B-Hadron Properties
at the Tevatron:
Lifetimes, $B_c$, Excited States

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(for the D0 and CDF experiments)
B-Hadron Properties

- Triggers
- Lifetimes
  - $\Lambda_B$
  - $B_s$

- $B_c$
  - Lifetime
  - Mass
  - Cross section

- Excited States
  - Masses, properties
Final States and Triggers

▶ Dimuon Final State
• At least two muons in final state
• **Dimuon trigger**
  ▪ Typically used for signals with J/ψ in the final state
  ▪ Require at least one track with matching muon segment along with another track (2 tracks required in total)
  ▪ $p_T > 1.5 \text{ GeV/c} \text{ (CDF)}$
  ▪ No lifetime bias from trigger

▶ Semileptonic Final States
• At least one muon
• **Single lepton trigger**
  ▪ Require track with muon matching segment or calorimeter energy consistent with a MIP
  ▪ $p_T > 2 \text{ GeV}$
  ▪ No lifetime bias from trigger
Final States and Triggers

- **Hadronic final state**
  - All or most final state particles are hadrons

- **Trigger on displaced track vertices**
  - Usually two tracks: *Two Track Trigger*

- At CDF, at Level 2, cut on SVT impact parameter: 100 – 1000 μm

- **Biases lifetime measurement**
  - Bias accounted for using MC

- **Increases statistics and allows measurements in different channels**
$\Lambda_b$ Lifetime
**$\Lambda_b$ Lifetime: $\Lambda_b \rightarrow J/\psi \Lambda$, $\Lambda \rightarrow \rho \pi^-$**

- $B^0 \rightarrow J/\psi K_s^0$, $B^0 \rightarrow J/\psi K^*0$, $B^+ \rightarrow J/\psi K^+$ measured to control systematics
- $J/\psi$ trigger
- Rectangular cuts used to select $J/\psi$ candidates and $\Lambda$ (or $K_s$) candidates, avoiding bias from $\Lambda$ lifetime
- Use $J/\psi$ to determine decay vertex
- Use a prompt $J/\psi$ sample to extract resolution function and apply to non-prompt $J/\psi$ vertices

$$ct = L_{xy} \frac{M_B}{p_T}$$

$$c\tau(\Lambda_b) = 473.8 \pm 23.1 \text{(stat.)} \pm 3.48 \text{(syst.)} \mu\text{m}$$

$$\tau(\Lambda_b) = 1.580 \pm 0.077 \text{ (stat.)} \pm 0.012 \text{ (syst.)} \text{ps}$$

$$\tau(\Lambda_b)/\tau(B^0) = 1.018 \pm 0.062 \text{ (stat.)} \pm 0.007 \text{ (syst.)}$$

Triggers with no IP cuts; most are dimuon or single muon triggers
Simultaneous unbinned maximum likelihood fit to the mass and PDL
Systematic uncertainties from alignment, distribution models, long-lived components, and contamination
Measure ratio w/r/t $B^0 \rightarrow J/\psi K^0_s$
  • Similar topology
  • Cross checks

\[ \tau(\Lambda_b) = 1.218^{+0.130}_{-0.115}(\text{stat}) \pm 0.042(\text{syst}) \text{ ps} \]
\[ \frac{\tau(\Lambda_b)}{\tau(B^0)} = 0.811^{+0.096}_{-0.087}(\text{stat}) \pm 0.034(\text{syst}) \]
Semileptonic Decay
Inclusive single muon trigger
No impact parameter cuts
MC used to correct for the unreconstructed neutrino
Yield measured in bins of ct
Yield: $4437 \pm 329$ (stat) candidates

$\tau(\Lambda_b^0) = 1.290^{+0.119}_{-0.110}$ (stat)$^{+0.087}_{-0.091}$ (syst) ps

Combined result with D0 $\Lambda_b \rightarrow J/\psi \Lambda$:

$\tau(\Lambda_b^0) = 1.251^{+0.102}_{-0.096}$ ps
$\Lambda_b$ Lifetime: $\Lambda_b \rightarrow \Lambda_c \pi$, $\Lambda_c^+ \rightarrow p^+ K^- \pi^+$

- Use large signal $\Lambda_0 \rightarrow \Lambda_c^+ \pi^-$ from the displaced vertex trigger
- $5.565 < M(\Lambda_c^+ \pi^-) < 5.67$ GeV/c$^2$
- $\Lambda_0$ yield: 2927 ± 58 events
- Take into account lifetime bias due to displaced vertex trigger

$\Lambda_b$ Lifetime: $\Lambda_b \rightarrow \Lambda_c \pi$, $\Lambda_c \rightarrow p^+ K^- \pi^+$ (2)

- Use MC to extract trigger efficiency distribution
- Fit exponential convoluted with trigger efficiency and detector resolution function

Systematics are dominated by MC model of trigger efficiency and decay

$ct(\Lambda_b) = 420.0 \pm 13.8 \text{(stat)} \pm 10.5 \text{(syst)} \, \mu\text{m}$

$\tau(\Lambda^0_b) = 1.401 \pm 0.046 \text{(stat)} \pm 0.035 \text{(syst)} \, \text{ps}$
Comparison with other experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( \Lambda_b ) Lifetime [ps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH ( \Lambda_c^+ + \Lambda_c^0 )</td>
<td>1.21 ± 0.11</td>
</tr>
<tr>
<td>OPAL ( \Lambda_c^+ )</td>
<td>1.29 ± 0.24</td>
</tr>
<tr>
<td>DELPHI ( \Lambda_c^+ )</td>
<td>1.11 ± 0.16</td>
</tr>
<tr>
<td>CDF Run I ( \Lambda_c^+ )</td>
<td>1.32 ± 0.15</td>
</tr>
<tr>
<td>D0 Run II ( \Lambda_c^+ )</td>
<td>1.290 ± 0.120 ± 0.087 ± 0.031</td>
</tr>
<tr>
<td>D0 Run II J/( \psi ) ( \Lambda )</td>
<td>1.218 ± 0.130 ± 0.042</td>
</tr>
<tr>
<td>CDF Run II J/( \psi ) ( \Lambda )</td>
<td>1.593 ± 0.083 ± 0.078</td>
</tr>
<tr>
<td>CDF Run II ( \Lambda_c \pi ) (PRELIMINARY)</td>
<td>1.401 ± 0.046 ± 0.035</td>
</tr>
</tbody>
</table>

PDG 2008

\( \Lambda_b \) lifetime [ps]

H. Gerberich
10 Sep 2009
Beauty 2009, Heidelberg University, Germany
B_s Lifetime
**B$_s$ Lifetime: Hadronic Modes**

- Displaced track trigger
- Partially and Fully Reconstructed B$_s$ Modes:
  - Fully: $B_s \rightarrow D_s^-(\phi\pi^-)\pi^+$
  - Partially: $B_s \rightarrow D_s^-\rho^+(\pi^+\pi^0)$; $B_s \rightarrow D_s^-K^+$; $B_s \rightarrow D_s^*\pi^+$
- Double statistics!

- MC used to quantify the effect of partially reconstructed modes
  - “K” factor accounts for missing momentum and mass:
    $$ct \equiv \frac{L_{xy} \cdot m_{B}^{\text{rec}}}{p_{T_B}} \cdot \text{K}$$

- Several control samples used for lifetime validation and calibration
  - $B^0 \rightarrow D^- (K^+\pi^-\pi^-)\pi^+$
  - $B^0 \rightarrow D^*^- [D^0 (K^+\pi^-)\pi^-] \pi^+$
  - $B^+ \rightarrow D^0 (K^+\pi^-)\pi^+$

Effect of trigger on ct distribution is evident

The effect of the displace vertex trigger is taken into account using “trigger efficiency” curve from MC

\[ c\tau(B_s \rightarrow D_s^- (\phi \pi^-) \pi^+) = 455.0 \pm 12.2 \text{(stat.)} \pm 8.2 \text{(syst.)} \ \mu\text{m} \]

\[ \tau(B_s^0 \rightarrow D_s^- (\phi \pi^-) \pi^+) = 1.52 \pm 0.04 \text{(stat)} \pm 0.03 \text{(syst)} \ \text{ps} \]

B_s Lifetime: $B_s^0 \rightarrow D_s^- \mu^+ \nu X$, $D_s^- \rightarrow \phi \pi^-$

- Semileptonic final state
- Partially reconstructed
- Inclusive single muon trigger
  - No impact parameter cuts
- Monte Carlo used to determine K-factor to correct for the unreconstructed neutrino:
  \[ K = \frac{p_T(D_s^- \mu^+)}{p_T(B_s^0)} \]

\[ \tau(B_s^0) = 419.1 \pm 13.2 \text{ (stat)} ^{+8.4}_{-7.5} \text{ (syst)} \text{ \mu m} \]

\[ \tau(B_s^0) = 1.398 \pm 0.044 \text{ (stat)} ^{+0.028}_{-0.025} \text{ (syst)} \text{ ps} \]

PRL 97, 241801 (2006)
$B_c$ Lifetime, Mass, Cross section
B_c Lifetime: B_c → J/ψμ+X and B_c → J/ψe+X

- J/ψ trigger (semileptonic decay)
- Scale K factor determined by MC to account for unreconstructed particles – missing momentum, correct pseudo-lifetime

\[
ct = K \times ct^* \\
ct^* = \frac{M(B_c) L_{xy}(J/ψ + l)}{p_T(J/ψ + l)} \\
K = \frac{p_T(J/ψ + l)}{p_T(B_c)}
\]

Main challenge is multiple backgrounds:
- real J/Ψ + fake lepton / fake J/Ψ + real lepton
- real J/Ψ + real lepton → from bb events
- prompt J/Ψ + lepton
- residual conversion (J/ψ+e only)

http://www-cdf.fnal.gov/physics/new/bottom/080327.blessed-BC_LT_SemiLeptonic/
$B_c$ Lifetime: $B_c \rightarrow J/\psi \mu + X$ and $B_c \rightarrow J/\psi e + X$ (2)

Combined measurement using likelihood:

$$c\tau = 142.5^{+15.8}_{-14.8} \text{ (stat.)} \pm 5.5 \text{ (syst.)} \mu m$$

$$\tau = 0.475^{+0.053}_{-0.050} \text{ (stat.)} \pm 0.018 \text{ (syst.)} \text{ ps}$$

http://www-cdf.fnal.gov/physics/new/bottom/080327.blessed-BC_LT_SemiLeptonic/
$B_c$ Lifetime: $B_c \rightarrow J/\psi \mu + X$

- Semileptonic decay
- Single muon trigger – no IP cut
- $K$ factor distribution from MC used to correct for unreconstructed particle
- Mass – lifetime simultaneous fit used to extract the small $B_c$ signal among large fractions of backgrounds
- Yield: $881 \pm 80$ (stat)

$$c\tau(B_c) = 134.3^{+11.4}_{-10.8} \text{(stat)} \pm 9.59 \text{ (syst)} \mu m$$

$$\tau(B_c^{\pm}) = 0.448^{+0.038}_{-0.036} \text{(stat)} \pm 0.032 \text{ (syst)} \text{ ps}$$

PRL 102, 092001 (2009)
B_{c}^{+} \rightarrow J/\psi \mu^{+} \nu \text{ Cross section}

\frac{\sigma(B_{c}^{+}) \cdot BR(B_{c}^{+} \rightarrow J/\psi + \mu^{+} + \nu)}{\sigma(B^{+}) \cdot BR(B^{+} \rightarrow J/\psi + K^{+})} = \frac{N_{B_{c}^{+}}}{N_{B^{+}}} \times \epsilon_{rel}

Need to model B^{+}, B_{c}^{+} \ p_T\ spectra to calculate relative efficiency between decays

Backgrounds:
- Misidentified J/\psi
- Misidentified muons
- bb background
- other b hadrons

<table>
<thead>
<tr>
<th>( p_T(B) ) value</th>
<th>( R = \frac{\sigma(B_{c}^{+}) \cdot BR(B_{c}^{+} \rightarrow J/\psi + \mu^{+} + \nu)}{\sigma(B^{+}) \cdot BR(B^{+} \rightarrow J/\psi + K^{+})} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_T(B) &gt; 4 \text{ GeV}/c )</td>
<td>( 0.295 \pm 0.040 \text{(stat)}^{+0.033}_{-0.026} \text{(sys)} \pm 0.036 \text{(}( p_T ) spectrum) }</td>
</tr>
<tr>
<td>( p_T(B) &gt; 6 \text{ GeV}/c )</td>
<td>( 0.227 \pm 0.033 \text{(stat)}^{+0.024}_{-0.017} \text{(sys)} \pm 0.014 \text{(}( p_T ) spectrum) }</td>
</tr>
</tbody>
</table>

http://www-cdf.fnal.gov/physics/new/bottom/090305.blessed-bc-slXsec/
**B_c Lifetime Summary**

**CDF Run II Preliminary: ~1 fb^{-1}**

- Averaged for World Average
- Combined for CDF II J/\psi+l (1 fb^{-1})
- World Average

- CDF Run I, J/\psi+l
- D0, J/\psi+\mu (1.35 fb^{-1})
- CDF Run II, J/\psi+e (1 fb^{-1})
- CDF Run II, J/\psi+\mu (1 fb^{-1})
- CDF Run II, J/\psi+l (1 fb^{-1})
- Average = 137.7\pm11.0 \mu m

**B_c c\tau (\mu m)**
Cuts optimized for $B^+ \to J/\psi K^+$ selection

- Backgrounds:
  - Combinatorial
  - Cabibbo-suppressed $B^+_c \to J/\psi K^+$

- $80 < ct < 300 \mu m$
- Signal of $108 \pm 15$ $B_c$ candidates with significance of $8\sigma$
- First Observation in this mode

- All muon triggers considered
- Rectangular cuts
- Unbinned log likelihood fit
- Signal of $54 \pm 12$ Candidates with a significance of $5.2\sigma$
- $M(B_c) = 6300 \pm 14(\text{stat}) \pm 5(\text{syst})$ MeV/c$^2$
- Primary systematic from selection criteria – mostly $\pi$ kinematic cut

$M(B_c) = 6275.6 \pm 2.9(\text{stat}) \pm 2.5(\text{syst})$ MeV/c$^2$
Excited States
Orbitally (L=1) Excited $B^0$ Mesons

Heavy-light quark meson is similar to the hydrogen atom in understanding QED.

Spin of b quark: $j_b = 1/2$

<table>
<thead>
<tr>
<th>$j_q = 1/2$ states</th>
<th>$j_q = 3/2$ states</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Particle Name</strong></td>
<td><strong>Decay Mode(s)</strong></td>
</tr>
<tr>
<td>$B_0^*$</td>
<td>Broad Resonance</td>
</tr>
<tr>
<td>$B_1'$</td>
<td>Broad Resonance</td>
</tr>
</tbody>
</table>

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<tr>
<th><strong>Particle Name</strong></th>
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</tr>
</thead>
<tbody>
<tr>
<td>$B_1$</td>
<td>$B_1 \rightarrow B^{<strong>\pi^-}, B^{</strong>} \rightarrow B^+\gamma$</td>
</tr>
<tr>
<td>$B_2^*$</td>
<td>$B_2^* \rightarrow B^+\pi^-$, $B^{<strong>} \rightarrow B^{*+\pi^-}, B^{</strong>} \rightarrow B^+\gamma$</td>
</tr>
</tbody>
</table>

($\gamma$ not reconstructed in $B^* \rightarrow B\gamma$ decay)
Orbitally Excited (L=1) B° Mesons

<table>
<thead>
<tr>
<th>Particle Name</th>
<th>J</th>
<th>Decay Mode(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B_1</td>
<td>1</td>
<td>B_1 \rightarrow B^{<strong>}\pi^-, B^{</strong>}\rightarrow B^{+}\gamma</td>
</tr>
<tr>
<td>B_2^*</td>
<td>2</td>
<td>B_2^* \rightarrow B^{+}\pi^-</td>
</tr>
</tbody>
</table>

- B^+ \rightarrow J/\psi K^+, J/\psi \rightarrow \mu\mu
  - Dimuon trigger
- B^+ \rightarrow D^0(3)\pi^+, D^0 \rightarrow K^+\pi^-
  - Two track Trigger
- B^+ selection based on Neural Network which combines topological, kinematic, and particle identification
- B^{**} candidates are selected using additional Neural Networks

\[
N(B_2^{*0} \rightarrow B^+\pi^-) = 385_{-45}^{+48} \text{ (stat.)}
\]
\[
N(B_2^{*0} \rightarrow B^{**}\pi^-) = 351_{-43}^{+46} \text{ (stat.)}
\]
\[
N(B_1^0 \rightarrow B^*\pi) = 503_{-62}^{+75} \text{ (stat.)}
\]

Most precise mass measurements of these states
First measurement of B_2^{*0} width

\[
m(B_1^0) = 5725.3_{-2.2}^{+1.6} \text{ (stat.)} +1.4_{-1.5} \text{ (syst.)} \text{ MeV/c}^2
\]
\[
m(B_2^{*0}) = 5740.2_{-1.8}^{+1.7} \text{ (stat.)} +0.9_{-0.8} \text{ (syst.)} \text{ MeV/c}^2
\]
\[
\Gamma(B_2^{*0}) = 22.7_{-3.2}^{+3.8} \text{ (stat.)} +3.2_{-10.2} \text{ (syst.)} \text{ MeV/c}^2
\]

PRL 102, 102003 (2009)
Orbitally Excited (L=1) B⁰ Mesons

<table>
<thead>
<tr>
<th>jq=3/2 states</th>
<th>J</th>
<th>Decay Mode(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B₁</td>
<td>1</td>
<td>B₁ → B*⁺π⁻, B**⁺→B⁺γ</td>
</tr>
<tr>
<td>B₂⁺</td>
<td>2</td>
<td>B₂⁺→B⁺π⁻, B₂⁺⁺→B⁺γ</td>
</tr>
</tbody>
</table>

- B⁺ is reconstructed in the exclusive decay B⁺→J/ψK⁺, J/ψ→μμ

- Backgrounds:
  - B⁺→J/ψπ⁺, B⁺→J/ψK⁺⁺
  - Combinatorial

B₁ and B₂⁺* production rate is (13.9±1.9±3.2)% the production rate of B⁺ meson

M(B₁) = 5720.6 ± 2.4 ± 1.4 MeV/c²
M(B₂⁺) = 5746.8 ± 2.4 ± 1.7 MeV/c²

PRL 99, 172001 (2007)
Orbitally (L=1) Excited $B_s$ Mesons

Spin of $b$ quark: $j_b=1/2$
Spin of $s$ quark: $j_s=1/2, 3/2$

| $j_s=1/2$ states |  |  |  |
|------------------|------------------|------------------|
| Particle Name | J | Decay Mode(s) |  |
| $B^*_0$ | 0 | Broad Resonance |  |
| $B^*_1$ | 1 | Broad Resonance |  |

| $j_s=3/2$ states |  |  |  |
|------------------|------------------|------------------|
| Particle Name | J | Decay Mode(s) |  |
| $B^*_{s1}$ | 1 | $B^*_{s1} \rightarrow B^{**}K^-$, $B^{**} \rightarrow B^+\gamma$ |  |
| $B^*_{s2}$ | 2 | $B^*_{s2} \rightarrow B^{+}K^-$, $B^{*+} \rightarrow B^{+}\gamma$ |  |

($\gamma$ not reconstructed in $B^* \rightarrow B\gamma$ decay)
Orbitally Excited (L=1) $B_s$ Mesons

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<th>Decay Mode(s)</th>
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<tbody>
<tr>
<td>$B_{s1}$</td>
<td>1</td>
<td>$B_{s1} \to B^{<strong>}K^-, B^{</strong>} \to B^+\gamma$</td>
</tr>
<tr>
<td>$B_{s2}^*$</td>
<td>2</td>
<td>$B_{s2}^* \to B^+K^-$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$B_{s2}^* \to B^{<strong>}K^-, B^{</strong>} \to B^+\gamma$</td>
</tr>
</tbody>
</table>

$B^+$ is reconstructed in:
- $B^+ \to J/\psi K^+$, $J/\psi \to \mu \mu$
  - $J/\psi$ trigger
- $B^+ \to D^0\pi^+$, $D^0 \to K^+p^-$
  - Displaced vertex trigger

$B^+$ and $B_{s2}^{**}$ selection based on Neural Network which combines topological, kinematic, and particle identification

$B_{s1} \to B^+K^-$ $6.3\sigma$
$B_{s2}^* \to B^+K^-$ $7.7\sigma$

$Q = m(B^+K^-) - m(B^+) - M_K$ [MeV/$c^2$]

\[
m(B_{s1}) = 5829.4 \pm 0.7 \text{ MeV}/c^2
\]
\[
m(B_{s2}^*) = 5839.6 \pm 0.7 \text{ MeV}/c^2
\]

PRL 100, 082001 (2008)
Orbitally (L=1) Excited $B_s$ Mesons

$\begin{array}{|c|c|c|}
\hline
\text{Particle Name} & J & \text{Decay Mode(s)} \\
\hline
B_{s1} & 1 & B_{s1} \rightarrow B^{*+}K^-, B^{**} \rightarrow B^+\gamma \\
B_{s2}^* & 2 & B_{s2}^* \rightarrow B^+K^-, B_{s2}^* \rightarrow B^{*+}K^-, B^{**} \rightarrow B^+\gamma \\
\hline
\end{array}$

- $B^+$ is reconstructed in
  - $B^+ \rightarrow J/\psi K^+$, $J/\psi \rightarrow \mu\mu$

To check for the presence of a $B_{s1}$ signal, fit $\Delta M$ with two mass hypothesis

- Peak around $Q=11.5\pm1.4\,(\text{stat})$ MeV/c$^2$ has statistical significance less than $3\sigma$

$$M(B_{s2}^*) = 5839.6 \pm 1.1 \pm 0.7 \text{ MeV/c}^2$$

$B_{s2}^*$ production rate is $(1.15\pm0.23\pm0.13)\%$

$125\pm25$ $B_{s2}^* \rightarrow B^+K^-$ decays

$B_{s2}^*$ meson

PRL 100, 082002 (2008)
Summary

- D0 and CDF have made lifetime measurements of the $B_s$, $\Lambda_b$, and $B_c$ particles
- D0 and CDF have made measurements of the $B_c$ mass
- D0 and CDF have observed $B$ and $B_s$ excited states

- We aren’t done!
- We have more data on the way
- We are using more sophisticated techniques (hardware and analysis) to squeeze out as much signal from the data as we can

- Look forward to new and improved results soon!