Results on $b$ hadron properties in CMS: $b$ hadron lifetime measurements at $\sqrt{s} = 8$ TeV

EXA 2017, Vienna

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on behalf of the CMS collaboration

HEPHY Vienna

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Lifetime measurements of $b$ hadrons

- Precise lifetime measurements play important role in study of nonperturbative aspects of QCD
- Phenomenological description by Heavy Quark Expansion (HQE) model
  - Based on perturbative expansion of interaction of a single heavy quark with light quarks
  - Provides accurate estimates of the ratio of lifetimes for hadrons containing a heavy quark
- Some discrepancies in experimental measurements in $\tau_{B_c^+}$
• Silicon pixel and strip detector modules
• Measurement of charged particles without particle identification
• Transverse impact parameter resolution $\sim 25 - 90 \mu m$

• Drift tubes, cathode strip chambers and resistive-plate chambers
• Used in first-level, hardware based trigger
• Segments are matched to charged tracks to identify muons
• High-level trigger has access to full event information
Reconstruction of b hadrons

- Using final states with a $J/\psi$
  - $J/\psi$ candidates reconstructed by combining oppositely charged muons
- Neutral particle candidates reconstructed by combining oppositely charged tracks with appropriate mass assignments
- Candidate $b$ hadrons reconstructed by combining a $J/\psi$ candidate with tracks or reconstructed neutral particles
  - Fit to a common vertex
  - Reconstructed muons and charged tracks have to satisfy quality requirements
- Production vertex (PV) determined from fitting of reconstructed tracks
- Distance between PV and decay vertex is proper decay length $ct$

$$ct = cL_{xy} \frac{M}{p_T}$$
Lifetime measurements of $b$ hadrons at $\sqrt{s} = 8$ TeV

Reconstructed in final states with a $J/\psi$

$$\begin{align*}
B^0 &\rightarrow J/\psi K^* (892)^0 \quad \text{with} \quad K^* (892)^0 \rightarrow K^\pm \pi^\mp \\
&\quad J/\psi K_S^0 \quad \text{with} \quad K_S^0 \rightarrow \pi^+ \pi^- \\
B_s^0 &\rightarrow J/\psi \pi^+ \pi^- \\
&\quad J/\psi \phi (1020) \quad \text{with} \quad \phi (1020) \rightarrow K^+ K^- \\
\Lambda_b^0 &\rightarrow J/\psi \Lambda^0 \quad \text{with} \quad \Lambda^0 \rightarrow p \pi^- \\
B_c^+ &\rightarrow J/\psi \pi^+
\end{align*}$$

• Using 19.7 fb$^{-1}$ of data collected in 2012 from $pp$ collisions at $\sqrt{s} = 8$ TeV
$B^0_s$ measurement

- Decay rate of neutral $B^0_q$ mesons characterized by
  \[ \Gamma_q = (\Gamma_L^q + \Gamma_H^q)/2 \quad \text{and} \quad \Delta \Gamma_q = \Gamma_L^q - \Gamma_H^q \]

- $B^0$ system: $\frac{\Delta \Gamma_d}{\Gamma_d} = (-0.3 \pm 1.5)\%$

- $B^0_s$ system: $\frac{\Delta \Gamma_s}{\Gamma_s} = (12.4 \pm 1.1)\%$

$B^0_s \rightarrow J/\psi \pi^+ \pi^-$:

- $0.9240 < M(\pi^+ \pi^-) < 1.0204$ GeV
  → dominated by $f_0(980)$
  → CP-odd final state
  → $c \tau^{CP-odd}_{B^0_s} \approx 1/\Gamma_H$

$B^0_s \rightarrow J/\psi \phi(1020)$:

- Admixture of one CP-odd and two CP-even states
  → Measurement of effective lifetime $c \tau_{eff}$

- Complementary to weak mixing phase analysis

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Event selection

b hadron requirements:
  • $p_T > 13$ GeV (except for $B_S^0$)
  • $ct > 0.02$ cm

$J/\psi$ requirements:
  • $p_T > 7.9$ GeV
  • $M_{\mu\mu}$ within 0.15 GeV of world average
  • Vertex $\chi^2$ probability > 0.5 %

Track and muon requirements:
  • Track $p_T > 0.5$ GeV
  • $|\eta(\mu)| < 2.2$

Mass windows for neutral states:

<table>
<thead>
<tr>
<th>state</th>
<th>min/GeV</th>
<th>max/GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^*(892)^0$</td>
<td>0.7960</td>
<td>0.9880</td>
</tr>
<tr>
<td>$K_S^0$</td>
<td>0.4876</td>
<td>0.5076</td>
</tr>
<tr>
<td>$\pi^+\pi^-$</td>
<td>0.9240</td>
<td>1.0204</td>
</tr>
<tr>
<td>$\phi(1020)$</td>
<td>1.0095</td>
<td>1.0295</td>
</tr>
<tr>
<td>$\Lambda^0$</td>
<td>1.1096</td>
<td>1.1216</td>
</tr>
</tbody>
</table>
Data modelling and fitting

• Signal decay length distribution

\[ T(\text{ct}, \sigma_{\text{ct}} \mid \tau_B) = \left[ E(\text{ct} \mid \tau_B) \otimes R(\text{ct}, \sigma_{\text{ct}}) \right] \cdot \mathcal{E}(\text{ct}) \]

\[ E(\text{ct} \mid \tau_B) \] – Decay distribution
\[ R(\text{ct}, \sigma_{\text{ct}}) \] – Detector resolution
\[ \mathcal{E}(\text{ct}) \] – Efficiency

• Signal decay length distribution parameters obtained from three dimensional fit using

  • \( b \) hadron mass
  • \( \text{ct} \)
  • per event \( \text{ct} \) uncertainty \( \sigma_{\text{ct}} \)

• Efficiency correction obtained from fully simulated MC samples as function of \( \text{ct} \)

  Generated distribution of selected events after reconstruction
  Exponential distribution with lifetime used in generation

\[ \text{°} \text{sum of two exponentials for } B_s^0 \rightarrow J/\psi \phi(1020) \]
Exemplary fit results and efficiency

\[ B_S^0 \rightarrow J/\psi \phi(1020) \]
### Results

<table>
<thead>
<tr>
<th>channel</th>
<th>This results/µm</th>
<th>PDG*/µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C\tau_{B^0} )</td>
<td>( J/\psi K^*(892)^0 )</td>
<td>453.0 ±1.6 ±1.5</td>
</tr>
<tr>
<td></td>
<td>( J/\psi K^0 )</td>
<td>457.8 ±2.7 ±2.7</td>
</tr>
<tr>
<td>( C\tau_{B^0_s} )</td>
<td>( J/\psi\pi^+\pi^- )</td>
<td>504.3 ±10.5 ±3.7</td>
</tr>
<tr>
<td></td>
<td>( J/\psi\phi(1020) )</td>
<td>443.9 ±2.0 ±1.2</td>
</tr>
<tr>
<td>( C\tau_{\Lambda_b^0} )</td>
<td>( J/\psi\Lambda )</td>
<td>443.1 ±8.2 ±2.7</td>
</tr>
</tbody>
</table>

All results in good agreement with current world average values

*Chin. Phys. C, **40**, 100001 (2016)

†Taken from HFLAV: arXiv:1612.07233 [hep-ex]
$B_c^+$ lifetime

- $B_c^+$ weak decay
  - $b$ quark decays with $c$ quark as spectator or vice versa
  - Annihilation process predicted to contribute up to 10% of decay width

- LHCb measures longer lifetimes than D0 and CDF

<table>
<thead>
<tr>
<th>channel</th>
<th>decay length/µm</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCb: $B_c^+ \to J/\psi\pi^+$</td>
<td>154.4 ± 3.7</td>
<td>PLB 742 (2015) 29</td>
</tr>
<tr>
<td>LHCb: $B_c^+ \to J/\psi\mu^+\nu_\mu\chi$</td>
<td>152.6 ± 4.3</td>
<td>JHEP 74 (2014) 2839</td>
</tr>
<tr>
<td>CDF: $B_c^+ \to J/\psi e^+\nu_e$</td>
<td>138.8 ± 24.3</td>
<td>PRL 97, 012002</td>
</tr>
<tr>
<td>CDF: $B_c^- \to J/\psi\pi^-$</td>
<td>135.5 ± 16.5</td>
<td>PRD 87, 011101(R)</td>
</tr>
<tr>
<td>D0: $B_c^{±} \to J/\psi\pi^{±}$</td>
<td>134.3 ± 14.9</td>
<td>PRL 102, 092001</td>
</tr>
</tbody>
</table>
**$B^+_c$ lifetime measurement**

- Use precise knowledge of $B^+$ lifetime to measure $B^+_c$ lifetime

\[
\frac{N_{B^+_c}(t)}{N_{B^+}(t)} = \mathcal{R}(t) = \frac{[E(t|\tau_{B^+_c}) \otimes R(t)]\mathcal{E}(t)}{[E(t|\tau_{B^+}) \otimes R(t)]\mathcal{E}(t)}
\]

- Ratio not significantly affected by resolution

\[
\rightarrow \mathcal{R}(t) = R_\varepsilon(t) \exp(-\Delta \Gamma t) \quad \text{with} \quad \Delta \Gamma = \Gamma_{B^+_c} - \Gamma_{B^+} = \frac{1}{\tau_{B^+_c}} - \frac{1}{\tau_{B^+}}
\]

- $R_\varepsilon(t)$ - ratio of efficiency functions evaluated from MC simulation absorbing residual resolution effects

- $N_{B^+}$ and $N_{B^+_c}$ obtained from fits to data in different $ct$ bins
\[ \Delta \Gamma = 4.12 \pm 0.30 \pm 0.16 \, \text{mm}^{-1}c \]
\[ c\tau_{B_c^+} = 162.3 \pm 8.2 \pm 4.7 \pm 0.1(\tau_{B^+}) \, \mu \text{m} \]

Results in agreement with LHCb measurement
Summary

• Lifetime measurements of
  • $B^0 \rightarrow J/\psi K^*(892)^0$
  • $B^0 \rightarrow J/\psi K^0_S$
  • $B^0_S \rightarrow J/\psi \pi^+ \pi^-$
  • $B^0_S \rightarrow J/\psi \phi(1020)$
  • $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$
  • $B^+_c \rightarrow J/\psi \pi^+$

at CMS at $\sqrt{s} = 8$ TeV have been presented

• All measurements are in good agreement with current world average values
• Some measurements are already at the precision level of the current world average
• Measurement of $B^+_c$ lifetime is in agreement with recent LHCb measurements
Supplementary Material
Systematic uncertainties for neutral $b$ hadrons

Common uncertainties:
- Production vertex (PV) selection
- Detector alignment
- $ct$ resolution
- MC finite size
- Efficiency modeling
- Absolute $ct$ accuracy
- Mass modelling
- $ct$ modelling

Channel specific uncertainties:
- $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$
  - $B^+$ contamination
  - Invariant $\pi^+ \pi^-$ mass window
- $B^0 \rightarrow J/\psi K^*(892)^0$
  - $K^\pm \pi^\mp$ mass assumption for $K^*(892)^0$
- $B_s^0 \rightarrow J/\psi \phi(1020)$
  - $ct$ range
  - S-wave contamination

Combined systematic uncertainty between 1.2 - 3.7 $\mu$m for all channels
### Detailed systematic uncertainties for neutral $b$ hadrons

<table>
<thead>
<tr>
<th>Source</th>
<th>$B^0 \to J/\psi K^{*0}$</th>
<th>$B^0 \to J/\psi K^0_S$</th>
<th>$B^0_s \to J/\psi \pi^+ \pi^-$</th>
<th>$\Lambda^0_b \to J/\psi \Lambda^0$</th>
<th>$B^0_s \to J/\psi \phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV selection</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Detector alignment</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
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<td>0.3</td>
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<tr>
<td>$ct$ resolution</td>
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<td>0.0</td>
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<tr>
<td>MC finite size</td>
<td>1.1</td>
<td>2.4</td>
<td>2.0</td>
<td>2.3</td>
<td>0.6</td>
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<tr>
<td>Efficiency modelling</td>
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<td>0.5</td>
<td>0.6</td>
<td>0.6</td>
<td>0.2</td>
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<tr>
<td>Absolute $ct$ accuracy</td>
<td>0.2</td>
<td>0.2</td>
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<td>0.2</td>
<td>0.2</td>
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<tr>
<td>Mass modelling</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
<td>0.9</td>
<td>0.0</td>
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<td>$ct$ modelling</td>
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<td>0.4</td>
<td>0.1</td>
<td>0.4</td>
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<tr>
<td>$B^+$ contamination</td>
<td>–</td>
<td>–</td>
<td>2.4</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Mass window of the $\pi^+ \pi^-$</td>
<td>–</td>
<td>–</td>
<td>1.5</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$K^\mp \pi^\mp$ mass assumption</td>
<td>0.3</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.1</td>
</tr>
<tr>
<td>$ct$ range</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.1</td>
</tr>
<tr>
<td>S-wave contamination</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.4</td>
</tr>
<tr>
<td>Total</td>
<td>1.5</td>
<td>2.7</td>
<td>3.7</td>
<td>2.7</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Systematic uncertainties in $\mu$m

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Systematic uncertainties for $B_c^+$

- Production vertex (PV) selection
- Fit model
- Binning definition
- Simulated sample sizes
- Detector alignment

<table>
<thead>
<tr>
<th>Source</th>
<th>$\sigma_{\Delta \Gamma}$ [c/mm]</th>
<th>$\sigma_{c_B}$ [\mu m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV choice</td>
<td>0.07</td>
<td>2.0</td>
</tr>
<tr>
<td>Fit model</td>
<td>0.12</td>
<td>3.7</td>
</tr>
<tr>
<td>ct binning</td>
<td>0.06</td>
<td>1.6</td>
</tr>
<tr>
<td>Simulation size</td>
<td>0.04</td>
<td>1.3</td>
</tr>
<tr>
<td>Misalignment</td>
<td>0.03</td>
<td>0.6</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>0.16</td>
<td>4.7</td>
</tr>
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</table>
Fit results

[Graphs showing fit results for CMS Preliminary 19.7 fb\(^{-1}\) (8 TeV) with events distribution and data-background fit comparison for different regions.]

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Fit results

**CMS Preliminary 19.7 fb⁻¹ (8 TeV)**

- **M(J/ψ π⁺π⁻) [GeV]**
  - Fit function
  - B signal
  - Comb. background
  - B background
  - Other B backgrounds
  - Events / 5.0 MeV

- **M(J/ψ K⁺K⁻) [GeV]**
  - Fit function
  - B₂⁻ signal
  - Background
  - Events / 2.6 MeV

- **B_s ct [cm]**
  - Fit function
  - B₂⁻ signal
  - Background
  - Events / 50 µm

**Data/Fit / σ**
- (Data - Fit) / σ

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Mass fits for $B^+$ and $B_c^+$

**Graph 1:**
- **Y-axis:** Events / 10 MeV
- **X-axis:** $M(J/\psi\pi)$ [GeV]
- **Legend:**
  - Fit function
  - $B^+_c$ signal
  - $B^+_c \rightarrow J/\psi K^+$
  - Comb. background

**Graph 2:**
- **Y-axis:** Events / 10 MeV
- **X-axis:** $M(J/\psi K^+)$ [GeV]
- **Legend:**
  - Fit function
  - $B^+$ signal
  - $B^0 \rightarrow J/\psi X$ background
  - $B^0 \rightarrow J/\psi\pi^+$
  - Comb. background

**Footnotes:**
- CMS Preliminary (8 TeV)
- 19.7 fb^{-1}
- Sept. 13, 2017

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Neutral $B$ meson decay

- Decay rate of neutral $B^0_q$ mesons characterized by
  \[
  \Gamma_q = (\Gamma^q_L + \Gamma^q_H)/2 \quad \text{average decay width}
  \]
  \[
  \Delta \Gamma_q = \Gamma^q_L - \Gamma^q_H \quad \text{decay width difference}
  \]
  \[
  \Gamma^q_{L,H} - \text{widths of light (L) and heavy (H) mass eigenstates}
  \]

- Decay rate into final state $f$
  \[
  \Gamma_{B^0_q \to f} = R^f_L e^{-\Gamma^q_L t} + R^f_H e^{-\Gamma^q_H t}
  \]
  \[
  R^f_{L,H} - \text{amplitudes of light and heavy mass eigenstates}
  \]

→ $ct$ distribution consists of two exponentials

- $B^0$ system: $\frac{\Delta \Gamma_d}{\Gamma_d} = (-0.3 \pm 1.5)\% \rightarrow ct$ distribution can be treated as one exponential

- $B^0_s$ system: $\frac{\Delta \Gamma_s}{\Gamma_s} = (12.4 \pm 1.1)\% \rightarrow$ sizeable deviations from exponential
$B_S^0$ measurements

- Measured in two final states: $J/\psi \phi(1020)$ and $J/\psi \pi^+ \pi^-$

- $J/\psi \pi^+ \pi^-$:
  - $0.9240 < M(\pi^+ \pi^-) < 1.0204$ GeV \rightarrow dominated by $f_0(980) \rightarrow$ CP-odd final state
  - $c\tau_{B_S^0}^{CP\text{-odd}} \approx 1/\Gamma_H$

- $J/\psi \phi(1020)$:
  - Admixture of one CP-odd and two CP-even states
  - $c\tau_{\text{eff}} = f_H c\tau_H + (1 - f_H) c\tau_L$
  - $f_H = |A_\perp|^2 c\tau_H / (|A|^2 c\tau_L + |A_\perp|^2 c\tau_H)$
  - Complementary to weak mixing phase analysis