Prospects for rare B decays at LHCb

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"Imagine if Fitch and Cronin had stopped at the 1% level, how much physics would have been missed"

A. Soni
RDs: finding a needle in a haystack

$B_s \to \mu\mu$ \( (\text{Br} \sim 10^{-9}) \)

$B_d \to K^*\mu\mu$, $B_s \to \phi\gamma$
\( (\text{Br} \sim 10^{-6(5)}) \)

Some Other rare decays : $B_{s,d} \to e\mu$, $B_d \to K^*e\mu$
The LHCb detector
The LHCb detector
The LHCb detector

Experiment installed and being commissioned! Eagerly waiting for DATA!
Introduction: (Semi)-leptonic B-decays

- Indirect searches are very promising for doing a precise test of SM in a model independent way;
- A FCNC NP contribution could be at the same level as SM contribution;
- NP virtual particles can vary amplitudes wrt SM expectations;
- The challenge is to find quantities which are theoretically clean and experimentally accessible.
Angular observables in $B_d \to K^* \mu \mu$

In the OPE formalism this decay is function of three coefficients: $C_7, C_9, C_{10}$ ($C_7', C_9', C_{10'}$).

$$H_{\text{eff}} = \frac{4G_F}{\sqrt{\alpha}} V_{tb} V_{ts} \Sigma_i C_i O_i$$

The most popular of these observables is the AFB:

$$AFB(s) = \frac{N_f(s) - N_b(s)}{N_f(s) + N_b(s)}$$

$S = \text{dimuon invariant mass squared}$. The point where AFB(s)=0 is very well predicted.

Sensitive to several NP models! (e.g. Sugra with low tan$\beta$, MIA SUSY, Left-right symmetric models)
AFB in $B_d \rightarrow K^* \mu \mu$

The AFB arise from the interference between the $\gamma$ and the Z in the electroweak penguin.

$$AFB(s = m_{\mu\mu}) = C_{10} \xi(s) (\Re(C_9)F_1 + \frac{1}{s} F_2 C_7)$$

The zero-crossing point is the most clean against theoretical uncertainty

$$S_{0}^{SM} = 4.36^{+0.33}_{-0.31} \text{GeV}^2$$
Most recent Measurements

Belle: arXiv:0810.0335v1

Babar/Belle ~ O(100) events
CDF ~ 20 events
LHCb~ 7200 events in 1 year

No evidence of NP ... yet...

LHCb will collect the world largest data sample with (200-300)pb⁻¹
\[ B_d \rightarrow K^* \left( \rightarrow K^+\pi^- \right) \mu^+\mu^- : \text{LHCb expectation} \]

Different fit methods studied:
- Binned counting experiment
- Unbinned counting experiment
- 4D Unbinned Fit

Ongoing studies to correct for acceptance, using the control channel \( B_d \rightarrow J/\psi \left( \rightarrow \mu^+\mu^- \right) K^* \).

The robustest method will be used at the beginning (e.g., counting experiment)
The $I_i$ terms are functions of the amplitudes $A^{L,R}_\parallel$, $A^{L,R}_\perp$ and $A^{L,R}_0$ (6 complex numbers, which depend on $q^2$).

$$\frac{d^4\Gamma}{dq^2 d\theta_L d\theta_K d\phi} = \frac{9}{32\pi} I(q^2, \theta_L, \theta_K, \phi) \sin \theta_L \sin \theta_K$$

Better sensitivity wrt counting analysis.
More observables.
caveat: systematics more difficult to understand.

(*)SUSY (b) of JHEP 0811:032,2008
$B_s \rightarrow \mu^+\mu^- :$ Branching Ratio

SM \hspace{1cm} \text{Br}(B_s \rightarrow \mu^+\mu^-) = (3.5 \pm 0.32)x10^{-9}

Sensitive to NP involving new (pseudo)scalar interactions e.g. models with 2Higgs doublets (like MSSM); For all MSSM models prop to $\tan^6\beta$.

For high $\tan(\beta)$

$$\text{Br}^{\text{MSSM}}(Bq \rightarrow l^+l^-) \propto \frac{m_b^2 m_l^2 \tan^6 \beta}{M_{A0}^4}$$

In NUHM (which includes mSugra)

Preferred value:

$\text{BR}(B_s \rightarrow \mu^+\mu^-) \sim 2.0 \times 10^{-8}$

Possible explanation of $3.4\sigma$ discrepancy in $(g_\mu - 2)$

Limits of Tevatron at 90%:

$4.5 \times 10^{-8}$ present

$2.0 \times 10^{-8}$ expected final
$B_s \rightarrow \mu^+\mu^-$: Analysis Strategy

- Soft Preselection
- Selection:
  - Geometrical Likelihood (5 Geo Variables)
  - PID
  - Invariant Mass

Modified Frequentist approach for BR extraction

$s_i =$ expected signal events in bin
$b_i =$ expected bkg. events in bin
$d_i =$ measured events in bin

$$X_i = \frac{\text{Poisson}(d_i, < d_i >= s_i + b_i)}{\text{Poisson}(d_i, < d_i >= b_i)}$$

$$X = \prod_{i=1}^{N} X_i$$

$$CL_{s+b} = P_{s+b}(X \leq X^{\text{OBSERVED}})$$

$$CL_b = P_b(X \leq X^{\text{OBSERVED}})$$

$$CL_{s+b} = CL_b \times CL_s$$

BR exclusion at 90% if $CL_{s}(BR) \leq 10\%$
Main background consists of two muons coming from different b-decays \( (b \rightarrow b\bar{b} \rightarrow \mu^+ \mu^-) \).
Many other specific background analyzed 
\( (B \rightarrow hh, B \rightarrow J/\psi \mu \nu, \ldots) \) and found to be negligible.

Geometrical likelihood distribution

We use a double ratio of control channels to account for the extra-track.

\[
R_1 = \frac{B_{s} \rightarrow \mu^+ \mu^-}{B^+ \rightarrow J/\psi K^+}
\]
\[
R_2 = \frac{B^+ \rightarrow J/\psi K^+}{B_d \rightarrow J/\psi K^-}
\]

Invariant mass calibration with the control channels \( B_s \rightarrow KK \) and \( B_d \rightarrow \pi \pi \);
Geometrical likelihood calibration with \( B_{(s)} \rightarrow h^+h^- \);
PID likelihood calibration with \( J/\psi \rightarrow \mu^+ \mu^- \) and with \( \Lambda \rightarrow p\pi \);
BR Normalization with the two channels \( B^+ \rightarrow J/\psi K^+ \) and \( B_d \rightarrow J/\psi K^- \).
\( B_s \rightarrow \mu^+\mu^- : \text{expected results} \)

Exclusion at 90% CL:
- Tevatron expected final limit reached @ 200pb\(^{-1}\)
- Reach SM prediction with @ 2fb\(^{-1}\)

Observation:
- 5\(\sigma\) observation of BR \(\sim 2 \times 10^{-8}\) @ 500pb\(^{-1}\)
- 3\(\sigma\) observation of SM BR @ 3fb\(^{-1}\)
- 5\(\sigma\) observation of SM BR @ 10fb\(^{-1}\)

\[
Br(B_s \rightarrow \mu^+\mu^-) = (3.35 \pm 0.32) \times 10^{-9}
\]

<table>
<thead>
<tr>
<th>Channel</th>
<th>Yield (2 fb(^{-1}))</th>
<th>B</th>
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<tbody>
<tr>
<td>(B_s \rightarrow \mu^+\mu^-)</td>
<td>21 (SM)</td>
<td>180(^{+140}_{-80})</td>
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Photon Polarization in $B_s \rightarrow \Phi \gamma$

Photon polarization is sensitive to V-A structure
Photon polarization can be measured by time dependent analysis

Dominated by the $C_7$ Wilson coefficient.

- In the SM, the photon is mostly LEFT-handed in $b$ decays and RIGHT-handed for anti-$b$ decays.
- Presence of NP can modify the handness of the photon.

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

SM prediction:  
$\text{Br}(B_s \rightarrow \Phi \gamma) = (39.4 \pm 10.7 \pm 5.4) \cdot 10^{-6}$
$B_s \to \Phi \gamma$: what to measure

Signal yield ($B_s \to \Phi(\to K^+K^-)\gamma$): 7700 in 2 fb$^{-1}$ (1 year of LHCb)
Background events (in 2 fb$^{-1}$): < 4700 (LHCb-2007-147).

Time dependent decay rate for $B$/anti-$B$:

$$B/\overline{B}(t) = B_0 e^{-\Gamma t} \left\{ \cosh\left(\frac{\Delta \Gamma}{2} t\right) - H \cdot \sinh\left(\frac{\Delta \Gamma}{2} t\right) \pm C \cdot \cos(\Delta m_s t) \mp S \cdot \sin(\Delta m_s t) \right\}$$

Free parameters: $C, S$ and $H$

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.

$H$ sensitive to right handed currents.

$$H \approx \sin(2 \cdot \psi), \quad tg(\psi) = \frac{A_R}{A_L}$$

SM prediction: $\frac{A_R}{A_L} \sim 0.04$

Sensitivity 2 fb$^{-1}$

$\sigma_H \sim 0.2$

$\sigma(\frac{A_R}{A_L}) \sim 0.1$
Some other RDs: $B_d \to K^* e^+e^-$

Another way for accessing the photon polarization in $b \to s \gamma$ is by measuring the virtual photon in $B_d \to K^* e^+e^-$ (possible thanks to the low electron inv mass). The region where the $\gamma$ is quasi-real is inaccessible in $B_d \to K^* \mu^+\mu^-$. 

Full angular analysis

$$\frac{d\Gamma}{dq^2 d\cos\Theta_e d\cos\Theta_K d\phi} = \frac{9}{32\pi} \left[ I_1 (\cos\Theta_K) + I_2 (\cos\Theta_K) \cos 2\Theta_\ell + I_3 (\cos\Theta_K) \sin^2 \Theta_\ell \cos 2\phi \\
+ I_9 (\cos\Theta_K) \sin^2 \Theta_\ell \sin 2\phi \right]$$

- $I_1 (\cos\Theta_K) = \frac{3}{4} (1 - F_L) \times (1 - \cos^2 \Theta_K) + F_L \times \cos^2 \Theta_K$
- $I_2 (\cos\Theta_K) = \frac{1}{4} (1 - F_L) \times (1 - \cos^2 \Theta_K) - F_L \times \cos^2 \Theta_K$
- $I_3 (\cos\Theta_K) = \frac{1}{2} (1 - F_L) \times A^{(2)}_T \times (1 - \cos^2 \Theta_K)$
- $I_9 (\cos\Theta_K) = A_{1\text{im}} \times (1 - \cos^2 \Theta_K)$
- $A^{(2)}_T \sim \frac{2 \cdot A_R}{A_L}$, SM prediction $\frac{A_R}{A_L} \sim 0.04$

$N_{\text{sig}} \sim 500$ in 2fb$^{-1}$ (1 nominal year) $\to \sigma(A_T^{(2)}) \sim 0.2 \to \sigma(A_R/A_L) \sim 0.1$

Competitive with $B_s \to \phi\gamma$
Some other RDs: $B_{s,d} \rightarrow e\mu$

LFV decay forbidden by the SM, but is allowed by some extensions of the SM involving Lepto-Quarks, as the Pati-Salam SU(4) model. It explains why quarks experience the strong force and lepton do not.

CDF limits:
$Br(B_d \rightarrow e^\pm \mu^{\mp}) < 6.4 \cdot 10^{-8}$ at 90% CL
$Br(B_s \rightarrow e^\pm \mu^{\mp}) < 2.0 \cdot 10^{-7}$ at 90% CL

LHCb limits in 1 year
$Br(B_s \rightarrow e^\pm \mu^{\mp}) < 1.1 \cdot 10^{-8}$ in 2 fb$^{-1}$ at 90% CL
$Br(B_d \rightarrow e^\pm \mu^{\mp}) < 3.2 \cdot 10^{-9}$ in 2 fb$^{-1}$ at 90% CL

Limit can improve with a multidimensional analysis (ongoing study)
Other ongoing studies

Some other RDs I have not mentioned (ongoing studies in LHCb):

Other semileptonic decays:
- $B_s \rightarrow \phi \mu \mu$
- $B \rightarrow K l^+l^-$

Other radiative decays:
- $\Lambda_b \rightarrow \Lambda \gamma$
- $B_d \rightarrow K^* \gamma$

Rare D-decays:
- $D \rightarrow \mu \mu$, $D \rightarrow e\mu$, $D \rightarrow V\mu\mu$
Conclusions:

- RDs allow for testing NP in model independent way: Left-Right symmetric models, NUHM (⊃ mSugra) with large/small tanβ;

- Combining different measurements allows us to understand NP;

- LHCb can significantly improve present knowledge of FCNC. (in particular for (semi)-leptonic and radiative decays).

- The challenge is now to control systematics and to achieve MC results with real data.
How difficult is it to find a needle in a haystack?

 Depends on how you do it!
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Questions