CP Violation and $B$ Physics at the LHC

Robert Fleischer

*CERN, Department of Physics, Theory Division*

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- Setting the Stage
- A Brief Look at the Current $B$-Factory Data
- Key Targets of the $B$ Physics Programme at the LHC
- Conclusions and Outlook
• **Standard Model (SM):** → Kobayashi–Maskawa mechanism of CP violation:

\[
\begin{align*}
D & \xrightarrow{V_{UD}} W^- \\
\overline{D} & \xrightarrow{\overline{V}_{UD}} W^+
\end{align*}
\]

Why Study Flavour Physics & CP Violation?

• **New Physics (NP):** \(\rightarrow\) typically new patterns in the flavour sector
  
  – SUSY scenarios;
  – left–right-symmetric models;
  – models with extra \(Z'\) bosons;
  – scenarios with extra dimensions;
  – “little Higgs” scenarios ...

• **\(\nu\) masses:** \(\rightarrow\) origin beyond the Standard Model (SM)!
  
  – CP violation in the neutrino sector?
  – Connection with quark-flavour physics?

• **Cosmology:** \(\rightarrow\) baryon asymmetry suggests new CP violation!
  
  – Could be associated with very high energy scales:
    
    * attractive mechanism: “leptogenesis”, involving new CP-violating sources in the decays of heavy Majorana neutrinos.
  
  – But could also be accessible in the laboratory ...
Challenging the Standard Model through Flavour Studies

Before searching for NP, we have to understand the SM picture!

- **Key problem:**
  - \textit{impact of strong interactions} \rightarrow \text{“hadronic” uncertainties}
  - Famous example: \text{Re}(\varepsilon'/\varepsilon)_K\text{, measuring “direct” CPV in }K\text{ decays.}

- **Prospects for the “good old” }K\text{-meson system [CPV in ’64: }\varepsilon_K \sim 10^{-3}]\text{:}
  - Clean tests of the SM are offered by }K^+ \to \pi^+\nu\bar{\nu}\text{ and }K_L \to \pi^0\nu\bar{\nu}\text{, as their hadronic pieces can be fixed through }K \to \pi\ell\nu\text{ decays!}
  - These “rare” decays are \textit{absent} at the tree level of the SM, i.e. originate there exclusively from loops, with BRs= \mathcal{O}(10^{-10}) \rightarrow \text{challenging}\textsuperscript{1}

- **The }B\text{-meson system is a \textit{particularly promising} probe:** \rightarrow \text{our focus}
  - Offers various strategies: simply speaking, there are \textit{many }B\text{ decays!}
  - Search for clean SM relations that could be spoiled by NP ...

\textsuperscript{1}Plans to measure }K^+ \to \pi^+\nu\bar{\nu}\text{ at the SPS (CERN) and }K_L \to \pi^0\nu\bar{\nu}\text{ at E391 (KEK/J-PARC).}
Where to Study $B$-Meson Decays?

- **$B$ factories:**
  
  | asymmetric $e^+e^-$ colliders @ $\Upsilon(4S) \rightarrow B^0_d\bar{B}^0_d, B^+_uB^-_u$ |
  |
  - PEP-II with the *Babar* experiment (SLAC);
  - KEK-B with the *Belle* experiment (KEK):
    
    \[ \rightarrow \left\{ \begin{array}{l}
      \text{could well establish CP violation in the } B \text{ system;} \\
      \text{many interesting results with } \sum \mathcal{O}(10^9) \ B\bar{B} \text{ pairs } \ldots
    \end{array} \right. \]
  - Discussion of a super-$B$ factory, with increase of luminosity by $\mathcal{O}(10^2)$.

- **Hadron colliders:**
  
  \[ \rightarrow \text{produce also } B_s \text{ mesons,}^2 \text{ as well as } B_c, \Lambda_b, \ldots \]
  
  - Tevatron: CDF and D0 have reported first $B_{(s)}$-decay results ...
  - ... to be continued at the LHC $\gtrsim 2007$:

  \[ \text{ATLAS & CMS (can also address some } B \text{ physics)} \]

  $\oplus$ *dedicated $B$-decay experiment: LHCb*

\[^2\text{Recently, data at } \Upsilon(5S) \text{ were taken by Belle, allowing also access to } B_s \text{ decays [hep-ex/0610003].}\]
• A recent picture of the LHCb experiment @ CERN:
Central Target: Unitarity Triangle (UT)

• Application of the Wolfenstein parametrization: \[\text{[Wolfenstein (1984)]}\]

\[
\hat{V}_{\text{CKM}} = \begin{pmatrix}
1 - \frac{1}{2} \lambda^2 & \frac{\lambda}{\lambda^2} & A \lambda^3 (\rho - i \eta) \\
-\lambda & 1 - \frac{1}{2} \lambda^2 & A \lambda^2 \\
A \lambda^3 (1 - \rho - i \eta) & -A \lambda^2 & 1
\end{pmatrix} + \mathcal{O}(\lambda^4)
\]

→ phenomenological expansion in \(\lambda \equiv |V_{us}| = 0.22\) [from \(K \to \pi \ell \bar{\nu}_\ell\)]

• Unitarity of the CKM matrix:

\[
\hat{V}_{\text{CKM}} \cdot \hat{V}_{\text{CKM}} = \hat{1} = \hat{V}_{\text{CKM}} \cdot \hat{V}_{\text{CKM}}
\]

\[
R_b = \left(1 - \frac{\lambda^2}{2}\right) \frac{1}{\lambda} \left|\frac{V_{ub}}{V_{cb}}\right|
\]

\[
R_t = \frac{1}{\lambda} \left|\frac{V_{td}}{V_{cb}}\right|
\]

\[
\bar{\rho} \equiv (1 - \lambda^2/2) \rho, \quad \bar{\eta} \equiv (1 - \lambda^2/2) \eta \quad \rightarrow \quad \text{NLO corrections [Buras et al. (1994)]}
\]
Key Processes for CP Violation: Non-Leptonic $B$ Decays

- **Tree diagrams:**
  
  \[ b \to u, c \quad W \quad \bar{u}, \bar{c} \quad d(\bar{s}) \]

- **Penguin diagrams:**
  
  - **QCD penguins:**
    
    \[ b \to u, c, t \quad W \quad q = u, c, d, s \]

  - **Electroweak (EW) penguins:**
    
    \[ b \to u, c, t \quad W \quad Z, \gamma \quad \bar{q} \]

- The calculation of the decay amplitudes is theoretically very challenging:

  \[
  A(B \to f) \sim \sum_k \frac{C_k(\mu)}{\text{pert. QCD}} \times \frac{f|Q_k(\mu)|B}{\text{“unknown”}}
  \]

  [Details and recent progress → talk by Martin Beneke]
Amplitude relations allow us in fortunate cases to eliminate the hadronic matrix elements (→ typically strategies to determine the UT angle $\gamma$):

- **Exact relations:** class of pure “tree” decays (e.g. $B \to DK$).
- **Approximate relations**, which follow from the flavour symmetries of strong interactions, i.e. $SU(2)$ isospin or $SU(3)_F$:

  \[ B \to \pi\pi, B \to \pi K, B(s) \to KK. \]

Decays of neutral $B_d$ and $B_s$ mesons:

- Interference effects through $B_q^0 - \overline{B_q^0}$ mixing:
- Lead to “mixing-induced” CP violation $\mathcal{A}_{CP}^{mix}$!
- If one CKM amplitude dominates:

  \[ \Rightarrow \text{hadronic matrix elements cancel!} \]

* Example: \[ B^0_d \to J/\psi K_S \Rightarrow \sin 2\beta \] [Bigi, Carter & Sanda (’80–’81)]
A Brief Roadmap of Quark-Flavour Physics

• CP-B studies through various processes and strategies:

\[ B \to \pi\pi \text{ (isospin)}, \ B \to \rho\pi, \ B \to \rho\rho \]

\[
\begin{align*}
R_b (b \to u, c \ell \bar{\nu}_\ell) & \quad R_t (B^0_q - \bar{B}^0_q \text{ mixing}) \\
\{ B_d \to \pi^+\pi^- \} & \quad \{ B_s \to K^+K^- \} \\
\gamma & \quad \beta
\end{align*}
\]

\[ B \to \pi K \text{ (penguins)} \]

\[
\begin{align*}
B_u^\pm & \to K^\pm D \\
B_d & \to K^{*0} D \\
B_c^\pm & \to D_s^\pm D
\end{align*}
\]

\[
B_d \to D^{(*)\pm} \pi^- : \gamma + 2\beta \\
B_s \to D_s^{\pm} K^- : \gamma + \phi_s
\]

• Moreover “rare” decays: \( B \to X_s \gamma, B_{d,s} \to \mu^+\mu^-, K \to \pi\nu\bar{\nu}, \ldots \)
  – Originate from loop processes in the SM. \([\to \text{talk by A. Weiler}]\)
  – Interesting correlations with CP-B studies.

\[
\text{New Physics} \quad \Rightarrow \quad \text{Discrepancies}
\]
Status of the Unitarity Triangle

- **Two competing groups:** → many plots & correlations ...

  - *UTfit* Collaboration [http://www.utfit.org]:

  ⇒ impressive global agreement with KM, but no longer “perfect” ...
A Brief Look at the Current $B$-Factory Data:

Two popular avenues for New Physics to manifest itself ...
1. New Physics @ Amplitude Level:

- Typically *small* effects if SM tree processes play the dominant rôle.

- Potentially *large* effects in the penguin sector through new particles in the loops or new contributions at the tree level: e.g. SUSY, $Z'$ models.

$\rightarrow$ hot topics ...
CP Violation in $b \rightarrow s$ Penguin Modes

- $B_d \rightarrow \phi K_S$ is the key example: amplitude structure of the SM $\Rightarrow$

$$\langle \sin 2\beta \rangle_{\phi K_S} = \langle \sin 2\beta \rangle_{\psi K_S} + \mathcal{O}(\lambda^2), \quad A_{\text{dir}}^{\text{CP}}(B_d \rightarrow \phi K_S) = 0 + \mathcal{O}(\lambda^2)$$

**Preliminary**

$$\sin(2\beta^\text{eff}) = \sin(2\phi_1^\text{eff})$$

**NP could be present, but still cannot be resolved** → stay tuned ...
The $B \to \pi K$ Puzzle

- Observables with a sizeable impact of EW penguins: $q, \phi$

$$R_c \equiv \frac{2}{\text{BR}(B^+ \to \pi^0 K^+) + \text{BR}(B^- \to \pi^0 K^-)}$$

$$R_n \equiv \frac{1}{2} \left[ \frac{\text{BR}(B_d^0 \to \pi^- K^+) + \text{BR}(\bar{B}_d^0 \to \pi^+ K^-)}{\text{BR}(B_d^0 \to \pi^0 K^0) + \text{BR}(\bar{B}_d^0 \to \pi^0 K^-)} \right]$$

→ NP in EWPs!?
• (Preliminary) Status after ICHEP ’06:

- The SM prediction is very stable, with further reduced errors!
- The $B$-factory data have moved quite a bit towards the SM.
- Suggested by constraints from rare $B \to X_s \ell^+\ell^-$ decays ...

- Furthermore puzzling CP asymmetries: $B^0_d \to \pi^0 K_S$, $B^\pm \to \pi^0 K^\pm$.

⊕ correlations with rare $B$ and $K$ decays

NP could be present, but still cannot be resolved → stay tuned ...
2. New Physics in $B^0_q - \bar{B}^0_q$ mixing:

- NP particles in boxes or tree contributions (e.g. SUSY, $Z'$ models):

  $$M^q_{12} = M^{q,\text{SM}}_{12} (1 + \kappa_q e^{i\sigma_q}) \Rightarrow$$

  - Mass difference: $\Delta M_q = \Delta M^{\text{SM}}_q |1 + \kappa_q e^{i\sigma_q}|$
  - Mixing phase: $\phi_q = \phi^{\text{SM}}_q + \phi^{\text{NP}}_q = \phi^{\text{SM}}_q + \text{arg}(1 + \kappa_q e^{i\sigma_q})$

Constraints in the NP Space of $B_q^0 - \bar{B}_q^0$ Mixing

- Contours in the $\sigma_q - \kappa_q$ plane following from $\rho_q \equiv \Delta M_q / \Delta M_q^{SM}$:

$$[0.6 \leq \rho_q \leq 1.4]$$

- Contours in the $\sigma_q - \kappa_q$ plane following from the NP phase $\phi_{q}^{NP}$:

$$[10^\circ \leq |\phi_{q}^{NP}| \leq 170^\circ]$$
Implications of the $B$-Factory Data for the $B_d$ System

- **Determination of $\rho_d = \Delta M_d / \Delta M_d^{SM}$**: \(\Delta M_d^{SM}\) required, involving ...

  - CKM parameter $|V_{td}^*V_{tb}|$: \(\rightarrow\) governed by $\gamma$, if unitarity is used.
  - Hadronic parameter $f_{B_d}^2\hat{B}_{B_d}$: lattice \(\rightarrow\) two benchmark sets:
    * JLQCD results (2 flavours of dynamical light Wilson quarks).
    * $f_{B_d}$ from HPQCD (3 dynamical flavours) with $\hat{B}_{B_d}$ from JLQCD.

- **Determination of the NP phase**: \(\rightarrow\) $\phi_d^{NP} = (2\beta)_{\psi K_S} - (2\beta)_{\text{true}}$

  - $\phi_d^{NP}$ is governed by $R_b \propto |V_{ub}/V_{cb}|$;
  - Unfortunately, discrepancy between $|V_{ub}|_{\text{excl}}$ and $|V_{ub}|_{\text{incl}}$ ...

![Graphs showing $\kappa_d$ vs. $\sigma_d$](image)

JLQCD and $\phi_d^{NP}|_{\text{excl}} = -(2.5 \pm 8.0)^\circ$

(HP+JL)QCD and $\phi_d^{NP}|_{\text{incl}} = -(10.1 \pm 4.6)^\circ$
Key Targets of the $B$ Physics Programme at the LHC

→ high statistics and *complementarity* to $B$ factories:

*fully exploit the $B_s$-meson system!*
General Features of the $B_s$ System

- **Rapid $B^0_s - \bar{B}^0_s$ oscillations**: $\Delta M_s \equiv \mathcal{O}(20 \text{ ps}^{-1}) \gg \Delta M_d \equiv 0.5 \text{ ps}^{-1}$
  
  $\Rightarrow$ challenging to resolve them experimentally!

- **The width difference $\Delta \Gamma_s$ is expected to be of $\mathcal{O}(10\%)$**: [→ talk by A. Lenz]
  
  - Experimental status: $B_s \to J/\psi \phi \oplus$ Tevatron $\Rightarrow$
    
    \[
    \frac{\Delta \Gamma_s}{\Gamma_s} = \begin{cases} 
    0.24^{+0.28+0.03}_{-0.38-0.04} & \text{[D0 ('05)]} \\
    0.65^{+0.25}_{-0.33} \pm 0.01 & \text{[CDF ('05)]} \\
    \end{cases} \quad \text{LHCb} \quad \text{[precision } \sim 0.01\text{]}
    \]

  - May provide interesting CPV studies through “untagged” rates:
    
    \[
    \langle \Gamma(B_s(t) \to f) \rangle \equiv \Gamma(B^0_s(t) \to f) + \Gamma(\bar{B}^0_s(t) \to f)
    \]

    * The rapidly oscillating $\Delta M_st$ terms cancel!
    * Various “untagged” strategies were proposed.
      
      [Dunietz ('95); R.F. & Dunietz ('96); Dunietz, Dighe & R.F. ('99); ...]

- **The CP-violating phase of $B^0_s - \bar{B}^0_s$ mixing is tiny in the SM:**
  
  \[
  \phi_s \equiv -2\lambda^2 \eta \approx -2^\circ \Rightarrow \text{interesting for NP searches (see below)!}
  \]
Hot News of this Spring:

- **Signals for $B_s^0 - \bar{B}_s^0$ mixing at the Tevatron:**
  - For many years, only lower bounds on $\Delta M_s$ were available from the LEP (CERN) experiments and SLD (SLAC)!
  - Finally, the value of $\Delta M_s$ could be pinned down: [→ talk by S. Menzemer]
    * D0: $\Rightarrow$ two-sided bound $17 \text{ ps}^{-1} < \Delta M_s < 21 \text{ ps}^{-1}$ (90% C.L.)
      $\Rightarrow 2.5 \sigma$ signal at $\Delta M_s = 19 \text{ ps}^{-1}$
    * CDF: $\Delta M_s = [17.77 \pm 0.10\text{(stat)} \pm 0.07\text{(syst)}] \text{ ps}^{-1} \gtrsim 5\sigma$

- **These new results have already triggered considerable theoretical activity:**

Space for NP

in the

$B_s$-Meson System:

$$M_{12}^s = M_{12}^{s,SM} \left(1 + \kappa_s e^{i\sigma_s}\right)$$

→ in analogy to the $B_d$ system ...

**Constraints on NP through \( \Delta M_s \)**

- **CKM unitarity and Wolfenstein expansion:** \[ |V_{ts}^* V_{tb}| = |V_{cb}| \left[ 1 + \mathcal{O}(\lambda^2) \right] \]

  \[ \Rightarrow \text{no information on } \gamma \text{ and } R_b \text{ needed (in contrast to } \Delta M_d)! \]

- **Numerical results:**
  \[
  \Delta M_s^{\text{SM}} \bigg|_{\text{JLQCD}} = (16.1 \pm 2.8) \text{ ps}^{-1}
  \]
  \[
  \rho_s \equiv \frac{\Delta M_s / \Delta M_s^{\text{SM}}}{\text{JLQCD}} = 1.08^{+0.03}_{-0.01}(\text{exp}) \pm 0.19(\text{th})
  \]
  \[
  \Delta M_s^{\text{SM}} \bigg|_{(\text{HP+JL})\text{QCD}} = (23.4 \pm 3.8) \text{ ps}^{-1}
  \]
  \[
  \rho_s \bigg|_{(\text{HP+JL})\text{QCD}} = 0.74^{+0.02}_{-0.01}(\text{exp}) \pm 0.18(\text{th})
  \]

- **Allowed regions in the } \sigma_s-\kappa_s \text{ plane:**

---

**Figure 8:** The allowed regions in the } \sigma_s-\kappa_s \text{ plane for different QCD calculations. The left panel shows the allowed regions for JLQCD, while the right panel shows the regions for (HP+JL)QCD.
Constraints on NP through $\Delta M_s$ and $\Delta M_d$

• The ratio $\Delta M_s/\Delta M_d$ involves just an $SU(3)$-breaking parameter:

$$\xi \equiv \frac{f_{B_s} \hat{B}_{B_s}^{1/2}}{f_{B_d} \hat{B}_{B_d}^{1/2}} \rightarrow \text{reduced th. uncertainty as compared to } f_{B_q} \hat{B}_{B_q}^{1/2}.$$

• Usually determination of UT side $R_t$. Different avenue (CKM unitarity):\(^3\)

$$\frac{\rho_s}{\rho_d} = \lambda^2 \left[ 1 - 2 R_b \cos \gamma + R_b^2 \right] \left[ 1 + \mathcal{O}(\lambda^2) \right] \frac{1}{\xi^2} \frac{M_{B_d} \Delta M_s}{M_{B_s} \Delta M_d}$$

\[^3\text{Scenario for 2010: } \gamma = (65 \pm 20)^\circ \overset{\text{LHCb}}{\longrightarrow} (70 \pm 5)^\circ \text{ with (HP+JL)QCD lattice values.}\]
Golden Process to Search for NP in $B_s^0 - \bar{B}_s^0$ Mixing:

$B_s^0 \rightarrow J/\psi \phi$

$\rightarrow B_s^0$ counterpart of $B_d^0 \rightarrow J/\psi K_S$ ...

Let’s have a closer look ...

- There is an important difference with respect to $B_d^0 \rightarrow J/\psi K_S$:
  
  **final state is an admixture of different CP eigenstates!**

- **Angular distribution** of the $J/\psi [\rightarrow \ell^+\ell^-] \phi [\rightarrow K^+K^-]$ decay products:
  
  $\Rightarrow$ the different CP eigenstates can be disentangled!

- **Linear polarization amplitudes**: $A_0(t), A_\parallel(t), A_\perp(t)$
  
  - $A_0(t)$ and $A_\parallel(t)$ correspond to CP-even final-state configurations;
  - $A_\perp(t)$ describes a CP-odd final-state configuration.
Simple: Time-Dependent One-Angle Distribution

\[
\frac{d\Gamma(t)}{d\cos \Theta} \propto \left( |A_0(t)|^2 + |A_\parallel(t)|^2 \right) \frac{3}{8} (1 + \cos^2 \Theta) + \left| A_\perp(t) \right|^2 \frac{3}{4} \sin^2 \Theta
\]

- The angular dependence allows us to extract the following observables:

\[
P_+(t) \equiv |A_0(t)|^2 + |A_\parallel(t)|^2, \quad P_-(t) \equiv |A_\perp(t)|^2
\]

- **Untagged data samples:** → untagged rates ...

\[
P_\pm(t) + \overline{P}_\pm(t) \propto [(1 \pm \cos \phi_s)e^{-\Gamma_Lt} + (1 \mp \cos \phi_s)e^{-\Gamma_Ht}]
\]

- **Tagged data samples:** → CP asymmetries ...

\[
\frac{P_\pm(t) - \overline{P}_\pm(t)}{P_\pm(t) + \overline{P}_\pm(t)} = \pm \frac{2 \sin(\Delta M_s t) \sin \phi_s}{(1 \pm \cos \phi_s)e^{+\Delta \Gamma_{st}/2} + (1 \mp \cos \phi_s)e^{-\Delta \Gamma_{st}/2}}
\]
Comments

\[ \phi_s = -2\lambda^2 R_b \sin \gamma + \phi_s^{\text{NP}} \approx \phi_s^{\text{NP}} \] ⇒

- CP-violating NP effects would be indicated by the following features:
  - The *untagged* observables depend on *two* exponentials;
  - *Sizeable* values of the CP-violating asymmetries.

- These general features hold also for the full *three-angle* distribution:
  - Much more involved than one-angle case [Dighe, Dunietz & R.F. (1999)].
  - But provides additional information through the following terms:
    \[ \text{Re}\{A_0^*(t)A_\parallel(t)\}, \quad \text{Im}\{A_f^*(t)A_\perp(t)\} \quad (f \in \{0, \parallel\}). \]
  - No experimental draw-back with respect to the one-angle case!

- Following these lines, \( \Delta \Gamma_s \) (see above) and \( \phi_s \) can be extracted:
  - Note: \( \Delta \Gamma_s = \Delta \Gamma_s^{\text{SM}} \cos \phi_s \) [Grossman (1996)] ⇒ *reduction* of \( \Delta \Gamma_s \).
News from the Tevatron & Reach at the LHC

• **Very recent (preliminary) analysis by D0:** [D0Conference note 5144 ('06)]
  
  – Untagged, time-dependent three-angle $B_s \to J/\psi \phi$ distribution:

  \[
  \Rightarrow \phi_s = -0.79 \pm 0.56 \text{ (stat.)} \pm 0.01 \text{ (syst.)} = -(45 \pm 32 \pm 0.6)°
  \]
  
  – Imposing also constraints form semilept. $B$ decays: [D0note 5144-Conf ('06)]

  \[
  \Rightarrow \phi_s = -0.56^{+0.44}_{-0.41} = -(32^{+25}_{-23})°
  \]

  \Rightarrow still not stringently constrained, but very accessible @ LHC ...

• **Experimental reach at the LHC:** [O. Schneider, M. Smizanska, T. Speer]

  – LHCb: $\sigma_{\text{stat}}(\sin \phi_s) \approx 0.031$ (1 year, i.e. $2 \text{ fb}^{-1}$) [0.013 (5 years)];
  
  – ATLAS & CMS: expect uncertainties of $\mathcal{O}(0.1)$ (1 year, i.e. $10 \text{ fb}^{-1}$).
Impact of CP Violation Measurements on $\sigma_s$, $\kappa_s$

- **Illustration through two scenarios ($\sim 2010$):**

  (i) $(\sin \phi_s)_{\text{exp}} = -0.04 \pm 0.02$: corresponds to the SM;

  (ii) $(\sin \phi_s)_{\text{exp}} = -0.20 \pm 0.02$: $\rightarrow$ NP @ $10\,\sigma$ [corresponds to the “tension” in the UT fits for $\kappa_s = \kappa_d$, $\sigma_s = \sigma_d$ $\rightarrow$ “magnification” in the $B_s$ system]

- **Remarks:**

  - It is very challenging to establish NP without new CP-violating effects.
  - But the data still leave a lot of space for such effects in specific NP scenarios (SUSY, $Z'$, ...), which could be detected at the LHC!

  [Details: P. Ball & R.F., hep-ph/0604249 $\oplus$ references therein]
Further Benchmark Decays

for the

LHCb Experiment

→ very rich physics programme ...
Two Major Lines of Research

1. **Precision measurements of $\gamma$:**
   - **Tree strategies**, with expected sensitivities after 1 year of taking data:
     - $B^0_s \to D^\mp K^\pm$: $\sigma_\gamma \sim 14^\circ$
     - $B^0_d \to D^0 K^*$: $\sigma_\gamma \sim 8^\circ$ ... to be compared with the
     - current $B$-factory data: $\gamma|_{D^(*)K^(*)} = \begin{cases} (62^{+35}_{-25})^\circ & \text{(CKMfitter)} \\ (65 \pm 20)^\circ & \text{(UTfit)} \end{cases}$
   - **Decays with penguin contributions:**
     - $B^0_s \to K^+ K^-$ and $B^0_d \to \pi^+ \pi^-$: $\sigma_\gamma \sim 5^\circ$
     - $B^0_s \to D^+_s D^-_s$ and $B^0_d \to D^+_d D^-_d$

2. **Analyses of rare decays which are absent at the SM tree level:**
   - $B^0_s \to \mu^+ \mu^-$, $B^0_d \to \mu^+ \mu^-$
   - $B^0_d \to K^{*0} \mu^+ \mu^-$, $B^0_s \to \phi \mu^+ \mu^-$; ...

→ let’s have a closer look at some decays ...

[For a recent experimental overview, see A. Schopper, hep-ex/0605113]
**CP Violation in** $B_s \rightarrow D_s^\pm K^\mp$ **and** $B_d \rightarrow D^\pm \pi^\mp$

- **General case:**

  $$B_q^0 \qquad \bar{B}_q^0$$

  $B_q^0$ appears in $D_q$ and $\bar{u}_q$.

  $$B_q^0 \qquad \bar{B}_q^0$$

  $\bar{B}_q^0$ appears in $D_q$ and $u_q$.

  $e^{-i\phi_q}$ is associated with $B_q^0$.

  $e^{i\gamma}$ is associated with $\bar{B}_q^0$.

  $\phi_q + \gamma$

  - **$q = s$:** $D_s \in \{ D_s^+, D_{s*}^+, \ldots \}$, $u_s \in \{ K^+, K_{*+}, \ldots \}$:

    \[ \rightarrow \text{hadronic parameter } X_s e^{i\delta_s} \propto R_b \Rightarrow \text{large interference effects!} \]

  - **$q = d$:** $D_d \in \{ D^+, D_{*+}, \ldots \}$, $u_d \in \{ \pi^+, \rho^+, \ldots \}$:

    \[ \rightarrow \text{hadronic parameter } X_d e^{i\delta_d} \propto -\lambda^2 R_b \Rightarrow \text{tiny interference effects!} \]
• \( \cos(\Delta M_q t) \) and \( \sin(\Delta M_q t) \) terms of the time-dependent decay rates:

\[
\Rightarrow \text{theoretically clean determination of } \phi_q + \gamma \quad \phi_q \text{ known} \quad [\gamma]
\]

[Dunietz & Sachs (1988); Aleksan, Dunietz & Kayser (1992); Dunietz (1998); ...]

• **However, there are also problems:**

  – We encounter an *eightfold* discrete ambiguity for \( \phi_q + \gamma \)!
  
  – In the \( q = d \) case, an additional input is required to extract \( X_d \) since \( \mathcal{O}(X_d^2) \) interference effects would have to be resolved \( \rightarrow \text{impossible} \) ...

• **Combined analysis of** \( B_s^0 \to D_s^{(*)+}K^- \) and \( B_d^0 \to D_s^{(*)+}\pi^- \): [R.F. (2003)]

\[
s \leftrightarrow d \quad \Rightarrow \quad U\text{-spin symmetry provides an interesting playground}^{4}
\]

  – An *unambiguous* value of \( \gamma \) can be extracted from the observables!
  
  – To this end, \( X_d \) has *not* to be fixed, and \( X_s \) may *only* enter through a \( 1 + X_s^2 \) correction, which is determined through *untagged* \( B_s \) rates!
  
  – Promising first studies by LHCb:  

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\(^4\)The \( U\)-spin is an \( SU(2) \) subgroup of the \( SU(3)_F \) flavour-symmetry group, connecting \( d \) and \( s \) quarks in analogy to the conventional isospin symmetry, which relates \( d \) and \( u \) quarks to each other.
Both expressions now giving very interesting precision on $\gamma$. Right hand plot has precision of 5 degrees, and small systematic. Ambiguous solutions now excluded.

[G. Wilkinson @ CKM 2005]
The $B_s \to K^+K^-$, $B_d \to \pi^+\pi^-$ System

- $B^0_s \to K^+K^-$:

- $B^0_d \to \pi^+\pi^-$:

\[ \Rightarrow \quad s \leftrightarrow d \]
• Structure of the decay amplitudes in the Standard Model:

\[ A(B_d^0 \to \pi^+ \pi^-) \propto \begin{pmatrix} e^{i\gamma} - de^{i\theta} \end{pmatrix} \]

\[ A(B_s^0 \to K^+ K^-) \propto \begin{pmatrix} e^{i\gamma} + \left( \frac{1 - \lambda^2}{\lambda^2} \right) d'e^{i\theta'} \end{pmatrix} \]

\[ d e^{i\theta} = \frac{\text{"penguin"}}{\text{"tree"}} \bigg|_{B_d \to \pi^+ \pi^-}, \quad d' e^{i\theta'} = \frac{\text{"penguin"}}{\text{"tree"}} \bigg|_{B_s \to K^+ K^-} \]

[d, d': real hadronic parameters; \( \theta, \theta' \): strong phases]

• General form of the CP asymmetries (time-dependent rate asymmetries):

\[ A_{\text{CP}}^{\text{dir}}(B_d \to \pi^+ \pi^-) = G_1(d, \theta, \gamma), \quad A_{\text{CP}}^{\text{mix}}(B_d \to \pi^+ \pi^-) = G_2(d, \theta, \gamma, \phi_d) \]

\[ A_{\text{CP}}^{\text{dir}}(B_s \to K^+ K^-) = G'_1(d', \theta', \gamma), \quad A_{\text{CP}}^{\text{mix}}(B_s \to K^+ K^-) = G'_2(d', \theta', \gamma, \phi_s) \]

• \( \phi_d = 2\beta \) (from \( B_d \to J/\psi K_S \)) and \( \phi_s \approx 0 \) are known parameters:

\[ - A_{\text{CP}}^{\text{dir}}(B_d \to \pi^+ \pi^-) \quad \& \quad A_{\text{CP}}^{\text{mix}}(B_d \to \pi^+ \pi^-): \Rightarrow \boxed{d = d(\gamma)} \quad \text{(clean!)} \]

\[ - A_{\text{CP}}^{\text{dir}}(B_s \to K^+ K^-) \quad \& \quad A_{\text{CP}}^{\text{mix}}(B_s \to K^+ K^-): \Rightarrow \boxed{d' = d'(\gamma)} \quad \text{(clean!)} \]
Example:

- Input parameter:
  - \( \phi_d = 43.4^\circ, \phi_s = -2^\circ, \gamma = 74^\circ, d = d' = 0.52, \theta = \theta' = 146^\circ \)

- CP asymmetries:
  - \( B_d \rightarrow \pi^+\pi^- \): \( A_{\text{dir}}^{\text{CP}} = -0.37, A_{\text{mix}}^{\text{CP}} = +0.50 \)
  - \( B_s \rightarrow K^+K^- \): \( A_{\text{dir}}^{\text{CP}} = +0.12, A_{\text{mix}}^{\text{CP}} = -0.19 \)
• The decays $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$ are related to each other through the interchange of all down and strange quarks:

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

- $d = d'$: ⇒ determination of $\gamma$, $d$, $\theta$, $\theta'$

- $\theta = \theta'$: ⇒ test of the $U$-spin symmetry!

• Detailed experimental feasibility studies show that the $B_s \to K^+K^-$, $B_d \to \pi^+\pi^-$ strategy is very promising for LHCb:

\[ \text{CERN-LHCb/2003-123 & 124; talk by A. Sarti at Flavour LHC Workshop, October '06, CERN} \]
• **Recent news from the Tevatron:** [CDF Collaboration, hep-ex/0607021]

  Observation of $B_s \to K^+K^-$ @ CDF

  – 236 ± 32 events were seen, which correspond to the branching ratio

  $$\text{BR}(B_s \to K^+K^-) = (33 \pm 5.7 \pm 6.7) \times 10^{-6};$$

  update @ BEAUTY ’06: $\to (24.4 \pm 1.4 \pm 4.6) \times 10^{-6}$.  

• **Theoretical prediction:** [Buras, R.F. Schwab & Recksiegel (’04)]

  – Requires the knowledge of an $SU(3)$-breaking form-factor ratio (which cancels in $de^{i\theta} = d'e^{i\theta'}$) [QCD sum rules: Khodjamirian et al. (’03)].

  – Dynamical assumptions (small annihilation) and $B_d \to \pi^\mp K^\pm$ data:

    $$\Rightarrow \text{BR}(B_s \to K^+K^-) = (35 \pm 7) \times 10^{-6}$$

    $\Rightarrow$ good agreement!
The Rare Decays $B_q \rightarrow \mu^+\mu^- \ (q \in \{d, s\})$

- Originate from $Z$ penguins and box diagrams in the Standard Model:


\[
\mathcal{H}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} \left[ \frac{\alpha}{2\pi \sin^2 \Theta_W} \right] V_{tb}^* V_{tq} \eta_Y Y_0(x_t) (\bar{b}q)_{V-A} (\bar{\mu}\mu)_{V-A}
\]

- $\alpha$: QED coupling; $\Theta_W$: Weinberg angle.
- $\eta_Y$: short-distance QCD corrections (calculated ...)
- $Y_0(x_t \equiv m_t^2/M_W^2)$: Inami–Lim function, with top-quark dependence.

- Hadronic matrix element: $\rightarrow$ very simple situation:

- Only the matrix element $\langle 0 | (\bar{b}q)_{V-A} | B_q^0 \rangle$ is required: $f_{B_q}$

$\Rightarrow$ belong to the cleanest rare $B$ decays!
Most recent SM predictions: [Blanke, Buras, Guadagnoli, Tarantino ('06)]

\[ \text{use the data for the } \Delta M_q \text{ to reduce the hadronic uncertainties:} \]

\[
\begin{align*}
\text{BR}(B_s \rightarrow \mu^+ \mu^-) &= (3.35 \pm 0.32) \times 10^{-9} \\
\text{BR}(B_d \rightarrow \mu^+ \mu^-) &= (1.03 \pm 0.09) \times 10^{-10}
\end{align*}
\]

Most recent experimental upper bounds from the Tevatron:

- CDF collaboration @ 95% C.L.: [CDF Public Note 8176 (2006)]
  \[ \text{BR}(B_s \rightarrow \mu^+ \mu^-) < 1.0 \times 10^{-7}, \quad \text{BR}(B_d \rightarrow \mu^+ \mu^-) < 3.0 \times 10^{-8} \]

- D0 collaboration @ 90% C.L. (95% C.L.): [D0note 5009-CONF (2006)]
  \[ \text{BR}(B_s \rightarrow \mu^+ \mu^-) < 1.9 (2.3) \times 10^{-7} \]

\[ \Rightarrow \text{still a long way to go (?) } \rightarrow \text{LHC} \quad \text{(background under study)} \]

However, NP may significantly enhance \( \text{BR}(B_s \rightarrow \mu^+ \mu^-) \):

- In SUSY scenarios: \( \text{BR} \sim (\tan \beta)^6 \rightarrow \text{dramatic enhancement (!!)}; \)
  [see, e.g., Foster et al. and Isidori & Paride ('06) for recent analyses]

- NP with modified EW penguin sector: sizeable enhancement.
The Rare Decay $B^0_d \rightarrow K^{*0} \mu^+ \mu^-$

- **Key observable for NP searches:** Forward–Backward Asymmetry

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

- $\theta$ is the angle between the $B^0_d$ momentum and that of the $\mu^+$ in the dilepton centre-of-mass system,
- and $\hat{s} = s/M_B^2$, with $s = (p_{\mu^+} + p_{\mu^-})^2$.

- **Particularly interesting:**

$$A_{FB}(\hat{s}_0)_{SM} = 0$$  
[Burdman ('98); Ali *et al.* ('00); ...]

- The value of $\hat{s}_0$ is very robust with respect to hadronic uncertainties!
- SUSY extensions of the SM:
  → may yield $A_{FB}(\hat{s})$ of opposite sign or without a zero point →
- **Sensitivity at the LHC:**
  - LHCb: $\sim 4400$ decays/year, yielding $\Delta \hat{s}_0 = 0.06$ after one year.
  - ATLAS will collect about $1000$ $B^0 \rightarrow K^{*0} \mu^+\mu^-$ decays per year.
- **Other $b \rightarrow s\mu^+\mu^-$ decays under study:** $\Lambda_b \rightarrow \Lambda\mu^+\mu^-$, $B_s^0 \rightarrow \phi\mu^+\mu^-$ ...
- **Current $B$-factory data:** inclusive $b \rightarrow s\ell^+\ell^-$ BRs and the integrated asymmetries $\int A_{FB}$ in accordance with SM, but still large uncertainties.

Conclusions and Outlook (I)

- Tremendous progress in $B$ physics during the recent years:
  
  Fruitful interplay between theory and experiment

  - $e^+e^- B$ factories: have already produced $\sum \mathcal{O}(10^9) B\bar{B}$ pairs;
  - Tevatron: has recently succeeded in observing $B^0_s-\bar{B}^0_s$ mixing.

- Status in October 2006:
  
  - The data agree globally with the Kobayashi–Maskawa picture!
  - But we have also hints for discrepancies: $\rightarrow$ first signals of NP??

- New perspectives for $B$-decay studies @ LHC $\gg$ autumn 2007:
  
  - Large statistics and full exploitation of the $B_s$ physics potential, thereby complementing the physics programme of the $e^+e^- B$ factories.
  - Precision determinations of $\gamma$: $\rightarrow$ key ingredients for NP searches!
  - Powerful studies of rare decays: $B_{s,d} \rightarrow \mu^+\mu^-$, ...

  $\rightarrow$ much more stringent CKM consistency tests!
Conclusions and Outlook (II)

*Flavour physics & CP violation in direct context with LHC*

- **Main goals of the ATLAS and CMS experiments:**
  - Exploration of the mechanism of EW symmetry breaking: Higgs!?
  - Production and observation of *new* particles ...
  - Then back to questions of dark matter, baryon asymmetry ...
  - ⊕ complementary and further studies at ILC/CLIC

- **Synergy with the flavour sector:**

  $B \oplus K, D$, top physics & lepton/neutrino sector

  - If discovery of new particles, which kind of new physics?
  - Insights into the corresponding new flavour structures and possible new sources of CP violation through studies of flavour processes.
  - Sensitivity on very high energy scales of new physics through precision measurements, also if NP particles cannot be produced at the LHC ...

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