In Pursuit of New Physics with $B$ Decays

Robert Fleischer

Nikhef (Theory Group)

Moriond 2011 – QCD and High Energy Interactions
La Thuile, Italy, 20–27 March 2011

• Setting the Stage

• $B$ Physics in the LHC Era: → Promising Channels for NP Signals:

  - $B_s^0 \to J/\psi \phi$: critical look at hadronic corrections.
  - $B_d^0 \to \pi^+ \pi^-$, $B_s^0 \to K^+ K^-$: picture from current data.
  - $B_s^0 \to \mu^+ \mu^-$: fragmentation functions are crucial for measurement.

• Concluding Remarks
Setting the Stage

[→ also the talk by Rob Lambert]
(New) Flavour Physics: Where Do We Stand?

- Lessons from the $B$, $D$, $K$, ... data collected so far:
  - CKM matrix is the dominant source of flavour and CP violation.
  - New effects not yet established, although there are potential signals:
    
    * Example: CP violation in $B^0 \rightarrow \pi^0 K_S$

    \[
    \frac{\Gamma(\bar{B}^0(t) \rightarrow \pi^0 K_S) - \Gamma(B^0(t) \rightarrow \pi^0 K_S)}{\Gamma(\bar{B}^0(t) \rightarrow \pi^0 K_S) + \Gamma(B^0(t) \rightarrow \pi^0 K_S)} = A_{\pi^0K_S} \cos(\Delta M_d t) + S_{\pi^0K_S} \sin(\Delta M_d t)
    \]

[R.F., S. Jäger, D. Pirjol & J. Zupan ('08)]
• Implications for the structure of New Physics (NP):

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{NP}}(\varphi_{\text{NP}}, g_{\text{NP}}, m_{\text{NP}}, \ldots) \]

- Large characteristic NP scale \( \Lambda_{\text{NP}} \), i.e. not just \( \sim \) TeV, which would be bad news for the direct searches at ATLAS and CMS, or (and?) ...
- Symmetries prevent large NP effects in FCNCs and the flavour sector; most prominent example: \textit{Minimal Flavour Violation (MFV)}:
  \[ \rightarrow \] essentially the same CP & flavour violation as in the SM.

• Comments:
- MFV is still far from being experimentally established!
- There are various non-MFV scenarios with room for sizeable effects: \textit{SUSY, warped extra dimensions, little Higgs, 4th generation, Z', \ldots}
- Nevertheless, we have to be prepared to deal with “smallish” NP effects.

• \textbf{Excellent news:}
- We are at the beginning of a new era in particle physics: \( \rightarrow \) LHC era
$B$ Physics in the LHC era:

→ promising probes for New Physics ...
Search for NP in $B_s^0 - \bar{B}_s^0$ mixing:

- Standard Model
- New Physics (e.g. SUSY, $Z'$ models)

- FCNC process: ⇒ strongly suppressed in the SM ("box" diagrams)

- involves a CP-violating phase $\phi_s = \phi_s^{\text{SM}} + \phi_s^{\text{NP}}$

  ⇒ SM piece is tiny: $\phi_s^{\text{SM}} \approx -2^\circ$

  ⇒ sensitive probe for NP
Constraints on NP Parameter Space

- Parameter (complex number) to characterize NP in $B_s^0 - \bar{B}_s^0$ mixing:
  \[ \kappa_s e^{i\sigma_s} \equiv "NP" / "SM" \]

- Mass difference: \[ \Delta M_s = \Delta M_s^{SM} |1 + \kappa_s e^{i\sigma_s}| \]
- Mixing phase: \[ \phi_s = \phi_s^{SM} + \phi_s^{NP} = \phi_s^{SM} + \text{arg}(1 + \kappa_s e^{i\sigma_s}) \]

- Allowed region in the $\sigma_s - \kappa_s$ plane:

  \[ \Delta M_s \Rightarrow \text{yellow band}; \]
  \[ \phi_s \Rightarrow \text{contours} \ldots \]

[Details: P. Ball & R.F. (2006)]
CP Violation in $B^0_s \rightarrow J/\psi \phi$

- **Interference effects through $B^0_s-\bar{B}^0_s$ mixing:**
  - *Mixing-induced* CP violation in time-dependent rates.
  - Hadronic parameters cancel to good approximation:
    \[ \Rightarrow \text{CP asymmetries} \sim \sin \phi_s \]

- **Final state is mixture of CP-odd and -even eigenstates:**
  \[ \Rightarrow \text{disentangle through } J/\psi \rightarrow \mu^+\mu^- \phi \rightarrow K^+K^- \text{ angular distribution.} \]

- **Smallish CPV in the SM:**
  \[ \Rightarrow \text{sensitive probe for NP in } B^0_s-\bar{B}^0_s \text{ mixing} \]

[Dighe, Dunietz & R.F. ('99); Dunietz, R.F. & Nierste ('01); Faller, R.F. & Mannel ('08)]
Tevatron $B_s^0 \rightarrow J/\psi \phi$ Results

• Current picture (early '11 and Summer '10): [Dictionary: $\phi_s = -2\beta_s$]

- DØ includes also the anomalous like-sign dimuon charge asymmetry;
- CDF plot uses only $B_s \rightarrow J/\psi \phi$ data. [→ talk by Satyajit Behari]

• Bad news: situation is (still...) not conclusive (?)
Prospects for $B_s \rightarrow J/\psi\phi$ Measurements @ LHCb

- **Experimental reach @ LHCb:** very impressive ...
  - LHCb on track for first $\phi_s$ results [→ talk by Christoph Langenbruch]
  - One nominal year of operation, i.e. $2 \text{ fb}^{-1}$: $\sigma(\phi_s)_{\text{exp}} \sim 1^\circ$
  - LHCb upgrade with integrated lumi of $100 \text{ fb}^{-1}$: $\sigma(\phi_s)_{\text{exp}} \sim 0.2^\circ$

- **However:** SM penguin effects were so far fully neglected: \footnote{\(\lambda \equiv |V_{us}| = 0.22\) is the Wolfenstein parameter.}

\[
A(B_s^0 \rightarrow J/\psi\phi) \propto A_f \left[ 1 + \lambda^2 (ae^{i\theta})e^{i\gamma} \right]
\]

- Impact of these corrections: $A_{\text{CP}}^{\text{mix}} = \sin \phi_s \rightarrow \sin(\phi_s + \Delta \phi_s)$.
- Hadronic shift $\Delta \phi_s$ can be controlled through $B_s^0 \rightarrow J/\psi \bar{K}^*0$.
  [CDF reported observation of this channel @ ICHEP 2010]

- **Two scenarios:** [$\Delta \phi_s$ must in any case be controlled to match LHCb accuracy]
  - Optimistic: $A_{\text{CP}}^{\text{mix}} \sim -40\%$ would be an unambiguous signal of NP!
  - Pessimistic: $A_{\text{CP}}^{\text{mix}} \sim -(5...10)\%$ would require more work from theorists and experimentalists to clarify the picture ...
Penguin Probe @ LHCb: $B^0_s \rightarrow J/\psi K_S$

\[ A(B^0_s \rightarrow J/\psi K_S) \propto \mathcal{A} \left[ 1 - ae^{i\theta} e^{i\gamma} \right] \]

- **$U$-spin symmetry:**
  - Determination of the UT angle $\gamma$.
  - Control of penguins in the determination of $\phi_d$ from $B^0_d \rightarrow J/\psi K_S$.

- **CDF reported observation @ ICHEP2010:** → first BR measurement:
  
  \[ (3.53 \pm 0.61\text{ (stat.)}) \pm 0.35\text{ (syst.)} \pm 0.43\text{ (frag.)} \pm 0.13\text{ (PDG)} ) \times 10^{-5} \]

  - $SU(3)$ flavour-symmetry test:

\[ \Xi_{SU(3)} \equiv \frac{\text{BR}(B^0_s \rightarrow J/\psi \bar{K}^0)}{2\text{BR}(B^0_d \rightarrow J/\psi \pi^0)} \frac{\tau_{B_d}}{\tau_{B_s}} \frac{\Phi^d_{J/\psi \pi^0}}{\Phi^s_{J/\psi K_S}} = 1.01 \pm 0.25 \quad SU(3) \rightarrow 1 \]

\(^2U\) spin is an $SU(2)$ subgroup of strong $SU(3)_F$ relating down and strange quarks to each other.
- **Fresh look:** [with Kristof De Bruyn & Patrick Koppenburg, arXiv:1010.0089 [hep-ph]]

  - First LHCb (toy) feasibility study: $\rightarrow \gamma$ extraction;
  - **Main application:** control of the penguin effects in $\left(\phi_d\right)_{J/\psi K_S}$:

    \begin{align*}
    \Delta\phi_d \text{ [deg]} & \quad 90 \quad 110 \quad 130 \quad 150 \quad 170 \quad 190 \quad 210 \quad 230 \quad 250 \quad 270 \\
    \theta \text{ [deg]} & \quad [6 \text{ fb}^{-1}] \\
    \Delta\phi_d \text{ [deg]} & \quad 90 \quad 110 \quad 130 \quad 150 \quad 170 \quad 190 \quad 210 \quad 230 \quad 250 \quad 270 \\
    \theta \text{ [deg]} & \quad [100 \text{ fb}^{-1}]
    \end{align*}

$\Rightarrow$ interesting study for the LHCb upgrade
The System

\[ B_s \rightarrow K^+K^-, \ B_d \rightarrow \pi^+\pi^- \]
Decay Topologies & Amplitudes

- $B_{s}^{0} \rightarrow K^{+}K^{-}$:

  \[ A(B_{s}^{0} \rightarrow K^{+}K^{-}) \propto C' \left[ e^{i\gamma} + \left( \frac{1-\lambda^2}{\lambda^2} \right) d' e^{i\theta'} \right] \]

- $B_{d}^{0} \rightarrow \pi^{+}\pi^{-}$:

  \[ A(B_{d}^{0} \rightarrow \pi^{+}\pi^{-}) \propto C \left[ e^{i\gamma} - d e^{i\theta} \right] \]

\[ \Rightarrow \quad s \leftrightarrow d \]
The decays \( B_d \rightarrow \pi^+\pi^- \) and \( B_s \rightarrow K^+K^- \) are related to each other through the interchange of all down and strange quarks:

\[
U\text{-spin symmetry} \quad \Rightarrow \quad d' = d, \quad \theta' = \theta
\]

- Determination of \( \gamma \) and hadronic parameters \( d(= d') \), \( \theta \) and \( \theta' \).
- Internal consistency check of the \( U\)-spin symmetry: \( \theta \overset{?}{=} \theta' \).


Detailed studies show that this strategy is very promising for LHCb:

\[
A_{\text{dir}} \cos(\& m t) + A_{\text{mix}} \sin(\& m t)
\]

\( A_{\text{dir}} \) and \( A_{\text{mix}} \) depend on weak phases \( !d \) (or \( !s \)), and on ratio of penguin to tree amplitudes \( d_e \).

- Under \( U\)-spin symmetry [Fleischer] \( d $$ = d_\text{KK} $$ and \( $$ = $$ K\text{K} $$ can solve for !d from \( \text{B} \) $$ h^+h^- $$.
- Time-dependent \( CP \) asymmetries for \( \text{B}_0 \rightarrow \pi^+\pi^- \) and \( \text{B}_s \rightarrow K^+K^- \).

\[ [ \text{LHCb Collaboration (B. Adeva \textit{et al.})} \text{, LHCb-PUB-2009-029, arXiv:0912.4179v2} ] \]
Let’s have a fresh look:

→ get ready for LHCb data...

- Use $B$-factory data as input, as well as ...

- BR($B_s \to K^+K^-$) measurements by CDF and Belle @ $\Upsilon(5S)$,

- updated information of $U$-spin-breaking form-factor ratios.

Current Picture for $\gamma$

- **Input data:**
  - Information on $K \propto \text{BR}(B_s \to K^+K^-)/\text{BR}(B_d \to \pi^+\pi^-)$;
  - CP violation in $B_d^0 \to \pi^+\pi^-$ and $B_d^0 \to \pi^\mp K^\pm$;
  - $U$-spin-breaking corrections: $\xi \equiv d'/d = 1\pm0.15$, $\Delta \theta \equiv \theta' - \theta = \pm20^\circ$:

\[
\Rightarrow \quad \gamma = (68.3^{+4.9}_{-5.7}|_{\text{input}}^{+5.0}_{-3.7}|\xi^{+0.1}_{-0.2}|_{\Delta \theta})^\circ
\]

(2-fold ambiguity can be resolved [R.F. ('07)])

- **Fits of the UT:** $\gamma = (67.2^{+3.9}_{-3.9})^\circ$ (CKMfitter), $(69.6 \pm 3.1)^\circ$ (UTfit).
The Effective $B_s^0 \rightarrow K^+ K^-$ Lifetime

- Particularly nice and simple observable: $\langle \Gamma(B_s(t) \rightarrow f) \rangle \rightarrow “untagged”$ rate

$$\tau_{K^+ K^-} = \frac{\int_0^\infty t \langle \Gamma(B_s(t) \rightarrow K^+ K^-) \rangle \, dt}{\int_0^\infty \langle \Gamma(B_s(t) \rightarrow K^+ K^-) \rangle \, dt}$$

- Using $K$, $A_{CP}^{\text{dir}}(B_d \rightarrow \pi^\mp K^\pm)$ and $\gamma = (68 \pm 7)^\circ$ $\lhd U$-spin-breaking]: $\Rightarrow$

\[
\begin{align*}
\Delta \Gamma_{\text{SM}}^{\text{SM}} &= 0.140 \pm 0.020 \\
\tau_{K^+ K^-}/\tau_{B_s} &= 1.04 \pm 0.12
\end{align*}
\]

$\Rightarrow$ probe for NP in $B_s^0 - \bar{B}_s^0$ mixing $\Rightarrow$ CDF & LHCb (?)

[CDF (2006): $\tau_{K^+ K^-} = (1.53 \pm 0.18 \pm 0.02)\text{ps}^{-1} \Rightarrow \tau_{K^+ K^-}/\tau_{B_s} = 1.04 \pm 0.12$]
Mixing-Induced $B^0_s \to K^+ K^-$ CP Asymmetry

- The next observable to enter the stage: $A_{\text{CP}}^{\text{mix}}(B_s \to K^+ K^-)$

$$a_{\text{CP}}(t) = \frac{A_{\text{CP}}^{\text{dir}} \cos(\Delta M_s t) + A_{\text{CP}}^{\text{mix}} \sin(\Delta M_s t)}{\cosh(\Delta \Gamma_s t/2) + A_{\Delta \Gamma} \sinh(\Delta \Gamma_s t/2)}$$

- Using $K$, $A_{\text{CP}}^{\text{dir}}(B_d \to \pi^\mp K^\pm)$, $\gamma \oplus U$-spin-breaking effects: $\Rightarrow$

- Correlation is very robust with respect to uncertainties.
- Allows also an unambiguous determination of $\phi_s$ with $\sin \phi_s$.

$\Rightarrow$ Another interesting probe for NP in $B^0_s - \bar{B}^0_s$ mixing
Optimal Determination of $\gamma$

- Measurement of the CP asymmetries of $B_s^0 \rightarrow K^+ K^-$:

  $\Rightarrow$ theoretically clean contour in the $\gamma - d'$ plane:

![Diagram showing the theoretical clean contour in the $\gamma - d'$ plane.]

  [Green band represents the $1\sigma$ errors of the current SM projection.]

- Intersection with the $\gamma - d$ contour fixed through the CP asymmetries of $B_s^0 \rightarrow \pi^+ \pi^-$ allows us to determine $\gamma$, $d = d'$ and $\theta$, $\theta'$ [→ $U$-spin test].

- Expect a stable situation with respect to $U$-spin-breaking corrections.
Search for New Physics

in

\[ B_s \rightarrow \mu^+ \mu^- \]

[→ also talks by Marc-Olivier Bettler (LHCb) ⊕ Dmitri Tsybychev (Tevatron)]
Search for New Physics in $B^0_s \to \mu^+\mu^-$

- Only loop contributions in the SM ("penguins’ & “box” diagrams):

$$B^0_s \rightarrow W^+ t Z t \rightarrow B^0_s \rightarrow W^+ t Z t \mu^+ \mu^-$$

$\Rightarrow$ strongly suppressed & sensitive to NP

- **Hadronic sector:** → simple situation (only $B$ decay constant $f_{B_s}$ enters):

$\Rightarrow B^0_s \rightarrow \mu^+ \mu^-$ is one of the cleanest rare $B$ decays

- **SM prediction:** $\text{BR}(B_s \rightarrow \mu^+\mu^-) = (3.6 \pm 0.4) \times 10^{-9}$ [A.J. Buras ('09)]

- Most recent experimental upper bounds (95% C.L.):

$\text{BR}(B_s \rightarrow \mu^+\mu^-) < 4.3 \times 10^{-8}$ (CDF), $5.1 \times 10^{-8}$ (DØ), $5.6 \times 10^{-8}$ (LHCb) [new!]

$\Rightarrow$ still a long way (?)
NP may enhance BRs significantly...

- **Example of a recent analysis:** → *supersymmetric flavour models:*

![Graphs showing BR(B_d → µ⁺µ⁻) vs BR(B_s → µ⁺µ⁻) for RVV2 and δLL models.](image)

(RVV2 model)  
(δLL model)

Prospects for $B_s \rightarrow \mu^+ \mu^- @ LHCb$

- At LHCb, the extraction of $\text{BR}(B_s^0 \rightarrow \mu^+\mu^-)$ will rely on normalization channels ($B_u^+ \rightarrow J/\psi K^+$, $B_d^0 \rightarrow K^+\pi^-$ and/or $B_d^0 \rightarrow J/\psi K^{*0}$):

$$\text{BR}(B_s^0 \rightarrow \mu^+\mu^-) = \text{BR}(B_q \rightarrow X) \frac{\epsilon_X N_{\mu\mu} f_q}{\epsilon_{\mu\mu} N_X f_s}$$

  - $\epsilon$ factors are total detector efficiencies.
  - $N$ factors denote the observed numbers of events.
  - $f_q$ are fragmentation functions, which describe the probability that a $b$ quark will fragment in a $B_q$ meson ($q \in \{u, d, s\}$).

- A closer look shows: $f_q/f_s$ is the major source of uncertainty

  - Limits the ability to detect a $5\sigma$ deviation from the SM at LHCb to $\text{BR}(B_s^0 \rightarrow \mu^+\mu^-) > 11 \times 10^{-9}$ (assuming $\Delta f_d/f_s = 13\%$).
  - How can we meet the high precision at LHCb?

New Strategy: $f_d/f_s \oplus \text{LHCb}$


First LHCb result @ Moriond 2011: → talk by Marc-Olivier Bettler
In a nutshell...

- **Starting point:** \( \frac{N_s}{N_d} = \frac{f_s}{f_d} \times \frac{\epsilon(B_s \to X_1)}{\epsilon(B_d \to X_2)} \times \frac{\text{BR}(B_s \to X_1)}{\text{BR}(B_d \to X_2)} \)

- Knowing the ratio of the branching ratios, we could extract \( f_d/f_s \).

- In order to implement this feature in practice, the \( B_s \to X_1 \) and \( B_d \to X_2 \) decays have to satisfy the following requirements:
  - the ratio of their branching ratios must be “easy” to measure at LHCb;
  - the decays must be robust with respect to the impact of NP;
  - the ratio of their BRs must be theoretically well understood:

\[ \Rightarrow \quad \text{U-spin-related } \bar{B}_s^0 \to D_s^+ \pi^-, \bar{B}_d^0 \to D^+ K^- \text{ system:} \]

* Factorization is expected to work very well in these decays;
* Theoretical precision limited by non-fact., U-spin-breaking effects.
Resulting NP Reach for $B_s \rightarrow \mu^+\mu^-$ at LHCb

- Contours corresponding to the detection of a $5\sigma$ NP signal:

\[ \Rightarrow B_s \rightarrow \mu^+\mu^- \text{ NP reach at LHCb is increased by } \sim 2 \]

- Non-fact. $U$-spin-breaking effects: $\Rightarrow$ few percent uncertainty $[\rightarrow \text{data}]$.

- Factorizable $U$-spin-breaking effects: $\Rightarrow$ $F_0^{(s)}(m^2_\pi)/F_0^{(d)}(m^2_K)$, required with $\sim 20\%$ precision to match LHCb $[\rightarrow \text{lattice QCD: in progress ...}]$.

- Lower bound on $\text{BR}(B_s \rightarrow \mu^+\mu^-)$: independent of the form-factor ratio.
Tests & Variant: $B \to D_s^{(*)} P \ (P \in \{\pi, K\})$

- Tests of factorization and $SU(3)$ relations:
  - Cannot resolve non-factorizable effects within the experimental resolution:
    $\Rightarrow$ as small as 5% (most fortunate cases).
  - No indication for non-factorizable $SU(3)$-breaking corrections, with an experimental resolution as small as $\sim 5\%$, even for decays with large colour-suppressed tree contributions ($\to$ non-factorizable).
  - Moreover: exchange topologies are as small as naively expected $\Rightarrow$

- Replace $\bar{B}_d^0 \to D^+ K^-$ (Cabibbo-suppressed) by the $\bar{B}_d^0 \to D^+ \pi^-$ channel:
  - (2006) CDF data for the $\bar{B}_s^0 \to D_s^+ \pi^-$, $\bar{B}_d^0 \to D^+ \pi^-$ system:\[^3]\n    $\Rightarrow (f_s/f_d)_{\text{NL}} = 0.285 \pm 0.036$ [vs. $(f_s/f_d)_{\text{SL}} = 0.284 \pm 0.038$]
  - Preliminary LHCb analysis of semileptonic decays:
    $f_s/(f_d + f_u) \to f_s/f_d = 0.260 \pm 0.008(\text{stat.}) \pm 0.026(\text{syst.})$

[^3]Assumes that the corresponding $SU(3)$-breaking form-factor ratio equals 1 $\to$ lattice QCD (see above).
Concluding Remarks
Moving towards New Frontiers ... 

- Great news for $B_{(s)}$ physics @ Moriond 2011:
  - Lots of activity at the Tevatron $\oplus$ *first physics results from LHCb.*

- $B$ (flavour) physics takes part in the big adventure of this decade: $\text{LHC}$
  - Specific NP scenarios still leave room for sizeable effects.
  - Promising channels to find *first* NP signals @ LHCb [and the LHC(?)]:
    * $B^0_s \rightarrow J/\psi\phi$, nicely complemented by $B^0_s \rightarrow K^+K^-;$
    * $B^0_s \rightarrow \mu^+\mu^-$ [$\oplus$ $B^0_d \rightarrow K^{*0}\mu^+\mu^-$, $B^0_s \rightarrow \phi\mu^+\mu^-$].

- Theoretical topics: $\leftrightarrow$ strong interaction with the LHCb community]
  - Further critically review SM phenomena, develop strategies to control hadronic uncertainties (preferably through guidance by data).
  - Further progress with lattice QCD/non-pert. methods is very desirable.
  - Explore the patterns in specific NP scenarios:
    $\Rightarrow$ *correlations $\Rightarrow$ what kind of NP?*
  - Exploit/look for synergies with the high-$Q^2$ physics @ ATLAS & CMS.