions:
  \[
  \begin{align*}
  \text{BR}(B_d \rightarrow X_s \gamma)_{\text{exp.}} &= 3.15 \pm 0.23 \times 10^{-4} \quad \text{[A. Linosani et al.]}
  \\
  \text{BR}(B_d \rightarrow X_s \gamma)_{\text{th.}} &= 3.56 \pm 0.26 \times 10^{-4} \quad \text{[M. Misiak]}
  \end{align*}
  \]

- Large deviations still possible in asymmetries, e.g. \( A_{CP}(B_d \rightarrow K^{*0}\gamma) \).

- Worlds best measurement from \textit{BABAR} based on 2400 signal candidates:
  \[
  A_{CP} = -0.016 \pm 0.022 \pm 0.007 \quad \text{[B. Aubert et al.]} \]
$B_d \rightarrow K^{*0} \gamma$ at LHCb

- LHCb currently observe $\sim 50$ candidates in $\sim 26 \text{ pb}^{-1}$ with $\sigma_{m_B} \sim 130 \text{ MeV}$.
- The yield is significantly below expectations from the MC.
- Work on-going to improve the Calorimeter calibration. Expect improvements in yield and $m_B$ resolution with updated calibration.

![Graph showing data points and fitted curves for $B_d \rightarrow K^{*0} \gamma$](image)
\( \gamma \) polarisation

- With 1 fb\(^{-1}\) aim to make measurement of photon polarisation. Right-handed component suppressed by \( m_s/m_b \) in SM.

- Two approaches:
  - Time dependent measurement of \( B_s \to \phi \gamma \) [R.Zwicky et al.],

\[
\Gamma_{B(\bar{B})\to fCP\gamma}(t) \propto \cosh \left( \frac{\Delta \Gamma}{2} t \right) - A^\Delta \sinh \left( \frac{\Delta \Gamma}{2} t \right) \pm C \cos \Delta m t \mp S \sin \Delta m t
\]

where \( A^\Delta \) and \( S \) are sensitive to the “wrong” polarisation fraction.

- Angular analysis of \( B_d \to K^{*0}e^+e^- \) [LHCb-PUB-2009-008].
$B_s \rightarrow \mu^+ \mu^-$: Introduction

- Highly sensitive to new operators.
- Enhancements possible in BR:
  \[ \propto \tan^6 \beta / m_A^4 \]
  in models with second Higgs doublet (e.g. MSSM).
- At LHCb extract potential signal using a three-component likelihood:
  - Based on the mass distribution, muon identification and Geometrical likelihood.

[J. Ellis. et al.]
$B_s \rightarrow \mu^+\mu^-$: Geometrical likelihood

- Discriminate signal and background using geometrical likelihood based on $B$ kinematics:
  - Lifetime, Impact Parameter, Isolation
- Calibrate the geometrical likelihood using $B \rightarrow hh$ decays with same kinematics.

Also, excellent mass resolution of $\sigma_{m_B} \sim 23$ MeV for $B \rightarrow hh$. 
Good agreement between mass distribution of background events between Data and MC. No evidence for excess of background in data.

Background events populate the low Geometrical Likelihood region. Signal & $B \rightarrow hh$ control channels are flat in geometrical likelihood.

Background in $B_s$ mass region: $M(B_s) \pm 600$ MeV; Data/MC = 1.5±0.4
**$B_s \rightarrow \mu^+ \mu^-$: Sensitivity**

- Expected exclusion limit (versus integrated luminosity) for toy MC with $\sqrt{s} = 7$ TeV and $\sigma(pp \rightarrow b\bar{b}) = 284 \pm 20 \pm 49 \mu$b.
- Limit with $\sim 37 \text{ pb}^{-1}$ expected to be close to existing DØ limit.
- Expect world's best measurement with $\mathcal{O}(100)$ pb$^{-1}$.

\[ \text{BR}(B_s \rightarrow \mu^+ \mu^-) \times 10^9 \]

**Integrated Luminosity (fb$^{-1}$)**

- 2010
- CDF (3.7 fb$^{-1}$)
- DØ (6.1 fb$^{-1}$)
- LHCb
- End 2011

@ 3.5 + 3.5 TeV

SM prediction
\[ B_s \rightarrow \mu^+ \mu^- : \text{Normalisation} \]

\[
\text{BR}(B_s \rightarrow \mu^+ \mu^-) = \text{BR}(B_q \rightarrow X) \times \frac{f_q}{f_s} \times \frac{\varepsilon_{B_q \rightarrow X}}{\varepsilon_{B_s \rightarrow \mu^+ \mu^-}} \times \frac{N_{B_s \rightarrow \mu^+ \mu^-}}{N_{B_q \rightarrow X}}
\]

Two options for normalisation:

- Normalise to \( B_s \rightarrow J/\psi \phi \)?
  - Currently have 25% uncertainty on measured BR from Belle at \( \Upsilon(5S) \).

- Normalise to \( B^+ \rightarrow J/\psi K^+ \) or \( B_d \rightarrow J/\psi K^{*0} \)?
  - \( f_s/(f_u + f_d) \) measured at LEP and at TeVatron. Is it possible to improve at LHCb?
  - Use ratio of semileptonic \( b \rightarrow c \mu \nu \) decays or ratio \( B_s \rightarrow D_s^- \pi^+ / B_d \rightarrow D^- K^+ \) [R. Fleischer et al.]
Follow the approach used in the LHCb $\sigma(pp \rightarrow b\bar{b})$ cross-section measurement [R. Aaij et al.] to estimate $f_s/(f_u + f_d)$ using:

$$b \rightarrow D^0 \mu X\nu , \quad b \rightarrow D^+ \mu X\nu \quad \text{and} \quad b \rightarrow D_s^+ \mu X\nu$$

decays where only the $D$ and the $\mu$ are reconstructed and the prompt “$D$” are separated from “$D$” from “$B$” decays (DfB).

Extract $f_s/(f_u + f_d)$ from the ratio between the $D_s^+$ and $D^0/D^+$ modes taking into account the relative efficiencies and cross feed.
"D" from "B"

\[ D^0 \rightarrow K^- \pi^+ \]

\[ D^+ \rightarrow K^- \pi^+ \pi^+ \]

\[ D_s^+ \rightarrow K^+ K^- \pi^+ \]
$f_s/(f_u + f_d)$ preliminary result

LHCb 2010 preliminary result:

$$\frac{f_s}{f_u + f_d} = 0.130 \pm 0.004\,\text{(stat.)} \pm 0.013\,\text{(sys.)}$$

- Preliminary estimate of $f_s/(f_u + f_d)$ in agreement with the LEP measured value of $0.129 \pm 0.012$ from PDG. TeVatron value is $0.18 \pm 0.03$.

- Largest systematic uncertainties come from:
  - Estimation of the $B_s \rightarrow D^0 K \mu X \nu$ yield (6.3%).
  - The Charm Hadronic branching ratios (5.5%).
LHC and LHCb performance in 2010 has been excellent.

37 pb\(^{-1}\) integrated luminosity collected in 2010. Expect 1 fb\(^{-1}\) in 2011.

Expect world best measurement with \(B_s \rightarrow \mu^+\mu^-\) and \(B_d \rightarrow K^{*0}\mu^+\mu^-\) in 2011.
Expect numerous Rare Decay results in 2011

- Have only given a brief introduction to the wide range of rare decay measurements being performed by LHCb. Expect results in 2011-2012!

- $R_K$
- $D^0 \rightarrow \mu^+ \mu^-$
- $B_s \rightarrow \phi \mu^+ \mu^-$
- $\Lambda_B \rightarrow \Lambda \mu^+ \mu^-$
- $B^+/D^+_{(S)} \rightarrow K^- \mu^+ \mu^+$
- $D \rightarrow K^+ K^- \mu^+ \mu^-$
- $B_d \rightarrow K^0 e^+ e^-$
- $B \rightarrow e \mu$
- $\tau^+ \rightarrow \mu^+ \mu^- \mu^+$
- $B_s \rightarrow \phi \gamma$
- $B_d \rightarrow K^0 \gamma$
- $B_d \rightarrow K^* \mu^+ \mu^-$
- $B_s \rightarrow \mu^+ \mu^-$
- Isospin analysis in $B_{u,d} \rightarrow X_{s(u,d)} \mu^+ \mu^-$
Tracking performance

- Long lever arm for tracking $\rightarrow \Delta p/p \sim 0.4\%$.

VELO: Vertex Locator, $r - \phi$ geometry silicon strip detector.

TT + IT: Silicon strip detectors, covering small polar angles (55 hit $\mu m$ resolution).

OT: Straw tubes (250 $\mu m$ hit resolution)
For rare decay modes can take advantage of the typical $B$ lifetime of $\sim 7\,\text{mm}$ to separate signal and background with lifetime biasing selections.

Good proper time resolution of $60\,\text{fs}$ in data (c.f. $40\,\text{fs}$ in MC).

Remaining differences between data and MC understudy. Can realistically expect some improvement with e.g. updated alignment.
Particle identification

- $\pi$, $K$ and $p$ separation in range 2 - 100 GeV/c provided by pair of Ring Imaging Cherenkov detectors.

Performance measured using tagged $D^* \to D(\to K\pi)\pi$ close to MC prediction.
Muon identification

- Muon ID performance estimated using $J/\psi$ tag and probe is excellent for high momentum muons.
- Good agreement between data and MC efficiencies.
Muon identification

- Muon ID performance estimated using $J/\psi$ tag and probe is excellent for high momentum muons.
- Good agreement between data and MC efficiencies.
- Good agreement between muon mis-id from $K_S^0 \rightarrow \pi^+ \pi^-$ between data and MC.
$B_d \rightarrow K^{*0} \mu^+ \mu^-$: Angular observables

- The forward-backward asymmetry, $A_{FB}$ is given by:

  $$A_{FB}(q^2) = \frac{N(\cos \theta_L > 0) - N(\cos \theta_L < 0)}{N(\cos \theta_L > 0) + N(\cos \theta_L < 0)}$$

  where $\theta_L$ is the angle between the direction of the $\mu^+ (\mu^-)$ and the direction of the $B_d (\bar{B}_d)$ in the rest frame of the $\mu^+ \mu^-$ pair. $A_{FB}$ varies as a function of $q^2 = m_{\mu^+ \mu^-}^2$.

- Hadronic uncertainties coming from the Form Factors cancel at LO when $A_{FB} = 0$.

- With $\gtrsim 2 \text{ fb}^{-1}$ can pursue wider range of angular and CP observables to probe Helicity structure of underlying theory.