B Hadron Spectroscopy and Lifetimes from Tevatron

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- **Not covered**
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  - Polarization Amplitudes of the $B_s^0 \rightarrow \phi\phi$ Decay

- Summary
CDF and DØ Detectors in Run 2

- Good electron, muon ID and acceptance
- Excellent tracking acceptance $|\eta| < 2-3$
- L2 trigger on displaced vertices
- Excellent tracking resolution
- Good low momentum PID
- Both detectors
  - Silicon microvertex tracker
  - Solenoid
  - High rate trigger/DAQ
  - Calorimeters and muons
B Production at Tevatron

Since $\sigma(bb) \ll \sigma(pp) \Rightarrow$ Events have to be selected with specific triggers

Trigger requirements: large bandwidth, background suppression, deadtimeless

Tevatron is a source of all B-hadron species, $B_d, B_u, B_c, B_s$ and $\Lambda_b$

$\sigma_b = 29.4 \pm 0.6 \pm 6.2 \mu b \ (|\eta| < 1) \ (CDF)$

Huge cross-sections compared to the the B-factories but proportionally large backgrounds as well
Triggers for B Physics

- **Single-/Di-lepton (CDF/DØ)**
  - A high $p_T$ lepton or two leptons with lower $p_T$
  - $J/\Psi$ modes, masses, lifetimes, $\times$-section
  - Yields higher than Run I (low $p_T$ threshold, increased acceptance)

- **Lepton + displaced track - semileptonic sample (CDF)**
  - $p_T(e/\mu) > 4$ GeV/c, $120$ $\mu$m $< d0(Trk) < 1$mm, $p_T(Trk) > 2$ GeV/c
  - Semileptonic decays, lifetimes, flavor tagging
  - B Yields 3x Run I

- **Two displaced vertex tracks - hadronic sample (CDF)**
  - $p_T(Trk) > 2$ GeV/c, $120$ $\mu$m $< d0(Trk) < 1$mm, $\sum p_T > 5.5$ GeV/c
  - $\times$-section, branching ratios, $B_s$ mixing…
Interests in B Hadron Lifetimes

Heavy Quark Expansion

\[ \Gamma = \frac{G_F^2 m_b^5}{192\pi^3} |V_{cb}|^2 \cdot \left[ A_0 + A_2 \left( \frac{\Lambda_{QCD}}{m_b} \right)^2 + A_3 \left( \frac{\Lambda_{QCD}}{m_b} \right)^3 \right] \]


Pauli Interference:
prolongs lifetimes,
+5\% for \( B^+ \), +3\% for \( \Lambda_b \)

Weak Annihilation and Exchange:
reduce lifetimes -7\% \( \Lambda_b \)

Spectator model:
b hadron lifetimes are equal.

\[ \tau(B^+) \geq \tau(B^0) \cong \tau(B_s^0) > \tau(\Lambda_b) > \tau(B_c) \]
The $B^+, B^0$ lifetimes are precisely measured at B-factories.

- **Experimental error on $\tau(B_s^0)/\tau(B^0)$ far higher than theory error!**

- **World average of $\tau(\Lambda_b)/\tau(B^0)$ too low compared to $O(1/m_b^3)$ HQE prediction. CDF 2006 measurement was precise but too high!**

- **Lifetime ratio world averages:**
  - $\tau(B^+)/\tau(B^0) = 1.071 \pm 0.009$
  - $\tau(B_s^0)/\tau(B^0) = 0.939 \pm 0.021$
  - $\tau(\Lambda_b)/\tau(B^0) = 0.904 \pm 0.032$

**PDG 2008**

**Theory $O(1/m_b^4)$ [2004]**

- $1.06 \pm 0.02$
- $1.00 \pm 0.01$
- $0.86 \pm 0.05$
Uses a **4.3 fb⁻¹** data sample obtained using CDF di-muon trigger.

- **Signal modes:** $B^+ \rightarrow J/\psi K^+$,  
  $B^0 \rightarrow J/\psi K_s^0$, $B^0 \rightarrow J/\psi K^{*0}$,  
  $\Lambda_b^0 \rightarrow J/\psi \Lambda$

- **Yields:**  
  $B^+ : 45000 \pm 230$,  
  $B^0 : 16860 \pm 140 (K_s^0)$, $B^0 : 12070 \pm 120 (K^{*0})$  
  $\Lambda_b^0 : 1710 \pm 50$

- Lifetimes are extracted by simultaneous unbinned likelihood fit to B mass, proper decay time $ct$ and its uncertainty $\sigma_{ct}$. Per candidate mass uncertainty, $\sigma_m$, is also used as an input to the fit.

- The proper decay time is modeled by an exponential convolved with a detector resolution functions comprised of 3 Gaussians.
Lifetime Projections from the Fits

CDF Run II Preliminary 4.3 fb$^{-1}$

$B^0 : K_s^0$

CDF Run II Preliminary 4.3 fb$^{-1}$

$B^+$

CDF Run II Preliminary 4.3 fb$^{-1}$

$\Lambda_b^0$

CDF Run II Preliminary 4.3 fb$^{-1}$

$B^0 : K^*^0$
Fit Results

\[ \tau_{B^+} = 1.639 \pm 0.009{\text{(stat.)}} \pm 0.009{\text{(syst.)}} \text{ ps} \]
\[ \tau_{B^0} = 1.507 \pm 0.010{\text{(stat.)}} \pm 0.008{\text{(syst.)}} \text{ ps} \quad \text{(Weighted Avg)} \]
\[ \tau_{\Lambda_b^0} = 1.537 \pm 0.045{\text{(stat.)}} \pm 0.014{\text{(syst.)}} \text{ ps} \]

\[ \frac{\tau_{B^+}}{\tau_{B^0}} = 1.088 \pm 0.009{\text{(stat.)}} \pm 0.004{\text{(syst.)}} \]
\[ \frac{\tau_{\Lambda_b^0}}{\tau_{B^0}} = 1.020 \pm 0.030{\text{(stat.)}} \pm 0.008{\text{(syst.)}} \quad \text{(Theory: 0.86 \pm 0.05)} \]
\( \tau(B^+) \) Comparison

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLD (ABE 97J)</td>
<td>1.66 ± 0.06 ± 0.05</td>
</tr>
<tr>
<td>L3 (ACCIAPPI 98S)</td>
<td>1.66 ± 0.06 ± 0.03</td>
</tr>
<tr>
<td>CDF (ABE 98Q)</td>
<td>1.637 ± 0.058 (+0.045,-0.043)</td>
</tr>
<tr>
<td>OPAL (ABBIENDI 99J)</td>
<td>1.643 ± 0.037 ± 0.025</td>
</tr>
<tr>
<td>ALEP (BARATE 00R)</td>
<td>1.648 ± 0.049 ± 0.035</td>
</tr>
<tr>
<td>BABR (AUBERT 01F)</td>
<td></td>
</tr>
<tr>
<td>CDF (ACOSTA 02C)</td>
<td>1.673 ± 0.032 ± 0.023</td>
</tr>
<tr>
<td>DLPH (ABDALLAH 04E)</td>
<td>1.636 ± 0.058 ± 0.025</td>
</tr>
<tr>
<td>BELL (ABE 05B)</td>
<td>1.624 ± 0.014 ± 0.018</td>
</tr>
<tr>
<td>CDF II 4.3 fb(^{-1})</td>
<td>1.635 ± 0.011 ± 0.011</td>
</tr>
<tr>
<td>PDG08</td>
<td>1.639 ± 0.009 ± 0.009</td>
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</tbody>
</table>

World best measurement!
**τ(B^0)** Comparison

- **DLPH (ABDALLAH 04E)**: 1.531±0.021±0.031
- **D0 (ABAZOV 05W)**: 1.530±0.043±0.023
- **CDF (ACOSTA 05)**: 1.540±0.050±0.020
- **CDF (ABULENCIA 07A)**: 1.524±0.030±0.016
- **BABR (AUBERT 03H)**: 1.533±0.034±0.038
- **BABR (AUBERT 01F)**: 1.546±0.032±0.022
- **BABR (AUBERT 02H)**: 1.529±0.012±0.029
- **BABR (AUBERT 05G)**: 1.504±0.013^{+0.018}_{-0.013}
- **BELL (ABE 05B)**: 1.534±0.008±0.010
- **CDF II 4.3 fb^{-1}**: 1.507±0.010±0.008

**PDG08**: 1.53±0.009

| 1.5 | 1.6 |

**τ (ps)**
Comparison

$\Lambda_b \rightarrow \Lambda_c \pi$

$\tau(\Lambda_{b0})$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEP EPJ C2 197</td>
<td>1.21±0.11±0.00</td>
</tr>
<tr>
<td>OPAL PL B426 161</td>
<td>1.29±0.24±0.06</td>
</tr>
<tr>
<td>DLPH EPJ C10 185</td>
<td>1.11±0.19±0.05</td>
</tr>
<tr>
<td>CDF I PRL 77 1439</td>
<td>1.32±0.15±0.07</td>
</tr>
<tr>
<td>DO II PRL 99 142001</td>
<td>1.218±0.130±0.115±0.042</td>
</tr>
<tr>
<td>D0 II PRL 99 182001</td>
<td>1.290±0.120±0.110+0.067-0.091</td>
</tr>
<tr>
<td>CDF II PRL 98 122001 j/γ,Λ (1.0 fb$^{-1}$)</td>
<td>1.593±0.083±0.078±0.033</td>
</tr>
<tr>
<td>CDF II 9406 Λ,π</td>
<td>1.401±0.046±0.035</td>
</tr>
<tr>
<td>CDF II 4.3 fb$^{-1}$</td>
<td>1.537±0.045±0.014</td>
</tr>
</tbody>
</table>

PDG06: 1.23±0.074

World best measurement!
Significantly above WA and in agreement with earlier measurement.
### $\tau(B^+)/\tau(B^0)$ Comparison

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>L3 (ACCIARRI 98S)</td>
<td>1.09±0.07±0.03</td>
</tr>
<tr>
<td>CDF (ABE 98Q)</td>
<td>1.110±0.056+0.033-0.030</td>
</tr>
<tr>
<td>OPAL (ABBIENDI 99J)</td>
<td>1.079±0.064±0.041</td>
</tr>
<tr>
<td>ALEP (BARATE 00R)</td>
<td>1.085±0.059±0.018</td>
</tr>
<tr>
<td>CDF (ACOSTA 02C)</td>
<td>1.093±0.066±0.028</td>
</tr>
<tr>
<td>BABR (AUBERT 01F)</td>
<td>1.082±0.026±0.012</td>
</tr>
<tr>
<td>DLPH (ABDALLAH 04E)</td>
<td>1.060±0.021±0.024</td>
</tr>
<tr>
<td>D0 (ABAZOV 05D)</td>
<td>1.080±0.016±0.014</td>
</tr>
<tr>
<td>BELL (ABE 05B)</td>
<td>1.066±0.008±0.008</td>
</tr>
<tr>
<td>CDF II 4.3 fb⁻¹</td>
<td>1.088±0.009±0.004</td>
</tr>
</tbody>
</table>

**PDG08: 1.071±0.009**

**Good agreement with WA**
Spectroscopy Results
Observation of New Y(4140) State

- Comes from the update of an earlier analysis comprising of 2.7 fb⁻¹ data, 14 ± 5 signal events. Reported significance 3.8σ. Published in Phys.Rev.Lett.102:242002,2009.
- Decay mode: B⁺ → Y(4140) K⁺, Y(4140) →J/ψ φ;
  J/Ψ → μ⁺μ⁻, φ → K⁺ K⁻
- Joins the fleet of exotic charmonium-like states, X(3872), Y(3930) etc., beyond open-charm pair production threshold.
- Analysis highlights:
  - Optimize signal: L_x,y(B⁺) > 500 μm cut requires displaced secondary vertex, Kaon PID likelihood ratio > 0.2 reduces combinatorics.
  - The signal is observed as an excess in the ∆M = M(μ⁺μ⁻K⁺K⁻) - M(μ⁺μ⁻) distribution, modeled by a S-wave relativistic BW function.
Observation of Y(4140)

- **B+ yield:** 115 ± 12 events
- **Signal region:** ± 3σ, Sidebands [-9,-6]σ or [6,9]σ
- **Dalitz distribution shows events uniformly distributed in the expected phase space.**
Observation of Y(4140)

- Comparison of old and updated samples show clear enhancement in the signal region.

- $\Delta M$ unbinned likelihood fit:
  - Signal: Rel. S-wave BW convoluted with a Gaus resolution function.
  - Background: 3-body phase space
  - $B^0_s \rightarrow \psi' \phi$ contamination in high $\Delta M$ region modeled from MC.

- Yield: 19 ± 6 events,
  - $\Delta M$: 1046.7 $^{+2.9}_{-3.0}$ MeV/c$^2$
  - Width: 15.3 $^{+10.4}_{-6.1}$ MeV/c$^2$

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Observation of $Y(4140)$

- Significant excess above background at $\Delta M=1.18$ GeV/c$^2$.
- Fitting it along with $Y(4140)$ doesn’t change the results compared to $Y(4140)$-only fit.
- Final results:
  - $Y(4140)$:
    - $m = 4143.4^{+2.9}_{-3.0}$ (stat.) $\pm 0.6$ (syst.) MeV/c$^2$
    - $\Gamma = 15.3^{+10.4}_{-6.1}$ (stat.) $\pm 2.5$ (syst.) MeV/c$^2$
  - Second peak:
    - $m = 4274.4^{+8.4}_{-6.7}$ (stat.) MeV/c$^2$
    - $\Gamma = 32.3^{+21.9}_{-15.3}$ (stat.) MeV/c$^2$

(Based on p-values from Toy MC tests)
First Observation of $B_s^0 \rightarrow J/\psi K^{*0}$ and $B_s^0 \rightarrow J/\psi K_s^0$

- $B_s^0 \rightarrow J/\psi K_s^0$:
  - CP eigenstate, lifetime measures $\tau(B_s^0)_{\text{heavy}}$

- $B_s^0 \rightarrow J/\psi K^{*0}$:
  - Admixture of CP final states. Estimate penguin contribution to $J/\psi \phi$.
  - A large sample can be used to measure $\sin(2\beta_s)$ as a complementary mode to $B_s^0 \rightarrow J/\psi \phi$.

- Procedure:
  - Reconstruct the signal modes in $B_s^0$ and $B^0$ samples from 6 fb$^{-1}$ of CDF di-muon triggered data.
  - After signal optimization apply binned likelihood fits to mass distributions to extract signal yield fractions between $B_s^0$ and $B^0$ modes.
  - Finally measure: $f_s BR(B_s \rightarrow J/\psi K^{(*)0}_{(S)}) / f_d BR(B^0 \rightarrow J/\psi K^{(*)0}_{(S)})$
First Observation of $B_s^0 \rightarrow J/\psi K^{*0}$ and $B_s^0 \rightarrow J/\psi K_s^0$

Yields: $B_s^0: 64 \pm 14$, $B^0: 5954 \pm 79$

BR($B_s \rightarrow J/\psi K^*) = (3.5 \pm 0.6 \text{ (stat.)} \pm 0.4 \text{ (syst.)} \pm 0.4 \text{ (frag.)} \pm 0.4 \text{ (PDG)}) \cdot 10^{-5}$

7.2$\sigma$ significance w.r.t. null hypothesis

Yields: $B_s^0: 151 \pm 25$, $B^0: 9530 \pm 110$

BR($B_s \rightarrow J/\psi K^*) = (8.3 \pm 1.2 \text{ (stat.)} \pm 3.3 \text{ (syst.)} \pm 1.0 \text{ (frag.)} \pm 0.4 \text{ (PDG)}) \cdot 10^{-5}$

8$\sigma$ significance w.r.t. null hypothesis
Bottom Baryon Resonances $\Sigma_b$ and $\Sigma_b^*$

- Discovered in 2006 by CDF.
- Uses 6 fb$^{-1}$ data from CDF.
- Two Track Trigger (TTT).
- Reconstruction mode:
  \[ \Sigma_{b}^{(*)\pm} \rightarrow \Lambda_{b}^{0} \pi^{\pm} \]
  \[ \Lambda_{b}^{0} \rightarrow \Lambda_{c}^{+} \pi^{-} \]
  \[ \Lambda_{c}^{+} \rightarrow pK^{-}\pi^{+} \]
- Analysis is performed on the Q-value, \( Q = m(\Lambda_{b}^{0} \pi^{\pm}) - m(\Lambda_{b}^{0}) - m(\pi^{\pm}) \), where the $\Lambda_{b}^{0}$ resolution is canceled out by taking the difference.
- **Main background:** random tracks from hadronization and underlaying events combining with real $\Lambda_{b}^{0}$.

**World’s largest $\Lambda_b$ sample!**

- Binned mass fit components
  - the $\Lambda_{b} \rightarrow \Lambda_{c}^{+} \pi^{-}$ signal
  - a combinatorial background
  - partially and fully reconstructed B mesons and $\Lambda_{b}^{0}$ baryons.
\( \Sigma_b \) and \( \Sigma_b^* \) Mass Fit

- The signal peaks are described by modified Breit-Wigner distributions convoluted with two gaussians to account for the detector resolution.

- Sources of systematics are:
  - Fit procedure.
  - Uncertainties on the momentum scale.
  - Assumptions made in the fitter for detector resolution and the background model.

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From the Q-values obtain isospin mass splittings:

\[ m(\Sigma_b^+) - m(\Sigma_b^-) = -4.2^{+1.1}_{-0.9} \text{(stat.)}^{+0.07}_{-0.09} \text{ (syst.) MeV/c}^2 \]

\[ m(\Sigma_b^{*+}) - m(\Sigma_b^{*-}) = -3.0 \pm 0.9 \text{(stat.)}^{+0.12}_{-0.13} \text{ (syst.) MeV/c}^2 \]

The widths:

\[ \Gamma(\Sigma_b^+) = 9.2^{+3.8}_{-2.9} \text{(stat.)}^{+1.0}_{-1.1} \text{ (syst.) MeV/c}^2 \]

\[ \Gamma(\Sigma_b^-) = 4.3^{+3.1}_{-2.1} \text{(stat.)}^{+1.0}_{-1.1} \text{ (syst.) MeV/c}^2 \]

\[ \Gamma(\Sigma_b^{*+}) = 10.4^{+2.7}_{-2.2} \text{(stat.)}^{+0.8}_{-1.2} \text{ (syst.) MeV/c}^2 \]

\[ \Gamma(\Sigma_b^{*-}) = 6.4^{+2.2}_{-1.8} \text{(stat.)}^{+0.7}_{-1.1} \text{ (syst.) MeV/c}^2 \]

Using the CDF Run2 \( \Lambda_b \) mass obtain the absolute masses:

\[ m(\Sigma_b^+) = 5811.2^{+0.9}_{-0.8} \text{(stat.)} \pm 1.7 \text{ (syst.) MeV/c}^2 \]

\[ m(\Sigma_b^-) = 5815.5^{+0.6}_{-0.5} \text{(stat.)} \pm 1.7 \text{ (syst.) MeV/c}^2 \]

\[ m(\Sigma_b^{*+}) = 5832.0 \pm 0.7 \text{(stat.)} \pm 1.8 \text{ (syst.) MeV/c}^2 \]

\[ m(\Sigma_b^{*-}) = 5835.0 \pm 0.6 \text{(stat.)} \pm 1.8 \text{ (syst.) MeV/c}^2 \]
Measurement of $B_s^0$ Semileptonic Asymmetry

- Measure flavor-specific asymmetry, $a_{fs}^s$, in $5 \text{ fb}^{-1}$
  - Time-dependent
  - Flavor-tagged
- Reconstruct $B_s^0 \rightarrow \mu^+ D_s^- X$
  - $D_s^- \rightarrow \phi \pi^- \rightarrow (K^- K^+) \pi^-$
  - $D_s^- \rightarrow K^0 K^-$
- Provides complementary way of measuring CP violating phase $\phi_s$

$$a_{fs}^s = \frac{\Gamma_{B_s^0(t) \rightarrow f} - \Gamma_{B_s^0(t) \rightarrow \bar{f}}}{\Gamma_{B_s^0(t) \rightarrow f} + \Gamma_{B_s^0(t) \rightarrow \bar{f}}}$$

arXiv:0904.3907

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Flavor-Specific Asymmetry

Extract asymmetry with un-binned maximum likelihood fit

\[
\begin{align*}
\Gamma_{B_s^0 \rightarrow \bar{f}} &= N_f |\bar{A}_f|^2 \frac{1}{2} (1 - \alpha_{fs}^s) e^{-\Gamma_{s} t} \left[ \cosh\left(\frac{\Delta \Gamma_{s} t}{2}\right) - \cos(\Delta \Gamma_{s} t) \right] \\
\Gamma_{B_s^0 \rightarrow f} &= N_f |\bar{A}_f|^2 \frac{1}{2} (1 + \alpha_{fs}^s) e^{-\Gamma_{s} t} \left[ \cosh\left(\frac{\Delta \Gamma_{s} t}{2}\right) - \cos(\Delta \Gamma_{s} t) \right]
\end{align*}
\]

Find

\[
\alpha_{fs}^s = \left[ -1.7 \pm 9.1 \text{(stat)} + 1.2 \text{(syst)} \right] \times 10^{-3}
\]

Uncertainties improved by factor of 2 over previous direct measurement!

Standard model prediction: \( \alpha_{fs}^s = (0.021 \pm 0.006) \times 10^{-3} \)
Conclusions

- Very rich heavy flavor program at the Tevatron. With over 8 fb\(^{-1}\) accumulated data per experiment and more to come, heavy flavor physics at Tevatron is in a high precision era.

- World’s best \(B_s\) and \(\Lambda_b\) lifetime measurements from CDF are in agreement with the world average and HQE predictions. The \(B^+\) and \(B^0\) lifetimes are competitive with B-factories.

- Observation of new hadrons and precision measurements of the properties of the established ones put the theoretical models to stringent tests.

- Stay tuned for more!!

  - DØ: [http://www-d0.fnal.gov/Run2Physics/WWW/results/b.htm](http://www-d0.fnal.gov/Run2Physics/WWW/results/b.htm)
BACKUP SLIDES
**B_s Lifetime in B_s → D_s^+(ϕπ) π^- X**

- **Data sample:**
  - 1.3 fb-1, collected with displaced vertex trigger
  - ~ 1100 fully reconstructed events
  - ~ 2000 partially reconstructed events

- Lifetime bias is modeled with a trigger efficiency curve from MC

- Partially reconstructed channels:
  - B_s → D_s^* π, D_s ρ^-(π^0 π^-)
  - triple the statistics!
B_s Lifetime in $B_s \rightarrow D_s^+(\phi\pi)\pi^- X$

Flavor-specific $\tau(B_s) = 1.518 \pm 0.041\,(\text{stat}) \pm 0.025\,(\text{syst})\,$ps

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World best measurement!