Flavour Physics and CP Violation

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Important Results from Lecture II

\[
\frac{\Gamma(B_q^0(t \to f)) - \Gamma(B_q^0(t \to \bar{f}))}{\Gamma(B_q^0(t \to f)) + \Gamma(B_q^0(t \to \bar{f}))} = \frac{A_{\text{CP}}^\text{dir} \cos(\Delta M_q t) + A_{\text{CP}}^\text{mix} \sin(\Delta M_q t)}{\cosh(\Delta \Gamma_q t/2) - A_{\Delta \Gamma} \sinh(\Delta \Gamma_q t/2)}
\]

- **Amplitude relations** allow us in several cases to eliminate the hadronic matrix elements (\(\rightarrow \text{CKM amplitude dominates}\) (e.g. \(B_d \to \psi \, \text{KS}\)):
  - hadronic matrix elements cancel \(\Rightarrow\)
- Otherwise amplitude relations ...  

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\[
\begin{align*}
\mathcal{A}_{\text{CP}}^\text{dir} &= \frac{1 - |\xi_f^{(q)}|^2}{1 + |\xi_f^{(q)}|^2} = \frac{|A(B_q^0 \to f)|^2 - |A(B_q^0 \to \bar{f})|^2}{|A(B_q^0 \to f)|^2 + |A(B_q^0 \to \bar{f})|^2} & \text{"direct" CP violation} \\
\mathcal{A}_{\text{CP}}^\text{mix} &= \frac{2 \, \text{Im} \, \xi_f^{(q)}}{1 + |\xi_f^{(q)}|^2} & \Rightarrow \text{"mixing-induced" CP violation} \\
A_{\Delta \Gamma} &= \frac{2 \, \text{Re} \, \xi_f^{(q)}}{1 + |\xi_f^{(q)}|^2} & \Rightarrow \text{not independent from } \mathcal{A}_{\text{CP}}^\text{dir} \text{ and } \mathcal{A}_{\text{CP}}^\text{mix}
\end{align*}
\]

\[
\xi_f^{(q)} \sim e^{-i\phi_q} \left[ \frac{A(B_q^0 \to f)}{A(B_q^0 \to f)} \right]
\]

\[
\phi_q^{\text{SM}} = 2 \arg(V_{tq}^* V_{tb}) = \begin{cases} +2\beta & (q = d) \\ -2\delta\gamma & (q = s) \end{cases}
\]
Lecture III: Moving Towards the LHC

• How Could New Physics (NP) Enter the B-Physics Landscape?
  - General features and 2 popular avenues:
    1. NP at the decay amplitude level
    2. NP in $B_q^0 - B_q^0$ mixing
  - Implications of the $B$-factory data.

• Key Targets of the B-Physics Programme at the LHC:
  - Implications of the measurement of $\Delta M_s$ at the Tevatron.
  - $B_s \rightarrow J/\psi \phi$: “golden” channel to search for NP in $B_s^0 - B_s^0$ mixing.
  - $B_s \rightarrow D_s^\pm K^\mp$, $B_s \rightarrow K^+ K^-$: determinations of $\gamma$.
  - $B_{s,d} \rightarrow \mu^+ \mu^-$, $B_d \rightarrow K^{*0} \mu^+ \mu^-$: rare decay NP probes.
How Could New Physics Enter the $B$-Physics Landscape?
Twofold Impact of NP: Effective Hamiltonians ...

• **Possibility I:** Modification of the “Strength” of the SM Operators

  – New short-distance functions, which depend on the NP parameters, such as masses of charginos, squarks, $\tan \beta \equiv v_2/v_1$ in the MSSM.
  – The NP particles enter in new box and penguin diagrams, and are “integrated out”, as the $W$ boson and the top quark:

    $$C_k(\mu = M_W) \rightarrow C_k^{\text{SM}} + C_k^{\text{NP}}$$

    initial conditions for RG evolution

  – The $C_k^{\text{NP}}$ may also involve new CP-violating phases.

• **Possibility II:** New Operators

  – Operators, which are absent or strongly suppressed in the SM, may actually play an important rôle:

    $$\{Q_k\} \rightarrow \{Q_k^{\text{SM}}, Q_l^{\text{NP}}\}$$

    operator basis

  – In general, new sources of flavour and CP violation.
A Brief Roadmap of Quark-Flavour Physics

- CP-B studies through various processes and strategies:

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

\[
R_b \ (b \rightarrow u, c\ell\bar{\nu}_\ell)
\]

\[
R_t \ (B^{0}_{q}B^{0}_{q} \text{ mixing})
\]

\[
\begin{align*}
B \rightarrow \pi K & \text{ (penguins)} \\
\{B^\pm_u \rightarrow K^\pm D \} & \text{ only trees} \\
B^0_d \rightarrow K^{*0} D \\
B^\pm_c \rightarrow D^\pm_s D \\
B^\pm_d \rightarrow D^{(*)\mp} & : \gamma + 2\beta \text{ only trees} \\
B^0_s \rightarrow D^{\pm}_s K^\mp & : \gamma + \phi_s
\end{align*}
\]

- Moreover “rare” decays: \( B \rightarrow K^*\gamma, \ B_{d,s} \rightarrow \mu^+\mu^-, \ K \rightarrow \pi\nu\bar{\nu}, \ldots \)
  - Originate from loop processes in the SM.
  - Interesting correlations with CP-B studies.

New Physics \( \Rightarrow \) Discrepancies \( \rightarrow \) 2 popular avenues ...
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.

→ hot topics ...
Key Example: $B_d \to \phi K_S$

- **Decay in CP eigenstate:** \( (+1) \times (+1) \times (-1)^1 = -1. \)

- **Structure of the decay amplitude:**

  \[
  K_S = \left( K^0 + \bar{K}^0 \right) / \sqrt{2} \\
  A(B_d^0 \to \phi K_S) = \lambda_u^{(s)} A_P^u + \lambda_c^{(s)} A_P^c + \lambda_t^{(s)} A_P^t
  \]

- **Unitarity of the CKM matrix:**

  \[
  \lambda_t^{(s)} = -\lambda_c^{(s)} - \lambda_u^{(s)} \Rightarrow \\
  A(B_d^0 \to \phi K_S) \propto \left[ 1 + \lambda^2 b e^{i\Theta} e^{i\gamma} \right] \\
  be^{i\Theta} = \left( \frac{R_b}{1 - \lambda^2} \right) \left[ \frac{A_P^u - A_P^t}{A_P^c - A_P^t} \right] \sim O(1)
  \]
• Consequently:

\[ \xi_{\phi K_S}^{(d)} = e^{-i\phi_d} \left[ 1 + \lambda^2 b e^{i\Theta} e^{-i\gamma} \right] \left[ 1 + \lambda^2 b e^{i\Theta} e^{i\gamma} \right] \]

• Since the essentially “unknown” hadronic parameter \( b e^{i\Theta} \) enters in a 
doubly Cabibbo-suppressed way (\( \lambda \equiv |V_{us}| = 0.22 \)):

\[
\begin{align*}
\mathcal{A}_{\text{CP}}^{\text{dir}}(B_d \rightarrow \phi K_S) &= 0 + \mathcal{O}(\lambda^2) \\
\mathcal{A}_{\text{CP}}^{\text{mix}}(B_d \rightarrow \phi K_S) &= -\sin \phi_d + \mathcal{O}(\lambda^2) \equiv -(\sin 2\beta)\phi K_S \\
\end{align*}
\]

• Moreover:

\[
\mathcal{A}_{\text{CP}}^{\text{mix}}(B_d \rightarrow \psi K_S) = -\sin \phi_d + \mathcal{O}(\lambda^3) \equiv -(\sin 2\beta)\psi K_S
\]

\[\Rightarrow (\sin 2\beta)\phi K_S = (\sin 2\beta)\psi K_S + \mathcal{O}(\lambda^2) \quad (\ast)\]

[R.F. ('97); Grossman & Worah ('97); London & Soni ('97)]

• \( B_d \rightarrow \phi K_S \) is a sensitive probe for new physics:

– Dominated by QCD penguins
  
  [London & Peccei ('89); Deshpande & Trampetic ('90); ...]

– EW penguins have a sizeable impact [R.F. ('94); Deshpande & He ('94)]

– Model-independent NP analyses [R.F. & Mannel ('01)]

\[\rightarrow \text{NP may well violate (\ast), and may induce } \mathcal{A}_{\text{CP}}^{\text{dir}}(B_d \rightarrow \phi K_S) \neq 0!\]
CP Violation in $b \rightarrow s$ Penguin-Dominated Modes

- Various channels of this kind, with different hadronic effects. Example: $B_d^0 \rightarrow \pi^0 K_S$ has colour-suppressed tree, in contrast to $B_d^0 \rightarrow \phi K_S$ ...

- NP may also enter differently: $\Rightarrow$ do not average CP asymmetries!

\[ \sin(2\beta_{\text{eff}}) = \sin(2\phi_1^{\text{eff}}) \]

Preliminary

\[ C_f = -A_f \]

NP could be present, but still cannot be resolved $\Rightarrow$ stay tuned ...
Another Example: $B \rightarrow \pi K$ Puzzle

- **Systematic strategy in 3 steps:**

  **Step 1.**  
  $B \rightarrow \pi \pi$ Decays described within SM (EW –Penguins small)  
  → Isospin Symmetry  
  → Hadronic Parameters in $B \rightarrow \pi \pi$  
  → Sizable Departures from QCDF, PQCD

  **Step 2.**  
  $d$, $\theta$, $x$, $\Delta$ + SU(3)$_F$  
  → Hadronic Parameters in $B \rightarrow \pi K$  
  → Enhanced EWP with large New Complex Phase  
  + $\gamma$

  **Step 3.**  
  Correlations between $B \rightarrow \pi K$, Rare K and $B$ Decays and other Processes  
  → Implications for Rare K and B Decays sensitive to EWP

Comprehensive analysis! Let’s here just have a look at ...

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

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

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

→ 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 $B \rightarrow X_s\ell^+\ell^-$ decays ...

- Furthermore puzzling CP asymmetries: $B_d^0 \rightarrow \pi^0 K_S$, $B^\pm \rightarrow \pi^0 K^{\pm}$.

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

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

\[
M_{12}^q = M_{12}^{q,SM} (1 + \kappa_q e^{i\sigma_q}) \Rightarrow
\]

- Mass difference: $\Delta M_q = \Delta M_q^{SM} |1 + \kappa_q e^{i\sigma_q}|$

- Mixing phase: $\phi_q = \phi_q^{SM} + \phi_q^{NP} = \phi_q^{SM} + \arg(1 + \kappa_q e^{i\sigma_q})$

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 $\phi_q^{NP}$:

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

- Determination of $\rho_d = \Delta M_d / \Delta M_d^{\text{SM}}$: \[ \Delta M_d^{\text{SM}} \text{ required, involving ...} \]
  - CKM parameter $|V_{td}^* V_{tb}|$: \[ \rightarrow \text{governed by } \gamma, \text{ if unitarity is used.} \]
  - Hadronic parameter $f^2_{B_d} \hat{B}_{B_d}$: lattice \[ \rightarrow \text{two benchmark sets:} \]
    * 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: \[ \phi_d^{\text{NP}} = (2\beta)\psi K_S - (2\beta)_{\text{true}} \]
  - $\phi_d^{\text{NP}}$ is governed by $R_b \propto |V_{ub}/V_{cb}|$;
  - Unfortunately, discrepancy between $|V_{ub}|_{\text{excl}}$ and $|V_{ub}|_{\text{incl}}$ ...

JLQCD and $\phi_d^{\text{NP}}|_{\text{excl}} = -(2.5 \pm 8.0)^\circ$ 
(HP+JL)QCD and $\phi_d^{\text{NP}}|_{\text{incl}} = -(10.1 \pm 4.6)^\circ$
Key Targets of the \textit{B}-Physics Programme at the LHC

$\rightarrow$ high statistics and \textit{complementarity} to $B$ factories:

\textit{fully exploit the $B_s$-meson system!}
General Features of the $B_s$ System (see Lecture II)

- **Rapid $B^0_s$–$ar{B}^0_s$ oscillations:** $\Delta M_s^{SM} = O(20 \text{ ps}^{-1}) \gg \Delta M_d^{exp} = 0.5 \text{ ps}^{-1}$

  $\Rightarrow$ challenging to resolve them experimentally!

- **The width difference $\Delta \Gamma_s$ is expected to be of $O(10\%)$:**
  
  - Experimental status: $B_s \rightarrow J/\psi \phi \oplus$ Tevatron $\Rightarrow$

    $\frac{\Delta \Gamma_s}{\Gamma_s} = \begin{cases} 0.24^{+0.28+0.03}_{-0.38-0.04} & [D0 ('05)] \\ 0.65^{+0.25}_{-0.33} \pm 0.01 & [CDF ('05)] \end{cases}$ LHCb $\rightarrow$ precision $\sim 0.01$

  - May provide interesting CPV studies through “untagged” rates:

    $\langle \Gamma(B_s(t) \rightarrow f) \rangle \equiv \Gamma(B^0_s(t) \rightarrow f) + \Gamma(\bar{B}^0_s(t) \rightarrow f)$

    * The rapidly oscillating $\Delta M_s t$ terms cancel!
    * Various “untagged” strategies were proposed.

      [Dunietz ('95); R.F. & Dunietz ('96); Dunietz, Dighe & R.F. ('99); ...]

- **The CP-violating phase of $B^0_s$–$ar{B}^0_s$ mixing is tiny in the SM:**

  $\phi_s^{SM} = -2 \lambda^2 \eta \approx -2^\circ$ $\Rightarrow$ 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:
    
    * 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: $\Delta M_s = [17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})] \text{ ps}^{-1} \approx 5\sigma$
  

• 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:** $|V_{ts}^* V_{tb}| = |V_{cb}| \left[ 1 + \mathcal{O}(\lambda^2) \right]$

  $\Rightarrow$ no information on $\gamma$ and $R_b$ needed (in contrast to $\Delta M_d$)!

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

- **Allowed regions in the $\sigma_s-\kappa_s$ plane:**

---

1. Very recent result by the HPQCD collaboration: $\Delta M_s^{\text{SM}} = 20.3(3.0)(0.8) \text{ ps}^{-1}$ [hep-lat/0610104].
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):\(^2\)

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

\[ = R_t^2 \]

\[ \rightarrow \frac{\rho_s}{\rho_d} \bigg|_{2010} = 1.07 \pm 0.09(\gamma)^{+0.06}_{-0.08}(\xi) = 1.07 \pm 0.12 \Rightarrow \square \]

\(^2\)Scenario for 2010: $\gamma = (65 \pm 20)^{\circ} \xrightarrow{\text{LHCb}} (70 \pm 5)^{\circ}$ 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 ...

• Decay topologies:

\[ \lambda_c^{(s)} = V_{cs} V_{cb}^* \]

\[ \lambda_j^{(s)} = V_{js} V_{jb}^* \quad (j \in \{u, c, t\}) \]

• Structure of the decay amplitude:

\[ A(B_s^0 \rightarrow J/\psi \phi) = \lambda_c^{(s)}(A_T^c + A_P^c) + \lambda_u^{(s)} A_P^u + \lambda_t^{(s)} A_P^t \]

• Unitarity of the CKM matrix: \( \lambda_t^{(s)} = -\lambda_c^{(s)} - \lambda_u^{(s)} \Rightarrow \)

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

\[ ae^{i\vartheta} = \left( \frac{R_b}{1 - \lambda^2} \right) \left[ \frac{A_P^u - A_P^t}{A_T^c + A_P^c - A_P^t} \right] \]
• There is an important difference with respect to $B_d^0 \to J/\psi K_S$:

  final state is an admixture of different CP eigenstates!

• *Angular distribution* of the $J/\psi \to \ell^+\ell^-\phi \to K^+K^-$ decay products:

  ⇒ the different CP eigenstates can be disentangled!

• *Time-dependent distribution* takes following form:

  \[
  f(\Theta, \Phi, \Psi; t) = \sum_k g^{(k)}(\Theta, \Phi, \Psi) b^{(k)}(t)
  \]

  – Kinematics is described by the $g^{(k)}(\Theta, \Phi, \Psi)$.
  – Time-dependent coefficients $b^{(k)}(t)$: → real or imaginary parts of

  \[
  A^*_f(t)A_f(t) = \langle (J/\psi\phi)_f | \mathcal{H}_{\text{eff}} | B_s^0(t) \rangle^* \langle (J/\psi\phi)_f | \mathcal{H}_{\text{eff}} | B_s^0(t) \rangle
  \]

  – $f$ and $\tilde{f}$: specify the relative polarization of the $J/\psi$- and $\phi$-mesons in given final-state configurations $(J/\psi\phi)_f$ and $(J/\psi\phi)_{\tilde{f}}$, respectively.
Structure of the Observables

- Consider linear pol. states of the vector mesons, which are longitudinal (0) or transverse to their directions of motion. In the latter case, the pol. states may be parallel (∥) or perpendicular (⊥) to one another.

- **Linear polarization amplitudes:** \( A_0(t), A_{∥}(t), A_{⊥}(t) \)
  - \( A_{⊥}(t) \) describes a CP-odd final-state configuration.
  - \( A_0(t) \) and \( A_{∥}(t) \) correspond to CP-even final-state configurations.
  - The observables \( b^{(k)}(t) \) are then given as follows:
    
    \[
    |A_f(t)|^2 \quad (f \in \{0, ||, ⊥\}) \\
    \text{Re}\{A_0^*(t)A_{∥}(t)\}, \quad \text{Im}\{A_f^*(t)A_{⊥}(t)\} \quad (f \in \{0, ||\}).
    \]

- **Application of the “standard” formalism to the \( A_f(t) \) (\( f \in \{0, ||, ⊥\} \)):**
  
  \[
  \xi_{(ψφ)}^{(s)}_f \propto e^{-iφ_s} \left[ 1 - 2i λ^2 a_f e^{iθ_f} \sin γ + O(λ^4) \right] \rightarrow e^{-iφ_s}
  \]

  \(^3\text{The hadronic penguin effects can be controlled through } B_d \rightarrow J/ψρ^0 \text{ [R.F. (1999)]} \).
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 ...

\[
P_\pm (t) + \overline{P}_\pm (t) \propto \left[ (1 \pm \cos \phi_s) e^{-\Gamma_L t} + (1 \mp \cos \phi_s) e^{-\Gamma_H t} \right]
\]

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

\[
\frac{P_\pm (t) - \overline{P}_\pm (t)}{P_\pm (t) + \overline{P}_\pm (t)} = \pm \frac{2 \sin (\Delta M_s t) \sin \phi_s}{(1 \pm \cos \phi_s) e^{+\Delta \Gamma_{st}/2} + (1 \mp \cos \phi_s) e^{-\Delta \Gamma_{st}/2}}
\]
\[ \phi_s = -2\lambda^2 R_b \sin \gamma + \phi_{s\text{NP}} \approx \phi_{s\text{NP}} \] \[
Rightarrow
\]

• 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:

\[ \text{Re}\{A_{0}^*(t)A_\| (t)\}, \quad \text{Im}\{A_{f}^*(t)A_\perp(t)\} \quad (f \in \{0, \|\}). \]
- 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)] \(\Rightarrow\) *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 $B_s \rightarrow J/\psi \phi$ distribution:
    \[
    \Rightarrow \phi_s = -0.79 \pm 0.56 \text{ (stat.)} \pm 0.01 \text{ (syst.)} = -(45 \pm 32 \pm 0.6)^\circ
    \]
  - Imposing also constraints form semilept. $B$ decays: [D0note 5144-Conf ('06)]
    \[
    \Rightarrow \phi_s = -0.56^{+0.44}_{-0.41} = -(32^{+25}_{-23})^\circ
    \]
  \[
  \Rightarrow \text{still not stingently constrained, but very accessible @ LHC ...}
  \]

- **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 fb$^{-1}$) [0.013 (5 years)];
  - ATLAS & CMS: expect uncertainties of $\mathcal{O}(0.1)$ (1 year, i.e. 10 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]
Impact of $\Delta M_s^{\text{exp}}$ on NP Scenarios: Examples

Extra $Z'$ boson with flavour non-diagonal couplings:

- **Illustration of the $\Delta M_s$ constraints under the following conditions:**
  - The $Z$ couplings stay flavour diagonal, i.e. $Z-Z'$ mixing is negligible.
  - The $Z'$ has flavour non-diagonal couplings only to left-handed quarks, which means that its effect is described by only one complex parameter.

- **The $Z'$ model is characterized by the following parameter:**
  \[
  \rho_L e^{i\phi_L} \equiv \frac{g'M_Z}{gM_{Z'}} B^L_{sb} \sim 10^{-3}
  \]

- **Translation of the $\sigma_s-\kappa_s$ space into the $\phi_L-\rho_L$ space:**
  \[
  \kappa_s < 2.5 \Rightarrow \rho_L < 2.6 \times 10^{-3} \Rightarrow 1.5 \text{ TeV} \left(\frac{g'}{g}\right) \left|\frac{B^L_{sb}}{V_{ts}}\right| < M_{Z'}
  \]

[along Barger, Chiang, Jiang and Langacker, hep-ph/0405108; other recent analysis addressing also $\Delta M_s$: Cheung et al., hep-ph/0604223; Baek et al., hep-ph/0607113]
MSSM in the mass insertion approximation:

- Illustration of the interplay between $\Delta M_s$ & mass insertions:

See also Becirevic et al. ('02); Ball, Khalil & Kou ('04); Ciuchini et al. ('06); Ciuchini & Silvestrini ('06); Endo & Mishima ('06); Khalil ('06); ...
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:
     - $B^0_s \rightarrow D^+_s K^\pm$: $\sigma_\gamma \sim 14^\circ$
     - $B^0_d \rightarrow D^0 K^*$: $\sigma_\gamma \sim 8^\circ$ ... to be compared with the current $B$-factory data: $\gamma \big|_{D^(*)K^(*)} = \begin{cases} (62^{+35}_{-25})^\circ & \text{(CKMfitter)} \\ (65 \pm 20)^\circ & \text{(UTfit)} \end{cases}$
     - $B^{\pm} \rightarrow D^0 K^\pm$: $\sigma_\gamma \sim 5^\circ$
   - Decays with penguin contributions:
     - $B^0_s \rightarrow K^+ K^-$ and $B^0_d \rightarrow \pi^+ \pi^-$: $\sigma_\gamma \sim 5^\circ$
     - $B^0_s \rightarrow D^+_s D^-_s$ and $B^0_d \rightarrow D^+_d D^-_d$

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

→ 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:**

  \[ B_0^q \rightarrow D_q \bar{u}_q \propto e^{i\gamma} \]

  \[ B_0^q \rightarrow D_q \bar{u}_q \propto e^{i\phi_q} \]

  \[ B_0 \rightarrow D \bar{u}_q \propto e^{i\phi_q + \gamma} \]

  \[ \phi_q + \gamma \]

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

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

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

  \[ \rightarrow \text{hadronic parameter } X_d e^{i\delta_d} \propto -\lambda^2 R_b \Rightarrow \text{tiny interference effects!} \]
• \( \cos(\Delta M_q t) \) 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 \( \rightarrow \) impossible ...

• Combined analysis of \( B^0_s \rightarrow D_s^{(*)+}K^- \) and \( B^0_d \rightarrow D^{(*)+}\pi^- \): [R.F. (2003)]

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

– 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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^4The \( U \)-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.

[Full U-Spin Symmetry: 5 years]

Consider, for example, ±20% U-spin symmetry breaking → shift of ±13 deg

20% U-spin breaking gives 3 degree shift

[1] (2)  

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

- $B_s^0 \rightarrow K^+K^-$:

- $B_d^0 \rightarrow \pi^+\pi^−$:

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

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

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

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

\[ [d, d']: \text{real hadronic parameters; } \theta, \theta': \text{strong phases} \]

• General form of the CP asymmetries:

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

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

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

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

\[ - A_{\text{dir}}(B_s \to K^+ K^-) \text{ } \& \text{ } A_{\text{mix}}(B_s \to K^+ K^-): \Rightarrow \boxed{d' = d'(\gamma)} \text{ (clean!)} \]
• 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:**
  
  * $B_d \rightarrow \pi^+\pi^-$: $A_{\text{CP}}^{\text{dir}} = -0.37$, $A_{\text{CP}}^{\text{mix}} = +0.50$
  
  * $B_s \rightarrow K^+K^-$: $A_{\text{CP}}^{\text{dir}} = +0.12$, $A_{\text{CP}}^{\text{mix}} = -0.19$
• 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:

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

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

- $\theta = \theta'$: $\Rightarrow$ test of the $U\text{-spin symmetry}$!

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

![Diagram showing experimental accuracy for $\gamma$ of a few degrees!](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** \( B_s \rightarrow K^+ K^- \) **@ CDF**

  - 236 ± 32 events were seen, which correspond to the branching ratio
    \[
    \text{BR}(B_s \rightarrow K^+ K^-) = (33 \pm 5.7 \pm 6.7) \times 10^{-6};
    \]
    update @ BEAUTY ’06: \( \rightarrow (24.4 \pm 1.4 \pm 4.6) \times 10^{-6} \).

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

  - Requires the knowledge of an \( SU(3) \)-breaking from-factor ratio (which cancels in \( de^{i\theta} = d'e^{i\theta'} \)) [QCD sum rules: Khodjamirian et al. ('03)].
  
  - Dynamical assumptions (small annihilation) and \( B_d \rightarrow \pi^\mp K^\pm \) data:
    \[
    \Rightarrow \text{BR}(B_s \rightarrow K^+ K^-) = (35 \pm 7) \times 10^{-6}
    \]
    \( \Rightarrow \) **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:

![Diagram of the process $B_q \rightarrow \mu^+\mu^-$]


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

- $\alpha$: 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)]

→ use the data for the $\Delta M_q$ to reduce the hadronic uncertainties:

$$\text{BR}(B_s \rightarrow \mu^+\mu^-) = (3.35 \pm 0.32) \times 10^{-9}$$
$$\text{BR}(B_d \rightarrow \mu^+\mu^-) = (1.03 \pm 0.09) \times 10^{-10}$$

• **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)]
    $$\text{BR}(B_s \rightarrow \mu^+\mu^-) < 1.9 (2.3) \times 10^{-7}$$

⇒ still a long way to go (?) → **LHC** (background under study)

• **However, NP may significantly enhance BR($B_s \rightarrow \mu^+\mu^-$):**

  – In SUSY scenarios: $\text{BR} \sim (\tan \beta)^6 \rightarrow$ 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:

  $\rightarrow$ may yield $A_{FB}(\hat{s})$ of opposite sign or without a zero point $\rightarrow$
- **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 flavour physics & CPV 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 $B_s^0$–$\bar{B}_s^0$ mixing.

• Status in November 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 $\approx$ 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:** [→ lecture by A. Höcker]
  - 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:**
  
  \[ B \oplus K, D, \text{top physics \& lepton/neutrino sector} \]

  - 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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\(^5\) Topic of CERN Workshop: http://flavlhfcern.ch/flavlhfc/