$B$ Physics in the LHC Era: Status and Perspectives

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- Setting the Stage
- Theoretical Framework
- $B$ Physics @ LHC: \( \rightarrow \) Promising Probes for New Physics
- Conclusions & Outlook
Setting the Stage
Quark Flavour Physics & CP Violation

key players in the history of the Standard Model (SM):

- **1963**: concept of flavour mixing [Cabibbo].

- **1964**: discovery of CP violation in $K_L \rightarrow \pi^+\pi^-$ [Christenson et al.].

- **1970**: introduction of the charm quark to suppress the flavour-changing neutral currents (FCNCs) [Glashow, Iliopoulos & Maiani].

- **1973**: quark-flavour mixing with 3 generations allows us to accommodate CP violation in the SM [Kobayashi & Maskawa].

- **1974**: estimate of the charm-quark mass with the help of the $K^0-\bar{K}^0$ mixing frequency [Gaillard & Lee].

- **1980s**: the large top-quark mass was first suggested by the large $B^0-\bar{B}^0$ mixing seen by ARGUS (DESY) and UA1 (CERN).

flavour physics has since continued to progress ...
The Quark-Flavour Code

- **Quark flavour physics and CP violation:** → rich phenomenology

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix}
=\begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
\]

quark-mixing matrix, also known as
Cabibbo–Kobayashi–Maskawa matrix \(\hat{V}_{\text{CKM}}\)
→ unitary matrix

⇒ encoded in weak decays of \(K\), \(D\) and \(B\) mesons

[antiquark–quark boundstates \(\bar{q}Q\) with \(Q=s, c\) and \(b\)]

- **The key problem:** strong interactions → “hadronic” uncertainties
  
  - The theory is formulated in terms of quarks, while flavour-physics experiments use their QCD bound states, i.e. \(B\), \(D\) and \(K\) mesons.
  
  - In the calculations of the relevant transition amplitudes, we encounter process-dependent, non-perturbative “hadronic” parameters!?
    
    [→ lattice QCD: lots of progress for some parameters, but still challenging...]

- \(\text{Cabibbo–Kobayashi–Maskawa (CKM)}\)
- Weak Interactions of Quarks
• **The $B$-meson system is a particularly promising flavour probe:**
  
  – Simplifications through the large $b$-quark mass $m_b \sim 5 \text{ GeV} \gg \Lambda_{\text{QCD}}$.
  
  – Offers various strategies to eliminate the hadronic uncertainties and to determine the hadronic parameters from the data.
  
  – Tests of SM relations that could be spoiled by physics beyond the SM.

• **The last decade was governed by the $e^+e^- B$ factories with the BaBar (SLAC) and Belle (KEK) experiments and $B$ results from the Tevatron:**
  
  – $CP$-violating phenomena in $B$-meson decays could be established.
  
  – The interplay with theory resulted in many new insights.
  
  – With the exception of a few “flavour puzzles” (not yet conclusive because of large errors), also the SM flavour sector is in good shape.

• **However, a large territory of the $B$-physics landscape was left unexplored:**
  
   → target of another LHC experiment: LHCb [→ talk by Val Gibson]
Species of $B$ Mesons

- **Charged $B$ mesons:**
  \[ B^+ \sim u \bar{b} \quad B^- \sim \bar{u} b \]
  \[ B^+_c \sim c \bar{b} \quad B^-_c \sim \bar{c} b \]

- **Neutral $B$ mesons:**
  \[ B^0_d \sim d \bar{b} \quad \bar{B}^0_d \sim \bar{d} b \]
  \[ B^0_s \sim s \bar{b} \quad \bar{B}^0_s \sim \bar{s} b \]

- $B^0_q - \bar{B}^0_q$ mixing: \[ \rightarrow \text{Quantum Mechanics} \]

\[ q \]
\[ W \]
\[ b \]
\[ u, c, t \]
\[ b \]
\[ W \]
\[ q \]
\[ W \]
\[ b \]
\[ u, c, t \]
\[ q \]

\[ \Rightarrow |B_q(t)\rangle = a(t)|B^0_q\rangle + b(t)|\bar{B}^0_q\rangle : \]

* **Schrödinger equation** \[ \Rightarrow \text{mass eigenstates:} \]

\[ \Delta M_q \equiv M^{(q)}_H - M^{(q)}_L, \quad \Delta \Gamma_q \equiv \Gamma^{(q)}_L - \Gamma^{(q)}_H \]

* **Decay rates:** \[ \Gamma(B^0_q(t) \rightarrow f) : \]

\[ \cos(\Delta M_q t) \& \sin(\Delta M_q t) \rightarrow \text{oscillations!} \]
Hope for New Physics ...

- We have indications that the SM cannot be complete:
  - Neutrino masses $\neq 0$: suggest see-saw mechanism, GUT scenarios ...
  - Baryon asymmetry of the Universe (SM cannot generate it ...)
  - The long-standing problem of dark matter (?)

- Fundamental theoretical questions/problems:
  - Hierarchy problem
  - Fine-tuning problem... → suggest New Physics in the TeV regime

- Popular specific models for physics beyond the SM:
  - Supersymmetry (SUSY)
  - Universal extra dimension (UED)
  - Warped extra dimension (WED)
  - Little Higgs models (LH, with T parity LHT)
  - $Z'$ models
  - 4th generation models → new sources of flavour & CP violation
How to Search for New Physics (NP) Beyond the SM?

- Search for direct signals of NP: \( \Rightarrow \) physics @ ATLAS \( \oplus \) CMS
  
  - Produce new particles (e.g. squarks, gauge bosons, ...) at colliders;
  - Study the decays of the new particles in general purpose detectors ...

  \( \rightarrow \) high-energy frontier

- Search for indirect footprints of NP: \( \Rightarrow \) \( B \) (flavour) physics @ LHCb

  - Sensitivity to NP effects through virtual quantum effects:

  \( \rightarrow \) high-precision frontier

\( \Rightarrow \) expect synergy between both avenues to search for NP
Theoretical Framework:
in a nutshell ...
Basic Language: Quantum Field Theory

- **Lagrangian:**
  \[ \mathcal{L} = \mathcal{L}_{\text{SM}}(g_k^{\text{SM}}, m_k^{\text{SM}}, \hat{V}_{\text{CKM}}) + \mathcal{L}_{\text{NP}}(g_k^{\text{NP}}, m_k^{\text{NP}}, \hat{V}_{\text{NP}}) \Rightarrow \{ \text{Feynman diagram calculations} \} \]

- **Lagrangian composed of SM and NP fields involves:**
  - Couplings: \( g_k^{\text{SM}} \oplus g_k^{\text{NP}} \)
  - Particle masses: \( m_k^{\text{SM}} \oplus m_k^{\text{NP}} \), and ...

- **Quark flavour mixing:** \( [D \in \{d, s, b\}, U \in \{u, c, t\}] \)
  - SM: \( D \rightarrow UW \) described by the Cabibbo–Kobayashi–Maskawa (CKM) matrix \( \hat{V}_{\text{CKM}} \) connecting the quark flavour states with their mass eigenstates through a unitary transformation: \( \hat{V}_{\text{CKM}}^\dagger \cdot \hat{V}_{\text{CKM}} = \hat{1} \).
  - In general, new sources of flavour mixing through NP: \( \hat{V}_{\text{NP}} \).

- **NP may induce flavour-changing neutral currents (FCNCs) @ tree level:**
  \( \rightarrow \) forbidden in the SM [Glashow–Iliopoulos–Maiani (GIM) mechanism (‘70)]
CP Violation in the Standard Model

- Behaviour of “charged-current” processes under CP transformations:

\[
\begin{align*}
& D & U \\
\rightarrow & V_{UD} & W^- \\
& \text{CP} & V_{UD}^* \\
\rightarrow & W^+ & \text{CP}^{-1}
\end{align*}
\]

- Kobayashi & Maskawa (1973):

  - \( N = 2 \): (real) quark-mixing-matrix parametrized by the Cabibbo angle.
  - \( N = 3 \): \( \hat{V}_{CKM} \) parametrized by three angles and one complex phase:

\[\Rightarrow \text{ allows us to accommodate CP violation:}^1\]

\[\rightarrow \text{Kobayashi–Maskawa (KM) mechanism}\]

\[\begin{align*}
& \hat{V}_{CKM} \text{ complex for } N \geq 3 \text{ generations}
\end{align*}\]

\[^1\text{Another source of CP violation: strong CP problem with “QCD vacuum angle” } \theta \text{ (neutron EDM).}\]
The Unitarity Triangle (UT)

- **Unitarity of the CKM matrix:**\(^2\) \(\Rightarrow \quad V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0 \Rightarrow\)

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

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

\[- \lambda \equiv |V_{us}| = 0.22 \rightarrow \text{phenomenological expansion of the CKM matrix.}\]

\[- \bar{\rho} \equiv (1 - \lambda^2/2)\rho, \quad \bar{\eta} \equiv (1 - \lambda^2/2)\eta \text{ take NLO effects into account, where } \rho, \eta \text{ appear in the CKM parametrization by Wolfenstein.}\]

**CP violation:** non-vanishing height of the UT (i.e. \(\gamma \neq 0^\circ\))

- **Theoretical interpretation of various flavour-physics observables:**

\[\Rightarrow \text{contours in the } \bar{\rho} - \bar{\eta} \text{ plane: } \Rightarrow \text{KM consistency checks } \ldots\]

\(^2\)Actually 6 unitarity triangles: 4 are extremely squashed; 2 non-squashed ones agree at LO in \(\lambda = 0.22\).
Status of the Unitarity Triangle

- Fits of the UT by two groups: \( \rightarrow \) many plots & correlations ...
  - *UTfit* Collaboration [http://www.utfit.org/UTfit/WebHome]:

\[ \Rightarrow \text{continuously updated results:} \]

\[ \Rightarrow \text{some tension between } \beta, \varepsilon_K, |V_{ub}/V_{cb}| \ (?) \]

[See, e.g., E. Lunghi & A. Soni ('09–'10); A. Buras & D. Guadagnoli ('09); ...]
• Lessons from the $B$, $D$ and $K$ decay 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 $B^0 \to \pi^0 K_S$ [Future @ LHCb: $B_s^0 \to \phi\phi$]

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

  Electroweak “penguin” contribution $\to$ NP?

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

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

– 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: *Minimal Flavour Violation (MFV):*
    \[ \rightarrow \text{essentially the same CP \\& flavour violation as in the SM.} \]

• **Comments:**

– MFV has not yet been experimentally established.

– There are various non-MFV scenarios with room for sizeable effects: SUSY, WED, LHT, \( Z' \) models, 4th generation, ...

– Nevertheless, we have to be prepared to deal with “smallish” NP effects

• **Excellent news:**

– We are at the beginning of a new era in particle physics: \( \rightarrow \) LHC era
$B$ Physics @ LHC:

⇒ promising probes for New Physics

[⇒ Val Gibson’s talk for the experimental aspects]
New Territory: $B_s$-Meson System

- $e^+e^- B$ factories:
  - Cannot access the $B_s$ system if operated @ $\Upsilon(4S)$: BaBar (SLAC) & Belle (KEK).
  - Belle has collected data @ $\Upsilon(5S')$ as well.
  
  The $B_s$ system is the domain of hadron colliders

- CDF & DØ @ Tevatron:
  - Observation of $B^0_s - \bar{B}^0_s$ mixing in 2006 (after long efforts).
  - Intriguing results for CP violation in $B^0_s \rightarrow J/\psi\phi$ since about 3 years.

- LHCb: promising processes for first NP signals:
  - CP violation in $B^0_s \rightarrow J/\psi\phi$.
  - Branching ratio of $B^0_s \rightarrow \mu^+\mu^-$ (ATLAS & CMS are competitive).
  - Various other decays & strategies ...
  
  → particularly interesting ...
Search for NP in $B_{s}^{0} - \overline{B}_{s}^{0}$ mixing:

- **Standard Model**
  - $W$ boson
  - CP-violating phase $\phi_{s} = \phi_{s}^{SM} + \phi_{s}^{NP}$
  - SM piece is tiny: $\phi_{s}^{SM} \approx -2^\circ$

- **New Physics (e.g. SUSY, Z’ models)**
  - FCNC process: strongly suppressed in the SM (“box” diagrams)

$\Rightarrow$ sensitive probe for NP
Constraints on NP Parameter Space

- Parameter (complex number) to characterize NP in $B_s^0 - \bar{B}_s^0$ mixing:

  $$\kappa_s e^{i\sigma_s} \equiv \text{“NP”} / \text{“SM”} \Rightarrow$$

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

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

  $\Delta M_s \Rightarrow$ yellow band;
  $\phi_s \Rightarrow \ldots$

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

- **Interference effects through** $B_s^0 - \bar{B}_s^0$ 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:**
  
  $\rightarrow$ disentangle through $J/\psi[\rightarrow \mu^+ \mu^-] \phi[\rightarrow K^+ K^-]$ angular distribution.

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

[Dighe, Dunietz & R.F. ('99); Dunietz, R.F. & Nierste ('01); Faller, R.F. & Mannel ('08)]
Examples of Specific NP Analyses \((S_{\psi\phi} = - \sin \phi_s)\)

- Littlest Higgs Model with T-Parity (LHT):\(^3\)

\[
A^s_{SL} \text{ versus } S_{\psi\phi}
\]

[Blanke, Buras, Poschenrieder, Recksiegel, Tarantino, Uhlig & Weiler (2007)]

- Warped Extra Dimensions:

\[
A^s_{SL} \text{ versus } S_{\psi\phi}
\]

[Blanke, Buras, Duling, Gori & Weiler (2009)]

\(3A^{sSM}_{SL} \sim 2 \times 10^{-5}\): “wrong-charge” lepton asymmetry measuring CP violation in \(B^0_s - \bar{B}^0_s\) oscillations.
Tevatron $B^0_s \rightarrow J/\psi\phi$ Results

- Interesting results on this channel since 2008 ...

- Picture in the Summer of 2011:

\[ \phi_s^{D\O} = -\left(31.5^{+20.6}_{-21.8}\right)^\circ \quad \quad \phi_s^{CDF} = [-59.6^\circ, -2.3^\circ] \text{ (68\% C.L.)} \]

- DØ includes also the anomalous like-sign dimuon charge asymmetry;
- CDF plot uses only $B_s \rightarrow J/\psi\phi$ data.

- Bad news: situation is (still...) not conclusive (?)
LHCb $B_s^0 \to J/\psi \phi$ Results

- Update at Lepton–Photon 2011:

**$B_s \to J/\psi \phi$: $\Delta \Gamma_s$ vs. $\phi_s$**

Most precise measurement of $\phi_s$:

- $\phi_s = 0.13 \pm 0.18$ (stat) $\pm 0.07$ (syst) rad
- Consistent with SM

4 $\sigma$ Evidence for $\Delta \Gamma_s \neq 0$:

- $\Delta \Gamma_s = 0.123 \pm 0.029$ (stat) $\pm 0.008$ (syst) ps$^{-1}$
- $\Gamma_s = 0.656 \pm 0.009$ (stat) $\pm 0.008$ (syst) ps$^{-1}$

- $\phi_s = (7.4 \pm 10.3 \pm 4.0)^\circ$ consistent with $\phi_s^{SM} = -2.1^\circ$ → stay tuned ...

[G. Raven @ Lepton–Photon 2011]
Prospects for $B_s \rightarrow J/\psi \phi$

- **Experimental reach @ LHCb:** very impressive ... 
  - End of first phase of LHCb ($5 \text{ fb}^{-1} \sim 2015$): $\sigma(\phi_s)_{\text{exp}} \sim 1^\circ$
  - LHCb upgrade ($50 \text{ fb}^{-1}$): $\sigma(\phi_s)_{\text{exp}} \sim 0.3^\circ$ [M. Merk @ Beauty 2011]

- **However:** SM penguin effects were so far fully neglected:

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

  - 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; LHCb @ Beauty 2011]

- **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: $A_{\text{CP}}^{\text{mix}} \sim -(5\ldots10)\%$ would require further work from theorists and experimentalists to clarify the picture ...
    
    [Faller, R.F. & Mannel (2009)]

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$^4\lambda \equiv |V_{us}| = 0.22$ is the Wolfenstein parameter of the CKM matrix.
Another (Emerging) Hot Topic: \( B_s^0 \rightarrow J/\psi f_0(980) \)

- \( f_0(980) \) is a scalar \( J^{PC} = 0^{++} \) state: \( \Rightarrow \) no angular analysis is required!

- Dominant mode: \( B_s^0 \rightarrow J/\psi f_0 \) with \( f_0 \rightarrow \pi^+\pi^- \).

- Recent observation of \( B_s^0 \rightarrow J/\psi f_0 \) at LHCb, Belle, DØ and CDF:

\[
R_{f_0/\phi} \equiv \frac{\text{BR}(B_s^0 \rightarrow J/\psi f_0; f_0 \rightarrow \pi^+\pi^-)}{\text{BR}(B_s^0 \rightarrow J/\psi \phi; \phi \rightarrow K^+K^-)} \sim 0.25
\]

... but as no angular analysis is required:

\( \Rightarrow B_s^0 \rightarrow J/\psi f_0 \) offers an interesting alternative to \( B_s^0 \rightarrow J/\psi \phi \)

[S. Stone & L. Zhang (2009)]
New Results for $B_s^0 \rightarrow J/\psi f_0(980)$

- First measurement of the effective lifetime: [CDF, arXiv:1106.3682 [hep-ex]]

\[ \tau_{J/\psi f_0} = [1.70^{+0.12}_{-0.11}\text{(stat)} \pm 0.03\text{(syst)}] \text{ ps} \]

- First study of CP violation in $B_s^0 \rightarrow J/\psi f_0$: [LHCb, G. Raven @ LP 2011]

\[ \phi_s = -(25 \pm 25 \pm 1)^\circ \rightarrow \text{stay tuned ...} \]
Theoretical Uncertainties?

- Decay topologies:

  - Colour-suppressed Tree Penguin Penguin Exchange
  - Penguin
  - Penguin Exchange
  - Penguin Annihilation

- The composition of the $f_0(980)$ is still poorly known: → 2 benchmarks:
  - Quark–antiquark: $|f_0(980)\rangle = \cos \varphi_M |s\bar{s}\rangle + \sin \varphi_M \frac{1}{\sqrt{2}} (|u\bar{u}\rangle + |d\bar{d}\rangle)$
  - Tetraquark: $|f_0(980)\rangle = \frac{1}{\sqrt{2}} ([su][\bar{s}\bar{u}] + [sd][\bar{s}\bar{d}]) \rightarrow$

  - no counterpart in $qq$!

- **Detailed analysis:** \[ A(B_s^0 \rightarrow J/\psi f_0) \propto [1 + \lambda^2 (b e^{i\theta}) e^{i\gamma}] \]

  - Effective \( B_s^0 \rightarrow J/\psi f_0 \) lifetime and mixing-induced CP asymmetry \( S \) are quite robust with respect to hadronic effects encoded in \( b e^{i\theta} \):

  ![Diagram of \( \tau_{J/\psi f_0}/\tau_{B_s} \) and \( S(B_s \rightarrow J/\psi f_0) \) for different values of \( \phi_s \).]

- **Should smallish CPV \(-0.1 \lesssim S \lesssim 0\) be found:** [LHCb@LP11: \( S = -0.43^{+0.43}_{-0.34} \)]

  ⇒ crucial to constrain hadronic corrections to disentangle NP from SM

- **Control channel:** \( B_d^0 \rightarrow J/\psi f_0(980) \) ⇒ search for it & add to agenda!

Implications of the Data for the $B_d^0$ System

- **Tension in fit of UT:** $(\phi_d)_J/ψK^0 - 2\beta_{\text{true}} = -(8.7^{+2.6}_{-3.6} \pm 3.8)° \rightarrow \text{NP!?}$

- **SM corrections:** doubly Cabibbo-suppressed penguins $(\lambda \equiv |V_{us}| = 0.22) \rightarrow$

$$A(B_d^0 \rightarrow J/ψK_S) \propto [1 + \epsilon a e^{i\theta} e^{i\gamma}] \quad (\epsilon \equiv \lambda^2/(1 - \lambda^2) \sim 0.05)$$

- **Generalized expression for mixing-induced CP violation:** $[\phi_d = 2\beta + \phi_d^{\text{NP}}]$

$$\frac{S(B_d \rightarrow J/ψK_S)}{\sqrt{1 - C(B_d \rightarrow J/ψK_S)^2}} = \sin(\phi_d + \Delta \phi_d)$$

$$\sin \Delta \phi_d \propto 2\epsilon a \cos \theta \sin \gamma + \epsilon^2 a^2 \sin 2\gamma$$

$$\cos \Delta \phi_d \propto 1 + 2\epsilon a \cos \theta \cos \gamma + \epsilon^2 a^2 \cos 2\gamma$$
• \( \Delta \phi_d \) cannot be calculated: \( \Rightarrow \) use \( B_d^0 \rightarrow J/\psi \pi^0 \) data & \( SU(3) \)

\[
A(B_d^0 \rightarrow J/\psi \pi^0) \propto [1 - ae^{i\theta} e^{i\gamma}]
\]

- Fit to all current data, allowing also for \( SU(3) \)-breaking corrections:
  \( \Rightarrow \) \( \Delta \phi_d \in [-6.7, 0.0]^\circ \), i.e. softens the tension in the fit of the UT.
- NP mixing phase: \( \phi_d^{NP} \in [-14.9, 4.0]^\circ \), i.e. no significant effect.

• Observation:

  - The quality of the \( B \)-factory data has essentially reached a level of precision where subleading SM effects have to be included!
  - This will be even much more relevant in the LHC era, but \( B_d^0 \rightarrow J/\psi \pi^0 \) is very challenging for this experiment (super-\( B \) factory could do) \( \Rightarrow \)

[S. Faller, R.F., M. Jung & T. Mannel (2008)]
A New Channel for LHCb: $B^0_s \rightarrow J/\psi K_S$

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

- **$U$-spin symmetry:**

  \begin{align*}
  B^0_s & \rightarrow J/\psi K_S \iff B^0_d \rightarrow J/\psi K_S \quad [\text{R.F. (1999)}]
  
  & \text{– Determination of the UT angle } \gamma. \\
  & \text{– Control of penguins in the determination of } \phi_d \text{ from } B^0_d \rightarrow J/\psi K_S.
  
  \end{align*}

- **Experimental status of the $B^0_s \rightarrow J/\psi K_S$ decay:**

  \begin{align*}
  & \text{– Recent news from LHCb [P. Koppenburg @ Physics in Collision 2011]:} \\
  & \frac{\text{BR}(B_s \rightarrow J/\psi K_S)}{\text{BR}(B_d \rightarrow J/\psi K_S)} = 0.0378 \pm 0.0058 \text{(stat)} \pm 0.0020 \text{(syst)} \pm 0.0030 \text{(frag)}
  \\
  & \text{– First observation by CDF @ ICHEP2010: } 0.041 \pm 0.007 \pm 0.004 \pm 0.005
  
  \end{align*}

$^5$\textit{U} 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 \( (\phi_d)_{J/\psi K_S} \):

\[
\Delta\phi_d [\text{deg}]
\]

\[
\theta [\text{deg}]
\]

\[
\text{Stat. error on} \Delta\phi_d [\text{deg}]
\]

\[
\text{Contours = 1} \sigma \text{ bands}
\]

\[
\text{Input value}
\]

\[
a = 0.8, \theta = 180^\circ, a = 0.7, \theta = 160^\circ, 220^\circ, a = 0.6, \theta = 140^\circ, 240^\circ, a = 0.5, \theta = 120^\circ, 260^\circ, a = 0.4, \theta = 100^\circ, 280^\circ, a = 0.3, \theta = 80^\circ, 300^\circ, a = 0.2, \theta = 60^\circ, 320^\circ, a = 0.1, \theta = 40^\circ, 340^\circ
\]

\[
\Rightarrow \text{interesting study for the LHCb upgrade} [100 \text{ fb}^{-1}]
\]
Further Benchmark Decays for the LHCb Experiment

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

1. **Precision measurements of the angle $\gamma$ of the UT:**
   - Tree strategies, with expected sensitivities after 1 *nominal* year:
     - $B_s^0 \to D_s^\pm K_s^\pm$: $\sigma_\gamma \sim 14^\circ$
     - $B_d^0 \to D^0 K^*$: $\sigma_\gamma \sim 8^\circ$ ... to be compared with the current $B$-factory data: $\gamma|_{D(\ast)K(\ast)} = \begin{cases} (71^{+21}_{-25})^\circ \quad \text{[CKMfitter]} \\ (73 \pm 11)^\circ \quad \text{[UTfit]} \end{cases}$
     - $B^\pm \to D^0 K^\pm$: $\sigma_\gamma \sim 5^\circ$
   - Decays with penguin contributions:
     - $\diamond B_s^0 \to K^+ K^-$ and $B_d^0 \to \pi^+ \pi^-$: $\sigma_\gamma \sim 5^\circ$
     - $B_s^0 \to D_s^+ D_s^-$ and $B_d^0 \to D_d^+ D_d^-$

2. “Rare” (strongly suppressed) decays which are absent at the SM tree level:
   - $B_s^0 \to \phi \phi$
   - $\diamond B_s^0 \to \mu^+ \mu^-, B_d^0 \to \mu^+ \mu^-$ (ATLAS & CMS are competitive)
   - $B_d^0 \to K^{*0} \mu^+ \mu^-, B_s^0 \to \phi \mu^+ \mu^-; ...$

   → let’s have a closer look at two of my “favourites” $\diamond$ ...
The System

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

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

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

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

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

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

[R.F. (1999)]

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

\[ \begin{align*}
& B_s \to K^+K^- \\
& B^0 \to \pi^+\pi^-
\end{align*} \]

\[ \rightarrow \quad \text{experimental accuracy for } \gamma \text{ of a few degrees!} \]

LHCb Collaboration (B. Adeva et al.)
A Fresh Look:

→ get ready for LHCb data...

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

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

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

Current Picture for $\gamma$

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

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

(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: $[\langle \Gamma(B_{s}(t) \rightarrow f) \rangle \rightarrow \text{“untagged” rate}]$

\[
\tau_{K^{+}K^{-}} \equiv \frac{\int_{0}^{\infty} t \langle \Gamma(B_{s}(t) \rightarrow K^{+}K^{-}) \rangle \, dt}{\int_{0}^{\infty} \langle \Gamma(B_{s}(t) \rightarrow K^{+}K^{-}) \rangle \, dt}
\]

- Using $K$, $A_{\text{CP}}^{\text{dir}}(B_{d} \rightarrow \pi^{\mp}K^{\pm})$ and $\gamma = (68 \pm 7)^{\circ} [\oplus U\text{-spin-breaking}]$: ⇒

![Graph showing $\tau_{K^{+}K^{-}}/\tau_{B_{s}}$ vs. $\phi_{s}$ with $\Delta \tau_{\text{SM}}^{\text{SM}} = 0.140 \pm 0.020$ and a shaded region indicating a 1% error]

⇒ probe for NP in $B_{s}^{0}-\bar{B}_{s}^{0}$ mixing

[CDF (2006): $\tau_{K^{+}K^{-}} = (1.53 \pm 0.18 \pm 0.02) \text{ps}^{-1} \Rightarrow \tau_{K^{+}K^{-}}/\tau_{B_{s}} = 1.04 \pm 0.12$]
Recent News from LHCb:

→ first results on the effective lifetime of $B_s^0 \to K^+K^-$:

- The error will be reduced soon.
- Analysis to measure CP violation in $B_s^0 \to K^+K^-$ is also in progress.

→ stay tuned ...
The next observable to enter the stage: $A_{CP}^{mix}(B_s \rightarrow K^+ K^-)$

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

Using $K$, $A_{CP}^{dir}(B_d \rightarrow \pi^\pm K^{\pm})$, $\gamma \oplus U$-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 $B_s^0 - \bar{B}_s^0$ mixing
Search for New Physics in

\[ B_s \rightarrow \mu^+ \mu^- \]
The Rare Decay $B_{s}^{0} \rightarrow \mu^{+}\mu^{-}$

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

  \[
  B_{s}^{0} \rightarrow \mu^{+}\mu^{-} \quad \Rightarrow \quad \text{strongly suppressed & sensitive to NP}
  \]

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

  \[
  B_{s}^{0} \rightarrow \mu^{+}\mu^{-} \quad \Rightarrow \quad \text{is one of the cleanest rare $B$ decays}
  \]

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

NP may enhance BRs significantly...

[Babu & Kolda, Dedes et al., Foster et al., Carena et al., Isidori & Paradisi, ...]
• **Example of a recent analysis:** → *supersymmetric flavour models:*

![Diagrams](image_url)

(RVV2 model)  
(δLL model)

Experimental Status:

- **Tevatron:**
  - DØ (2010): $\text{BR}(B^0_s \rightarrow \mu^+\mu^-) < 5.1 \times 10^{-8}$ (95% C.L.)
  - CDF (2011): $\text{BR}(B^0_s \rightarrow \mu^+\mu^-) < 4.0 \times 10^{-8}$ (95% C.L.)
  - report of observation of an excess of $B_s$ candidates (!):
    $$\text{BR}(B^0_s \rightarrow \mu^+\mu^-) = (18^{+11}_{-9}) \times 10^{-9} \ldots$$

- **Large Hadron Collider:**
  - CMS (2011): $\text{BR}(B^0_s \rightarrow \mu^+\mu^-) < 1.9 \times 10^{-8}$ (95% C.L.)
  - LHCb (2011): $\text{BR}(B^0_s \rightarrow \mu^+\mu^-) < 1.5 \times 10^{-8}$ (95% C.L.)
  - 1st LHC combined limit:
    $$\text{BR}(B^0_s \rightarrow \mu^+\mu^-) < 11 \times 10^{-9}$$ (95% C.L.)
  
    $\rightarrow$ LHC upper bound already $\sim 3 \times$ SM value ... 

[G. Raven @ Lepton–Photon 2011, LHCb-CONF-2011-047]
The Limiting Factor for the Measurement:

- The analysis of $B^0_s \rightarrow \mu^+\mu^-$ relies on normalization channels:

  \[
  \text{BR}(B^0_s \rightarrow \mu^+\mu^-) = \text{BR}(B_q \rightarrow X) \frac{\epsilon_X N_{\mu\mu} f_q}{\epsilon_{\mu\mu} N_X f_s}
  \]

  - $\epsilon$ 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: $f_s/f_d$ is the major source of uncertainty:

  $\Rightarrow$ “boring” non-perturbative, hadronic parameter ...

- New method: use non-leptonic $B$ decays to determine $f_s/f_d$ ...

  $\Rightarrow$ $U$-spin-related $\bar{B}^0_s \rightarrow D^+_s \pi^-, \bar{B}^0_d \rightarrow D^+K^-$ system:

  [R.F., Nicola Serra & Niels Tuning (2010)]
Prime examples for “factorization” (but so far no application ...) ⇒

Ratio of branching ratios can be calculated:

- Non-fact. \( SU(3) \)-breaking corrections: tiny (constrainted through data).
- Factorizable \( SU(3) \)-breaking corrections:
  → form-factor ratio \([\text{QCD sum rules } \oplus \text{lattice QCD (in progress)}]\
  \[
  \Rightarrow \frac{f_s}{f_d} = \frac{N_s}{N_d} \times \frac{\epsilon(\bar{B}_s^0 \to D^+ K^-)}{\epsilon(\bar{B}_d^0 \to D^+ \pi^-)} \times \frac{\text{BR}(\bar{B}_d^0 \to D^+ K^-)}{\text{BR}(B_s \to D_s^+ \pi^-)}
  \]
  - \( f_s, f_d \): experiment
  - \( \epsilon, \text{BR} \): theory

Niels Tuning @ Beauty 2011

[\text{LHCb}, \text{arXiv:1106.4435 [hep-ex]} \rightarrow \text{PRL}]
• Resulting NP Reach at LHCb through New Method for \( f_s/f_d \):

→ contours for the detection of a \( 5\sigma \) NP signal (“toy” study):

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

[R.F., N. Serra & N. Tuning (2010)]
Various

other

Interesting Topics ...
Examples

• **Charm physics:**  \( D^0 \rightarrow K^+K^- \), ...
  
  – While FCNCs in the \( B \) system are sensitive to new effects in the up sector, charm physics probes the down sector (\( b, s, d \) in SM loops)! 
  
  – \( D^0-\bar{D}^0 \) mixing seen in the ball park of the SM, but NP could be hiding there: we have to struggle with long-distance QCD effects. 
  
  – Interesting NP probe: search for CP-violating effects, which are tiny in the SM but could be enhanced through NP!

• **Search for lepton flavour violation:**  \( B_{d,s}^0 \rightarrow e^\pm\mu^\mp, B_{d,s}^0 \rightarrow \mu^\pm\tau^\mp \)
  
  – In the SM such processes are forbidden!
  
  – However, they may arise in NP scenarios, such as SUSY. 
  
  – Studies complement other searches of this phenomenon such as by means of \( \mu \rightarrow e\gamma, \tau \rightarrow \mu\gamma, \tau \rightarrow \mu\mu\mu, \ldots \)

Will we eventually see signals?
Conclusions & Outlook
Where Do We Stand in $B$ Physics?

- **Tremendous progress in $B$ physics in the last decade:**
  
  Fruitful interplay between *theory $\oplus$ experiment*
  
  - $e^+e^-$ $B$ factories: have produced $\sum O(10^9)$ $B\bar{B}$ pairs;
  - Tevatron: first pioneering $B_s$ results.

  $\rightarrow$ *Data agreed globally with CKM, but also a few potential deviations*

- **Towards new frontiers in $B$ physics:**
  
  LHC $\rightarrow$ already many results:
  
  - Full exploitation of the $B_s$ physics potential has started!
  - First studies of CP violation: $B^0_s \rightarrow J/\psi\phi$, ...
  - New analyses of rare decays: $B^0_s \rightarrow \mu^+\mu^-$, $B^0_d \rightarrow K^{*0}\mu^+\mu^-$, ...

- **Still no signals for New Physics (as from the direct searches):**
  
  - Impressive (also frustrating ...), but we are still at the beginning.
  - We will continue to see more and more precise measurements ...
An Optimistic Scenario: If Nature is Kind (!?) ...

• First unambiguous signs for NP @ LHC in the flavour sector:
  - Could eventually emerge @ LHCb as CP violation in $B_s^0 \rightarrow J/\psi\phi$.
  - Would imply *new sources of CP violation!*
  - Study correlations with observables provided by other $B$ decays.

  $\rightarrow$ **NP reach limited by precision**

• Ideally, NP signals would be complemented by collider physics:
  - Direct signals of new particles @ ATLAS and CMS ($\oplus$ Tevatron).
  - Measure masses, couplings of new particles (e.g. $Z'$ bosons, SUSY).
  - Flavour-physics observables determine then the new flavour- and CP-violating structures (NP particle masses, couplings important input).

  $\rightarrow$ **NP reach limited by the *energy* of the LHC (or ILC, CLIC, ...)**

• LHC data collected so far: $\Rightarrow$ *prepare to deal with smallish NP effects*...