MEASUREMENTS OF $B_s$ LIFETIMES
AT LHCb

Anna Phan
(Syracuse University)
on behalf of the LHCb collaboration
• Mixing and decay described by: \( \frac{i}{\hbar} \frac{d}{dt} \begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix} = \begin{pmatrix} M_{11} - \Gamma_{11} / 2 & M_{12} - i\Gamma_{12} / 2 \\ M_{12}^* - i\Gamma_{12}^* / 2 & M_{22} - i\Gamma_{22} / 2 \end{pmatrix} \begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix} \)

• Diagonalising the mixing matrix results in:
  - two eigenstates: \( |B_{sH}\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle, |B_{sL}\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle \) where \( |p|^2 + |q|^2 = 1 \)
  - with separate masses: \( m_H, m_L \) where \( \Delta m_s = m_H - m_L \) and \( m_s = (m_H + m_L) / 2 = M_{11} = M_{22} \)
  - and different lifetimes:
    \( \tau_H = 1 / \Gamma_H, \tau_L = 1 / \Gamma_L \) where \( \Delta \Gamma_s = \Gamma_L - \Gamma_H \) and \( \Gamma_s = (\Gamma_L + \Gamma_H) / 2 = \Gamma_{11} = \Gamma_{22} \)

LIFETIMES

- Effective lifetime is the lifetime measured by describing the untagged decay time distribution with a single exponential
  - In CP-eigenstates, is sensitive to $\Delta \Gamma_s$ and $\phi_s$ (mixing induced CP-violating phase)
    - $B_s \rightarrow K^+K^-$ is CP-even
    - $B_s \rightarrow J/\psi f_0(980)$ is CP-odd
    - $\Delta \Gamma_s$, $\Gamma_s$ and $\phi_s$ can be measured from analysis of $B_s \rightarrow J/\psi \phi$
    - All lifetime results use 1 fb$^{-1}$ of data recorded in $pp$ collisions at $\sqrt{s} = 7$ TeV

\[ \tau_{J/\psi f_0} = 1.70 \text{ ps } \pm 1\% \]
\[ \tau_{K^+K^-} = 1.44 \text{ ps } \pm 1\% \]
\[ \Delta \Gamma_s^{SM}/\Gamma_s = 0.133 \pm 0.032 \]

**B_s \rightarrow J/\psi\phi**

**INTRODUCTION**

- **B_s \rightarrow J/\psi\phi** is a pseudoscalar to vector vector decay:
  
  \[
  B_s \rightarrow J/\psi(\mu^+\mu^-) \quad \phi(K^+K^-)
  \]
  
  \[
  \text{Spin } = 0 \quad \text{Spin } = 1 \quad \text{Spin } = 1
  \]

- From spin conservation, the possible orbital angular momenta for the final state in the B_s rest frame are: L = 0, 1, 2

- CP-eigenvalues of the final state are:
  
  \[
  \text{CP}(J/\psi) \cdot \text{CP}(\phi) \cdot (-1)^L = +1, -1, +1
  \]
  
  → The final state is an admixture of CP-even (L=0,2) and CP-odd (L=1)

- Angular analysis is used to disentangle amplitudes
  
  - Fit is sensitive to \(\Delta \Gamma_s\) and \(\Gamma_s\)

*For more information about the analysis of this decay, see G. Cowan’s talk later this afternoon “Measurement of \(\phi_s\) at LHCb, Room 213, 16:15”*
• $B_s \rightarrow J/\psi \phi$ can be used to determine the sign of $\Delta \Gamma_s$

• Split data in bins of $m(K^+K^-)$
  - In each bin, measure the fraction of S-wave ($\delta_S$) and P-wave ($\delta_\perp$)
  - S-wave phase varies slowly across $\phi(1020)$ mass resonance while P-wave phase increases rapidly, so that the difference falls rapidly
  - Calculate the difference $\delta_{S \perp} = \delta_S - \delta_\perp$ in data for $\Delta \Gamma_s > 0$ and $\Delta \Gamma_s < 0$
    → The physical solution is the one where $\delta_{S \perp}$ falls rapidly

$\Delta \Gamma_s > 0$ preferred at $4.7\sigma$
Heavier $B_s$ meson lives longer

$LHCb$ $\Delta \Gamma_s < 0$

$LHCb$ $\Delta \Gamma_s > 0$

$B_s \rightarrow J/\psi\phi$ RESULTS

$\Gamma_s = 0.6580 \pm 0.0054 \pm 0.0066 \text{ ps}^{-1}$

$\Delta \Gamma_s = 0.116 \pm 0.018 \pm 0.006 \text{ ps}^{-1}$

First direct observation of a non-zero $\Delta \Gamma_s > 5\sigma$

[ICHEP, July 7, 2012]

Anna Phan – $B_s$ Lifetimes at LHCb

Slide 6 of 13
**B_s \rightarrow J/\psi f_0(980)**

**INTRODUCTION**

- **J/\psi f_0(980)** is a CP-odd eigenstate
  - Measured $\phi_s$ limits $\cos \phi_s > 0.99$
  - Selection provides $> 99.4\%$ CP-odd sample
  - $\tau_{J/\psi f_0}$ can be interpreted as $\tau_H$
- Lifetime measured relative to $B^0 \rightarrow J/\psi K^{*0}$
  - Decays have very similar kinematics
  - Compare signal yields in bins of decay time
  - Fit for width difference: $\Gamma_{J/\psi f_0} - \Gamma_{J/\psi K^*}$
  - Use well known $B^0$ lifetime to extract $B_s$ lifetime

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[**LHCb-PAPER-2012-017**, arXiv: 1207.0878]
**B_s \rightarrow J/\psi f_0(980) RESULTS**

\[ \Gamma_{J/\psi f_0} - \Gamma_{J/\psi K} = 0.070 \pm 0.014 \pm 0.001 \text{ ps}^{-1} \]

\[ \tau_{J/\psi f_0} = 1.700 \pm 0.040 \pm 0.026 \text{ ps} \]

\[ \Gamma_H = 0.588 \pm 0.014 \pm 0.009 \text{ ps}^{-1} \]

(additional systematic from \( \Gamma_{J/\psi f_0} \) due to non-zero \( \phi_s \))

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[LHCb-PAPER-2012-017, arXiv: 1207.0878]
\( B_s \rightarrow K^+K^- \) INTRODUCTION

- **K^+K^- is a CP-even eigenstate**
  - Dominantly a penguin decay
  - Doubly Cabibbo suppressed tree decay
- \( \tau_{KK} \) can only be interpreted as \( \tau_L \) with the assumption \( |A_{\Delta\Gamma}| = 1 \)

- Analysis uses minimal lifetime biasing selection
  - No selections on lifetime biasing variables like decay time or impact parameters
  - Trigger and event selection based on neutral networks primarily using particle identification
  - Flat acceptance verified on simulation
  - Used a different analysis technique
\[ \tau_{KK} = 1.468 \pm 0.046 \pm 0.006 \text{ ps} \]
**My Combination of LHCb Results**

**Theory**

\[ \Delta \Gamma_s = 0.087 \pm 0.021 \text{ ps}^{-1} \]

[Lenz and Nierste, arXiv:1102:4274]

\[ \Gamma_s = 0.6580 \pm 0.0085 \text{ ps}^{-1} \]

\[ \Delta \Gamma_s = 0.116 \pm 0.019 \text{ ps}^{-1} \]

[LHCB-CONF-2012-002]

\[ \Gamma_{J/\psi} = 0.588 \pm 0.017 \text{ ps}^{-1} \]

[LHCB-PAPER-2012-017]

\[ \Gamma_{K^+K^-} = 0.681 \pm 0.021 \text{ ps}^{-1} \]

[LHCB-PAPER-2012-013]

**Combined:** \[ \Gamma_s = 0.652 \pm 0.007 \text{ ps}^{-1} \]

\[ \Delta \Gamma_s = 0.111 \pm 0.016 \text{ ps}^{-1} \]
MY COMBINATION WITH OTHER RESULTS

DØ: $B_s \rightarrow J/\psi \phi$
$\Gamma_s = 0.693 \pm 0.018 \text{ ps}^{-1}$
$\Delta \Gamma_s = 0.163 \pm 0.065 \text{ ps}^{-1}$

CDF: $B_s \rightarrow J/\psi \phi$
$\Gamma_s = 0.654 \pm 0.012 \text{ ps}^{-1}$
$\Delta \Gamma_s = 0.075 \pm 0.036 \text{ ps}^{-1}$

CDF: $B_s \rightarrow J/\psi f_0(980)$
Assuming $\phi_s = 0$
$\Gamma_H = 0.588 \pm 0.042 \text{ ps}^{-1}$

CDF: $B_s \rightarrow D_s \pi$
$\tau_{D_s \pi} = 1.518 \pm 0.049 \text{ ps}$

Combined: $\Gamma_s = 0.657 \pm 0.005 \text{ ps}^{-1}$
$\Delta \Gamma_s = 0.109 \pm 0.014 \text{ ps}^{-1}$

Combined: 39% CL for the regions
68% CL for the bands
**CONCLUSIONS**

- LHCb has performed measurements of effective $B_s$ lifetimes in various decay modes
  - $B_s \rightarrow J/\psi \phi$
    - $\Delta\Gamma_s$ and $\Gamma_s$ determined through angular analysis
    - Found $\Delta\Gamma_s > 0$, implying that the heavy mass eigenstate lives longer
  - $B_s \rightarrow J/\psi f_0(980)$
    - Effective lifetime measured relative to $B^0 \rightarrow J/\psi K^*0$
    - Most precise measurement to date
  - $B_s \rightarrow K^+K^-$
    - Effective lifetime measured using specialised minimal bias selection
    - Most precise measurement to date
  - Other $B_s$ lifetime measurements in progress
    - So stay tuned…

$$
\Gamma_s = 0.6580 \pm 0.0054 \pm 0.0066 \text{ ps}^{-1} \\
\Delta\Gamma_s = 0.116 \pm 0.018 \pm 0.006 \text{ ps}^{-1} \\
\tau_{J/\psi f_0} = 1.700 \pm 0.040 \pm 0.026 \text{ ps} \\
\Gamma_H = 0.588 \pm 0.014 \pm 0.009 \text{ ps}^{-1} \\
\tau_{KK} = 1.468 \pm 0.046 \pm 0.006 \text{ ps}
$$
Thank You
Global Combination

\[ \Delta \Gamma_s = 0.102 \pm 0.013 \text{ ps}^{-1} \]
\[ 1/\Gamma_s = 1.513 \pm 0.011 \text{ ps} \]
\[ \tau_L = 1.405 \pm 0.017 \text{ ps} \]
\[ \tau_H = 1.639 \pm 0.021 \text{ ps} \]
\( B_s \rightarrow J/\psi f_0(980) \) EXTRA

**Systematics on the \( B_s \rightarrow J/\psi f_0(980) \) effective lifetime [ps]**

<table>
<thead>
<tr>
<th>Source</th>
<th>Systematic Error [ps]</th>
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<tbody>
<tr>
<td>Signal model</td>
<td>0.001</td>
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<tr>
<td>Background model</td>
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<tr>
<td>Kaon PID</td>
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<tr>
<td>Acceptance slope</td>
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<td>Statistical bias</td>
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<tr>
<td>CP even fraction</td>
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<tr>
<td>( \tau(B^0) ) error propagation</td>
<td>0.009</td>
</tr>
<tr>
<td><strong>Added in quadrature</strong></td>
<td><strong>0.026</strong></td>
</tr>
</tbody>
</table>

**Systematics on the \( B_H \) lifetime [ps]**

<table>
<thead>
<tr>
<th>Source</th>
<th>Systematic Error [ps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \cos \phi_s ) minimum</td>
<td>0.002</td>
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<tr>
<td><strong>Added in quadrature with effective lifetime</strong></td>
<td><strong>0.027</strong></td>
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</tbody>
</table>

**LHCb simulation**

slope = \( 0.0125 \pm 0.0036 \) \( \text{ps}^{-1} \)
$B_s \to K^+K^-$ EXTRA

LHCb simulation
slope = $-0.00009 \pm 0.00030\, \text{ps}^{-1}$

Systematics on the $B_s \to KK$ effective lifetime [ps]

<table>
<thead>
<tr>
<th>Source</th>
<th>Value</th>
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<tbody>
<tr>
<td>Reconstruction efficiency</td>
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<td>Signal model</td>
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<td>Background model</td>
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<td>Length Scale</td>
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<td>Minimum decay Time requirement</td>
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<td>Production asymmetry</td>
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<tr>
<td><strong>Added in quadrature</strong></td>
<td><strong>0.006</strong></td>
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