Sensitivities to the $B_s^0 - \overline{B_s^0}$ Mixing Parameters using $\bar{b} \rightarrow \bar{c}c\bar{s}$ Quark Transitions at LHCb

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- $B_s^0 - \overline{B_s^0}$ Mixing
- Physics Motivations
- Likelihood, Physics Models
- Expected Sensitivities & Conclusions
The $B_s^0 \overline{B_s^0}$ system will serve to test the Standard Model (SM) description of CP violation, based on the CKM picture

✶ The $\hat{V}_{\text{CKM}}$ matrix contains 4 independent weak phases $\beta^{(bd)} \equiv \beta_d$, $\gamma^{(bd)} \equiv \gamma_d$, $\beta^{(sd)} \equiv \chi'$ and $\beta^{(bs)} \equiv \beta_s \equiv \chi$

✶ These phases are in what we are interested in a CP-violating experiment

✶ The squashed $(bs)$ triangle is relevant for the $B_s^0$ system

\[ V_{ub}^*V_{us} + V_{cb}^*V_{cs} + V_{tb}^*V_{ts} = 0, \quad \beta^{(bs)} \equiv \arg \left( -V_{cb}V_{cs}^*/V_{tb}V_{ts}^* \right) \]

where $V_{tb}^*V_{ts}$ controls $B_s^0 - \overline{B_s^0}$ oscillations

✶ The $B_s^0 - \overline{B_s^0}$ weak mixing phase $\phi_s$ is expected to be small in the SM

\[ \phi_s \equiv 2 \arg [V_{ts}^*V_{tb}] \approx -2\lambda^2 \eta \approx -2\chi \sim \mathcal{O}(-0.04) \]

where $\lambda \equiv \sin(\theta_C)$ and $\eta$ are Wolfenstein's parameters
$b \rightarrow \bar{c}c\bar{s}$ Quark Transitions

- $B_s^0$ decays into CP self-conjugate final states caused by $b \rightarrow \bar{c}c\bar{s}$ quark-level transitions
- $B_s^0 \rightarrow J/\psi\phi$: admixture of CP eigenstates ($\eta_{J/\psi\phi} = +1, -1, +1$)
- $B_s^0 \rightarrow \eta_c\phi, B_s^0 \rightarrow J/\psi\eta(')$: pure CP-even eigenstates

Decays dominated by only one CKM phase

$$\arg[V_{cb}^* V_{cs}] \equiv -\phi_D$$ (penguin diagrams suppressed)

Due to the mixing, the flavor states $B_s^0\bar{B}_s^0$ can either remain unchanged and decay to $f$, or oscillate into each other, ...

- "Mixing-induced" CP violation arises from a phase mismatch ($\phi_{CKM}$) between the weak mixing phase $\phi_s \equiv 2\arg[V_{ts}^* V_{tb}]$ and the tree phase $\phi_D \equiv \arg[V_{cb} V_{cs}^*]$

$$\phi_{CKM} = \phi_s - 2\phi_D \approx \phi_s \neq 0, \pi$$

- $\phi_s \approx -2\chi \leftrightarrow$ strange counterpart of $\sin(2\beta_d)$ measurement for $B_d^0$ ($\phi_d \approx 2\beta_d$)
The study of CP violation implies the measurement of the time-dependent decay asymmetry $A_{\text{CP}}^{\text{obs}}(t)$ between the $\bar{B}_s^0$ and the $B_s^0$

$$A_{\text{CP}}^{\text{obs}}(t) = \frac{R\left(\bar{B}_s^0(t) \to f\right) - R\left(B_s^0(t) \to f\right)}{R\left(B_s^0(t) \to f\right) + R\left(\bar{B}_s^0(t) \to f\right)}$$

with $t$ the proper time, $R$ the observed decay rates and $f = \bar{f}$

When a signal $B$ is observed, we need to know the initial flavor of the reconstructed mesons ⇒ flavor tagging

- **opposite-side** tagging: identify the $b$-hadron containing the other $b$

- **same-side** tagging: use the companion of the $b$ quark in the signal $B$

The tagging procedure does not always give an answer: tagging efficiency $\varepsilon_{\text{tag}}$

Even if there is a tag, our identification could be incorrect: wrong tag $\omega$

⇒ The tagging will dilute the theoretical asymmetry $A_{\text{CP}}^{\text{th}}(t)$ with a factor $D$

$$A_{\text{CP}}^{\text{obs}}(t) = D \cdot A_{\text{CP}}^{\text{th}}(t)$$

which reduces to $D = (1 - 2\omega)$ for a perfect resolution and no background
Physics Motivations of $b \to c\bar{c}\bar{s}$ Transitions

- The mixing-induced CP asymmetry for a given CP eigenstate (with eigenvalue $\eta_f$) directly measures $\phi_s$ (tree phase $\phi_D \approx 0$)

$$A_{CP}^{th}(t) = \frac{-\eta_f \sin(\phi_s) \sin(\Delta M_s t)}{\cosh(\frac{\Delta \Gamma_s t}{2}) - \eta_f \cos(\phi_s) \sinh(\frac{\Delta \Gamma_s t}{2})}$$

where $\Delta M_s \equiv M_H - M_L$ and $\Delta \Gamma_s \equiv \Gamma_L - \Gamma_H$ are the mass and decay width differences of the physical (mass) eigenstates $|B_{L/H}\rangle = p |B_s^0\rangle \pm q |\bar{B_s^0}\rangle$

- Physics Motivations: measure the mixing parameters
  - extract $\Delta M_s \sim O(20)\,\text{ps}^{-1}$ and $\Delta \Gamma_s / \Gamma_s \sim O(10\%)$, with $\Gamma_s \equiv (\Gamma_H + \Gamma_L)/2$ the average decay width ($\tau_{B^0_s} = 1/\Gamma_s = 1.46\,\text{ps}$)
  - probe the $B^0_s - \bar{B}^0_s$ weak mixing phase $\phi_s$, expected to be small in the SM $\sim O(-0.04)$

$\Rightarrow$ $B^0_s$ system represents a prime candidate for the discovery of New Physics

- SUSY contributions (mainly induced by gluino exchange) to the $B^0_s - \bar{B}^0_s$ transitions could drastically change the SM predictions (hep-ph/0311361):

$$\sin(\phi_s) \sim O(-1), \Delta M_s = (10 - 10^4)\,\text{ps}^{-1}$$
The sensitivities of LHCb to the CP $B_s^0$ observables are assessed by the use of fast toy Monte Carlo (MC) experiments using

- $B_s^0 \rightarrow J/\Psi(\mu^+\mu^-)\phi(K^+K^-)$
- $B_s^0 \rightarrow \eta_c(2\pi 2K, 4\pi)\phi(K^+K^-)$
- $B_s^0 \rightarrow J/\Psi(\mu^+\mu^-)\eta(\gamma\gamma)$

The parameterizations used are obtained from the study of fully simulated and reconstructed MC events (see talk of Benjamin Carron)

- The computed per-event lifetime error $\sigma_t$ is used in the fast simulation such that an experimental uncertainty is assigned to each generated event
- The tagging efficiency $\varepsilon_{tag}$ and the mistag probability $\omega$ are taken from the full MC

For $B_s^0 \rightarrow J/\psi\phi$, the so-called transversity angle $\theta_{tr}$ is introduced to take into account the angular distribution of the two vectors in the final state

Physics parameters: extracted using an “unbinned extended maximum” likelihood fit to the proper time and mass distributions (and to $\cos(\theta_{tr})$ for $J/\psi\phi$)

The fit is simultaneously maximized with the control sample $B_s^0 \rightarrow D_s^-\pi^+$ which allows the determination of $\Delta M_s$, $\omega$ and $\Delta \Gamma_s$
Likelihood (1)

\[ \mathcal{L} = \prod_{i \in B_0^s \rightarrow f} N_{\text{obs}}^i \left[ f_{\text{sig}}(m^i) R_{\text{sig}}(t^i_{\text{rec}}, \sigma^i_t) + (1 - f_{\text{sig}}(m^i)) R_{\text{bkg}}(t^i_{\text{rec}}) \right] \]

- Sig and bkg probabilities \((f_{\text{sig}}, f_{\text{bkg}})\) of an event are based on its reconstructed mass
  - gaussian shape for the signal
  - exponential shape for the background

\( B_0^s \rightarrow \eta_c \phi \) mass distribution
  (with \( \mathcal{L} \) fit projection superimposed)

Annual yield = 3k
\( B/S = 0.8 \)
Mass resolution \( \sigma_{B_0^s} = 13\text{MeV}/c^2 \)
True \( B_0^s \) mass = 5369.6MeV/c^2
Bkg \( \mu_{\text{bkg}} = -0.6\text{MeV}/c^2 \)
Likelihood (2)

\[
\mathcal{L} = \prod_{i \in B^0_s \rightarrow f}^{N_{\text{obs}}} \left[ f^{\text{sig}}(m^i) R^{\text{sig}}(t^i_{\text{rec}}, \sigma^i_t) + (1 - f^{\text{sig}}(m_i)) R^{\text{bkg}}(t^i_{\text{rec}}) \right]
\]

\[ R^{\text{sig}}: \text{observed signal decay rate} \]

\[ R^{\text{sig}}(t^i_{\text{rec}}, \sigma^i_t | \alpha) = A(t^i_{\text{true}}) \left[ (1 - \omega) \Gamma_{B \rightarrow f}(t^i_{\text{true}}, \alpha) + \omega \Gamma_{\bar{B} \rightarrow f}(t^i_{\text{true}}, \bar{\alpha}) \right] \]

\[ \otimes \text{Res}(t^i_{\text{rec}} - t^i_{\text{true}}, s^1 \sigma^i_t, \mu^1 \sigma^i_t) \]

\[ \Gamma: \text{analytical decay rates} \]

\[ \bar{\alpha} = (\Delta M_s, \Delta \Gamma_s, \ldots): \text{physics parameters} \]

\[ \text{Res}: \text{Gaussian resolution scaled with } \sigma^i_t \]

\[ A: \text{flat acceptance} \]

\[ R^{\text{bkg}}: \text{background decay rate, exponential shape} \]

\[ \text{For } B^0_s \rightarrow D^- \pi^+, \tau_{\text{bkg}} \approx \tau_{B^0_s}/2 \]

\[ \text{For } B^0_s \rightarrow J/\psi \phi, \text{the signal likelihood is given by the sum of the CP-even and CP-odd components, including the corresponding } \theta_{\text{tr}} \text{ contribution} \]
$B_s^0 \rightarrow \eta_c \phi$ Proper Time – Full Monte Carlo Simulation

$B_s^0$ proper time $\tau$ resolution:

$\sigma \sim 33$ fs

$\tau = m_{B_s^0} \vec{p}_{B_s^0} \cdot \vec{L} / |\vec{p}_{B_s^0}|^2$

$\vec{L} = \vec{x}_S - \vec{x}_P$ decay length

Pull: $\sim 1$

$\sigma_\tau$: computed per-event error on $\tau$

using the tracks covariance matrices

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Sensitivities to the $D_{s}^{0}-\bar{D}_{s}^{0}$ Mixing Parameters using $\bar{b} \rightarrow \bar{c}c\bar{s}$ Quark Transitions at LHCb (9)
Physics Model: $B_s^0 \rightarrow \eta_c \phi$, $B_s^0 \rightarrow J/\psi \eta$

- $f = \eta_c \phi, J/\psi \eta$ CP-even eigenstates: $(CP) |f\rangle = \eta_f |f\rangle$, $\eta_f = +1$

- Observed transition rates of initially pure $B_s^0$ and $B_s^0$ states (perfect resolution, no bkg)

\[
R \left( B_s^0(t) \rightarrow f \right) = |A_f(0)|^2 \frac{e^{-\Gamma_s t}}{2} \times \\
\left[ \cosh \left( \frac{\Delta \Gamma_s t}{2} \right) - \eta_f \cos(\phi_s) \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) + D \eta_f \sin(\phi_s) \sin(\Delta M_s t) \right]
\]

\[
R \left( \overline{B_s^0}(t) \rightarrow f \right) = |A_f(0)|^2 \frac{e^{-\Gamma_s t}}{2} \times \\
\left[ \cosh \left( \frac{\Delta \Gamma_s t}{2} \right) - \eta_f \cos(\phi_s) \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) - D \eta_f \sin(\phi_s) \sin(\Delta M_s t) \right]
\]

- $A_f(0) \equiv A \left( B_s^0 \rightarrow f \right)$: instantaneous decay amplitude

- $D = (1 - 2\omega)$: dilution factor

- We get the corresponding analytical transition rates $\Gamma$ by setting $\omega = 0$ (i.e. no wrong tag) in the observed decay rates $R$
$B_s^0 \to \eta_c \phi$, $B_s^0 \to J/\psi \eta$ Decay Rates

Decay rates for $B_s^0 \to \eta_c \phi$ and $B_s^0 \to J/\psi \eta$ in case of a perfect resolution

- Blue: initial pure $\overline{B}_s^0$, Red: initial pure $B_s^0$
- $\Delta M_s = 20 \text{ps}^{-1}$, $\Delta \Gamma_s / \Gamma_s = 0.1$, $\sin(\phi_s) = -0.1$ (nominal $\sin(\phi_s) = -0.04$)

No wrong tag $\omega$ $\to$ perfect tagging

With wrong tag $\omega = 0.3$ $\to$ wiggles are flattened

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Sensitivities to the $D_s^0 - \overline{D}_s^0$ Mixing Parameters using $\bar{b} \to \bar{c} s \bar{s}$ Quark Transitions at LHCb (11)

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\( B_s^0 \rightarrow \eta_c\phi \), \( B_s^0 \rightarrow J/\psi\eta \): Asymmetry

Asymmetry \( A_{\text{CP}}(t) \) for \( B_s^0 \rightarrow \eta_c\phi \) and \( B_s^0 \rightarrow J/\psi\eta \) in case of a perfect resolution

- Solid green: \( A_{\text{CP}} \) with no mistag \( \omega=0 \)
- Dotted black: envelope due to non-zero \( \Delta \Gamma_s \)
- \( \Delta M_s = 20 \text{ps}^{-1} \), \( \Delta \Gamma_s / \Gamma_s = 0.1 \), \( \sin(\phi_s) = -0.04 \) (nominal parameters)

- Dashed blue: \( A_{\text{CP}} \) with \( \omega = 0 \) and \( \Delta \Gamma_s = 0 \)
- \( \rightarrow \) oscillation amplitude given by \( A_{\text{mix}} = -\eta_f \sin(\phi_s) \)

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Sensitivities to the \( D_s^0-B_s^0 \) Mixing Parameters using \( \bar{b} \rightarrow \bar{c}\bar{c}\bar{s} \) Quark Transitions at LHCb (12)

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Physics Model: $B^0_s \rightarrow J/\psi \phi$

- In $B^0_s \rightarrow J/\psi \phi$, the final state $f$ is an admixture of CP eigenstates
  - $f = 0, ||$: CP-even configuration, $\eta_f = +1$
  - $f = \perp$: CP-odd configuration, $\eta_f = -1$
- Linear polarization amplitudes corresponding to the different configurations are introduced (hep-ph/9804293, hep-ph/0012219): $A_f(t)$, for $f = 0, ||, \perp$
- The fraction of CP-odd decays is defined as $R_T \equiv |A_{\perp}(0)|^2 / \sum_{i=0,||,\perp} |A_f(0)|^2 \sim O(0.2)$
- Each of the $|A_f(t)|^2$ corresponds to an ordinary decay rate of a pure CP eigenstate for a $\bar{b} \rightarrow \bar{c}c\bar{s}$ transition (for a given $\eta_f$ eigenvalue)
- The one-angle $\theta_{tr}$ distribution enables us to disentangle the different CP eigenstates

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

The transversity angle $\theta_{tr}$ corresponds to the angle between the positive lepton from the $J/\Psi$ and the $\phi$ decay plane, in the $J/\Psi$ rest frame.
Physics Model: $B^0_s \rightarrow D^{-}_s \pi^+$

- The decay $B^0_s \rightarrow D^{-}_s \pi^+$ is flavor specific in which a single tree diagram contributes
  - $B^0_s$ decays instantaneously as $f = D^{-}_s \pi^+$ and $\bar{B}^0_s$ instantaneously as $D^+ D^-$
  - No expected CP violation in $B^0_s \rightarrow D^{-}_s \pi^+$
- Analytical decay rates with a possible mistag probability $\omega$

$$
R_f(t) = R_{B^0_s \rightarrow f}(t) = |A_f(0)|^2 \frac{e^{-\Gamma_s t}}{2} \left[ \cosh \left( \frac{\Delta \Gamma_s t}{2} \right) + (1 - 2\omega) \cos (\Delta M_s t) \right]
$$

$$
\bar{R}_f(t) = R_{\bar{B}^0_s \rightarrow f}(t) = |A_f(0)|^2 \frac{e^{-\Gamma_s t}}{2} \left[ \cosh \left( \frac{\Delta \Gamma_s t}{2} \right) - (1 - 2\omega) \cos (\Delta M_s t) \right]
$$

- Observed flavor asymmetry $A^{obs}_f$

$$
A^{obs}_f(t) = D \cdot A^{th}_f(t)
$$

with the theoretical flavor asymmetry $A^{th}_f$

$$
A^{th}_f(t) \equiv \frac{\bar{R}_f(t) - R_f(t)}{\bar{R}_f(t) + R_f(t)} = -\frac{\cos (\Delta M_s t)}{\cosh \left( \frac{\Delta \Gamma_s t}{2} \right)}
$$

where the dilution factor $D$ reduces to $D = (1 - 2\omega)$ in case of a perfect resolution
- $B^0_s \rightarrow D^{-}_s \pi^+$ allows the extraction of the parameters $\Delta M_s$, $\Delta \Gamma_s$ and $\omega$
$B_s^0 \rightarrow D_s^-\pi^+$ Decay Rates

$B_s^0 \rightarrow D_s^-\pi^+$ decay rates $\Gamma(t)$ in case of a perfect resolution

- Rates → Blue: initial pure $\overline{B}_s^0$, Red: initial pure $B_s^0$, Dashed green: no tag ($\omega = 0.5$)
- $\Delta M_s = 20\text{ps}^{-1}$, $\Delta \Gamma_s/\Gamma_s = 0.1$ (nominal parameters)

No wrong tag $\omega = 0$

With wrong tag $\omega = 0.3$

$\rightarrow \omega \neq 0$: raise of $\overline{B}_s^0$ and $B_s^0$ starting points
$\rightarrow$ attenuation of the oscillations
Toy Monte Carlo Setup

For every signal channel, events are generated with the following physics parameters:

- $\Delta M_s = 20 \text{ps}^{-1}$
- $\Delta \Gamma_s / \Gamma_s = 0.1$
- $1 / \Gamma_s = 1.46 \text{ps}$
- $\sin(\phi_s) = -0.04$
- $R_T = 0.2$, for $B_s^0 \to J/\psi \phi$
- $\omega$ and $\varepsilon_{\text{tag}}$ taken from the full MC, e.g. $\omega = 30\%$ and $\varepsilon_{\text{tag}} = 55\%$ for $B_s^0 \to \eta_c \phi$

The sig/bkg probabilities were obtained using parameterizations from the full MC.

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>$N_s$</th>
<th>$B/S$</th>
<th>Window [MeV/$c^2$]</th>
<th>$\sigma_{B_s^0}$ [MeV/$c^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0 \to J/\Psi (\mu^+ \mu^-) \phi (K^+ K^-)$</td>
<td>100 k</td>
<td>0.3</td>
<td>$\pm 50$</td>
<td>15</td>
</tr>
<tr>
<td>$B_s^0 \to \eta_c (2\pi 2K, 4\pi) \phi (K^+ K^-)$</td>
<td>3 k</td>
<td>0.8</td>
<td>$\pm 45$</td>
<td>13</td>
</tr>
<tr>
<td>$B_s^0 \to J/\Psi (\mu^+ \mu^-) \eta (\gamma \gamma)$</td>
<td>7 k</td>
<td>1.6</td>
<td>$\pm 90$</td>
<td>33</td>
</tr>
<tr>
<td>$B_s^0 \to D_s^- \pi^+$</td>
<td>80 k</td>
<td>0.5</td>
<td>$\pm 50$</td>
<td>13</td>
</tr>
</tbody>
</table>

$B/S$: 90% CL upper limit on the background level from inclusive $b\bar{b}$ events (dominant source)

For each signal channel, 1000 toy experiments each corresponding to one year of data taking at LHCb are generated.
Expected Sensitivities & Conclusions

Expected statistical precisions for one year of LHCb data taking (preliminary)

<table>
<thead>
<tr>
<th>Sensitivity</th>
<th>$\sigma(\Delta M_s)$ [ps$^{-1}$]</th>
<th>$\sigma(\Delta \Gamma_s/\Gamma_s)$</th>
<th>$\sigma(\phi_s)$ [rad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0_s \to J/\Psi(\mu^+\mu^-)\phi(K^+K^-)$</td>
<td>0.024</td>
<td>0.018</td>
<td>0.064</td>
</tr>
<tr>
<td>$B^0_s \to \eta_c(2\pi 2K, 4\pi)\phi(K^+K^-)$</td>
<td>0.017</td>
<td>0.031</td>
<td>0.153</td>
</tr>
<tr>
<td>$B^0_s \to J/\Psi(\mu^+\mu^-)\eta(\gamma\gamma)$</td>
<td>0.023</td>
<td>0.024</td>
<td>0.154</td>
</tr>
</tbody>
</table>

Combined $\phi_s$ sensitivity: $B^0_s \to \eta_c\phi$, $B^0_s \to J/\psi\eta$ 0.109

Combined $\phi_s$ sensitivity: $B^0_s \to \eta_c\phi$, $B^0_s \to J/\psi\eta$, $B^0_s \to J/\psi\phi$ 0.055

The following $\bar{b} \to \bar{c}c\bar{s}$ decays to pure CP eigenstates are currently under study at LHCb to increase the sensitivity to $\phi_s$

$\star$ $B^0_s \to J/\Psi(\mu^+\mu^-)\eta(\pi^+\pi^-\pi^0)$

$\star$ $B^0_s \to J/\Psi(\mu^+\mu^-)\eta'(\pi^+\pi^-\eta(\gamma\gamma))$

$\star$ $B^0_s \to J/\Psi(\mu^+\mu^-)\eta'(\pi^+\pi^-\gamma)$

Statistical sensitivity to $\phi_s$ after five years of LHCb data taking

$\to \sigma(\phi_s) \sim 0.025$, with $\phi_s \sim \mathcal{O}(-0.04)$ in the SM

$\star$ if $\phi_s$ (and/or $\Delta M_s$) large compared to the SM expectation $\to$ New Physics (SUSY, ...)

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