Measurement of the $\Lambda_b$ Lifetime in $\Lambda_b \rightarrow J/\psi \Lambda^0$ in $p\bar{p}$ Collisions at $\sqrt{s}=1.96$ TeV

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Lifetimes: Why Do We Care?

- The total width ($\Gamma$) of a particle, inversely related to the lifetime ($\tau$), characterizes underlying dynamics governing its decay
  → strong, electromagnetic, weak interactions

- Weak decay of hadrons depends upon fundamental parameters of the Standard Model we'd like to know
  → CKM matrix elements, quark masses

- Our world is one of quarks (and gluons) confined inside hadrons rather than weakly-decaying free quarks
  → Complicates theory interpretation of observations

- Lifetimes of weakly decaying hadrons of the same heavy flavor provide a quantitative connection between these two worlds
  → study of the interplay between the strong and weak interactions
  → important testbed for understanding of non-perturbative effects in QCD

\[ \frac{\tau(D^+)}{\tau(D^0)} \approx 2.5 \quad \frac{\tau(B^+)}{\tau(B^0)} \approx 1 \]

Increasing $m_Q \rightarrow \infty$ (spectator ansatz)
Lifetimes of $b$-Flavored Hadrons

Critical testbed for theoretical framework used to predict heavy quark quantities:

- Qualitatively expect: $\tau(B_c) \ll \tau(\Lambda_b) < \tau(B_s) \approx \tau(B^0) < \tau(B^+)$ but one can do better than this...!
- $b$-hadron lifetime ratios can be calculated with reasonable precision:
  - 2% for $\tau(B^+)/\tau(B^0)$, 1% for $\tau(B_s)/\tau(B^0)$, 6% for $\tau(\Lambda_b)/\tau(B^0)$

using Heavy Quark Expansion (HQE) since $m_b \gg \Lambda_{QCD} \rightarrow$ large energy release in decay.

**Pauli Interference**

Same final state $\Rightarrow$ interference (destructive)

**Weak Annihilation**

Only charged B mesons

**Weak Scattering/Exchange**

Different final states $\Rightarrow$ no interference

- $b$-hadron lifetime ratios can be calculated with reasonable precision:
  - 2% for $\tau(B^+)/\tau(B^0)$, 1% for $\tau(B_s)/\tau(B^0)$, 6% for $\tau(\Lambda_b)/\tau(B^0)$
Heavy Quark Expansion

Inclusive decay width expressed as an operator product expansion (OPE) in $\Lambda_{\text{QCD}}/m_b$ and $\alpha_s(m_b)$

\[
\Gamma = \frac{G_F^2 |V_{cb}|^2 m_b^5}{192\pi^3 (2M_B)} \left[ c^{(3)} \langle \bar{b}b \rangle + c^{(5)} \left( \frac{g_s}{m_b^2} \langle \bar{b} \sigma_{\mu\nu} G^{\mu\nu} b \rangle \right) + \frac{96\pi^2}{m_b^3} \sum_k c^{(6)}_k \langle O_k^{(6)} \rangle \right] + \mathcal{O}(1/m_b^4)
\]

- $c^{(n)}_i$ contain short-distance physics from scales $\geq \mu = \mathcal{O}(m_b)$ → perturbatively calculable
- Matrix elements contain long-distance physics → hard! especially for baryons
- Spectator contributions enter at $1/m_b^3$ (~5-10%)

NLO QCD and sub-leading spectator corrections can be important!
For $\tau(\Lambda_b)/\tau(B^0)$:
- NLO QCD: -8% (hep-ph/0203089)
- Sub-leading spectator: -(2-3)% (hep-ph/0407004)
**$\Lambda_b$ Lifetime: Before Us**

<table>
<thead>
<tr>
<th>$\Lambda_b$ Lifetime Measurements</th>
<th>$\tau_{\Lambda_c}/\tau_{B^0_{PDG}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH $\Lambda_c$ I $,(91-95)$</td>
<td>1.18 $^{+0.13}_{-0.12} \pm 0.03$</td>
</tr>
<tr>
<td>ALEPH $\Lambda^0 IT$ $,(91-95)$</td>
<td>1.30 $^{+0.26}_{-0.21} \pm 0.04$</td>
</tr>
<tr>
<td>OPAL $\Lambda_c$ I $,(90-95)$</td>
<td>1.29 $^{+0.24}_{-0.22} \pm 0.06$</td>
</tr>
<tr>
<td>DELPHI $\Lambda_c$ I $,(91-95)$</td>
<td>1.11 $^{+0.19}_{-0.18} \pm 0.05$</td>
</tr>
<tr>
<td>CDF $\Lambda_c$ I $,(92-95)$</td>
<td>1.32 $^{+0.15}_{-0.06} \pm 0.06$</td>
</tr>
<tr>
<td>CDF Prelim $J/\psi \Lambda^0 H$ 65 $,\text{pb}^{-1}$</td>
<td>1.25 $^{+0.26}_{-0.26} \pm 0.14$</td>
</tr>
<tr>
<td>D0 $J/\psi \Lambda^0$ $250 ,\text{pb}^{-1}$ $,(02-04)$</td>
<td>1.22 $^{+0.22}_{-0.18} \pm 0.04$</td>
</tr>
</tbody>
</table>

**Semi-leptonic modes (dominant)**

**Fully -reconstructed modes**

For $\tau(\Lambda_b)/\tau(B^0)$, early theory predictions ($\sim 0.94$) and experiment differed by more than $2\sigma$ $\rightarrow$ "$\Lambda_b$ lifetime puzzle"

Current NLO QCD $+1/m_b^4$ calculation: $\tau(\Lambda_b)/\tau(B^0) = 0.86 \pm 0.05$

consistent w/ HFAG 2005 world avg: $\tau(\Lambda_b)/\tau(B^0) = 0.803 \pm 0.047$

The situation is far from resolved - need more experimental input on $\tau(\Lambda_b)$!

Tarantino, et al. hep-ph/0203089
**Lifetime: Analysis Strategy**

**Pros:**
- Mass peak to distinguish signal & bkg
- Event-by-event measure of $\beta\gamma$ (boost)
  (Do not rely on MC to account for unobserved $\nu$ as in semi-leptonics)

**Con:**
- Smaller signal $\rightarrow$ larger stat. error

**Use $\tau(B^0)$ measurement in $B^0 \rightarrow J/\psi K_s$ as reference mode**

$\rightarrow$ similar decay: $J/\psi + V^0$ ($V^0 \equiv K^0_s, \Lambda^0$)

$\rightarrow$ larger sample: $\sim 6 \times \Lambda_b$

**Check lifetime in fully reconstructed $B_{u,d} \rightarrow (J/\psi, \psi') + X$ decay modes**

$\rightarrow$ validate lifetime analysis using $J/\psi$ vertex only for all decay modes

$$ct = \frac{L^b_{xy}}{(\beta\gamma)^b_T} = L^b_{xy} c M^b_b \frac{M^b_b}{P^b_t}, \text{ where } L^b_{xy} = |\bar{x}(J/\psi) - \bar{x}(PV)| \cdot \hat{P}^b_t$$

**Measure $\tau(\Lambda_b)$ in fully-reconstructed decay channel $\Lambda_b \rightarrow J/\psi \Lambda^0$**
# b-Hadron Lifetimes We Measure

<table>
<thead>
<tr>
<th>Process</th>
<th>Full systematics</th>
<th>Statistical errors only (for cross-$\sqrt{\cdot}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow J/\psi K_s$, $\psi(2S) K_s$, $\psi(2S) K_s$</td>
<td>$J/\psi \rightarrow \mu\mu$, $K_s \rightarrow \pi\pi$</td>
<td>$J/\psi \rightarrow \mu\mu$, $K_s \rightarrow \pi\pi$</td>
</tr>
<tr>
<td>$B^0 \rightarrow J/\psi K^{*0}$, $\psi(2S) K^{*0}$, $\psi(2S) K^{*0}$</td>
<td>$J/\psi \rightarrow \mu\mu$, $K^{*0} \rightarrow K\pi$</td>
<td>$J/\psi \rightarrow \mu\mu$, $K^{*0} \rightarrow K\pi$</td>
</tr>
<tr>
<td>$B^+ \rightarrow J/\psi K^+$, $\psi(2S) K^+$, $\psi(2S) K^+$</td>
<td>$J/\psi \rightarrow \mu\mu$</td>
<td>$J/\psi \rightarrow \mu\mu$</td>
</tr>
<tr>
<td>$B^+ \rightarrow J/\psi K^{*+}$</td>
<td>$J/\psi \rightarrow \mu\mu$, $K^{*+} \rightarrow K_s\pi$</td>
<td>$J/\psi \rightarrow \mu\mu$, $K^{*+} \rightarrow K_s\pi$</td>
</tr>
<tr>
<td>$\Lambda_b \rightarrow J/\psi \Lambda^0$, $J/\psi \rightarrow \mu\mu$, $\Lambda^0 \rightarrow p\pi$</td>
<td>$J/\psi \rightarrow \mu\mu$, $\Lambda^0 \rightarrow p\pi$</td>
<td>$J/\psi \rightarrow \mu\mu$, $\Lambda^0 \rightarrow p\pi$</td>
</tr>
</tbody>
</table>

Our primary goal
Results: Yield

\[ B^0 \rightarrow J/\psi K_s \]

\[ \Lambda^0 \rightarrow J/\psi \Lambda^0 \]

CDF Run II \( \int L \, dt = 1.0 \, \text{fb}^{-1} \)

\begin{align*}
N(B^0) &= 3376 \pm 88 \\
N(\Lambda_b) &= 538 \pm 38
\end{align*}
Overall probability density function (PDF) is a normalized sum of signal and background contributions:

\[
P(\lambda_i, \sigma^\lambda_i, m_i, \sigma^m_i \mid \bar{\xi}) = (1 - f_b) P_{\text{sig}} + f_b P_{\text{bkg}}
\]

where:

- \(\lambda_i\) = PDL
- \(\sigma^\lambda_i\) = PDL error
- \(m_i\) = mass
- \(\sigma^m_i\) = mass error

\(P_{\text{sig}}, P_{\text{bkg}}\) are products of PDL, PDL error, and mass PDFs:

\[
P_{\text{sig}, \text{bkg}} = P^\lambda_{\text{sig}, \text{bkg}}(\lambda_i \mid \sigma^\lambda_i, \tilde{\alpha}) P^{\sigma^\lambda}_{\text{sig}, \text{bkg}}(\sigma^\lambda_i \mid \tilde{\beta}) P^m_{\text{sig}, \text{bkg}}(m_i \mid \sigma^m_i, \tilde{\gamma})
\]

Unbinned maximum likelihood fit to extract \(\bar{\xi} = [\tilde{\alpha}, \tilde{\beta}, \tilde{\gamma}, \tilde{\delta}]\)

(\(\bar{\xi}\) contains 18 parameters, including signal c\(\tau\))
Signal PDL modeled as an exponential decay convoluted with a Gaussian resolution function:

$$P^\lambda_{\text{sig}}(\lambda_i, \sigma^\lambda_i | \tilde{\alpha}_{\text{sig}}) = E(\lambda_i | c\tau) \ast G(\lambda_i, \sigma^\lambda_i | s)$$

where:

- $\tau = \text{signal lifetime (the goal)}$
- $s = \text{overall scale factor on PDL errors}$

$$E(\lambda_i | c\tau) = \begin{cases} 
\frac{1}{c\tau} e^{-\lambda_i / c\tau}, & \lambda_i \geq 0 \\
0, & \lambda_i < 0 
\end{cases}$$

$$G(\lambda_i, \sigma^\lambda_i | s) = \frac{1}{\sqrt{2\pi s \sigma^\lambda_i}} e^{-\frac{-\lambda_i^2}{2(s\sigma^\lambda_i)^2}}$$

$c\tau = 368 \ \mu m$
$s\sigma = 36 \ \mu m$
Fit Model: Background PDL

Background PDL modeled as sum of four components:

\[ P_{\text{bkg}}^\lambda (\lambda_i|\sigma_i^\lambda, s, f_-, \lambda_-, f_+, \lambda_+, f_{++}, \lambda_{++}) = G(\lambda_i, \sigma_i^\lambda|s) \times \{ \]
\[ (1-f_-f_-f_{++}) \delta(0) + f_- E(-\lambda_i|\lambda_-) + f_+ E(\lambda_i|\lambda_+) + f_{++} E(\lambda_i|\lambda_{++}) \} \]

where:

- \( f_- \) = negative exponential fraction
- \( \lambda_- \) = negative exponential decay length
- \( f_{++} = 1^{\text{st}}(2^{\text{nd}}) \) positive exponential fraction
- \( \lambda_{++} = 1^{\text{st}}(2^{\text{nd}}) \) positive exponential decay length

Fits with different shape assumptions used to constrain systematic
Results: Lifetime

$B^0 \to J/\psi K_s$

CDF Run II

$\int L \ dt = 1.0 \ fb^{-1}$

$\tau(B^0) = 456.8^{+9.0}_{-8.9} \ \mu m$

$\Lambda^0 \to J/\psi \Lambda^0$

CDF Run II

$\int L \ dt = 1.0 \ fb^{-1}$

$\tau(\Lambda_b) = 477.6^{+25.0}_{-23.4} \ \mu m$
**b-Hadron Lifetime Summary**

These are not $\tau(B^0), \tau(B^+)$ measurements:

- Statistical errors only!

$\Rightarrow$ High-level validation of analysis for well-established $B^0/B^+$ lifetimes

We use these results to cross-$\sqrt{\text{our measurement of lifetimes}}$

in fully-reconstructed decay using $J/\psi$ to determine $B$ decay vertex
## Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>cτ (B^0) [μm]</th>
<th>cτ (Λ_b) [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fitter Bias</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Fit Model:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ct Resolution</td>
<td>3.1</td>
<td>5.5</td>
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<tr>
<td>Mass Signal</td>
<td>0.7</td>
<td>2.3</td>
</tr>
<tr>
<td>Mass Background</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>ct Background</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>σ^ct Distribution Modeling</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>σ^m Distribution Modeling</td>
<td>0.6</td>
<td>0.2</td>
</tr>
<tr>
<td>Mass-cτ Background Correlation</td>
<td>1.9</td>
<td>4.1</td>
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<tr>
<td>cτ-σ^ct Background Correlation</td>
<td>0.3</td>
<td>1.3</td>
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<tr>
<td>Primary Vertex Determination</td>
<td>0.2</td>
<td>0.3</td>
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<tr>
<td>Alignment:</td>
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<tr>
<td>SVX Internal</td>
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<tr>
<td>SVX/COT Global</td>
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<td>3.2</td>
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<tr>
<td>V^0 Pointing</td>
<td>0.6</td>
<td>5.4</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>4.9</strong></td>
<td><strong>9.9</strong></td>
</tr>
</tbody>
</table>
Summary of Results

We measure in decay mode $B^0 \rightarrow J/\psi K_s$:

$$c\tau (B^0) = 456.8 \pm 9.0 \text{ (stat.)} \pm 4.9 \text{ (syst.)} \mu m$$

$$= 1.524 \pm 0.030 \text{ (stat.)} \pm 0.016 \text{ (syst.)} \text{ ps}$$

consistent w/ PDG 2004 value of $1.530 \pm 0.009 \text{ ps}$

We also measure in decay mode $\Lambda_b \rightarrow J/\psi \Lambda^0$:

$$c\tau (\Lambda_b) = 477.6 \pm 25.0 \text{ (stat.)} \pm 9.9 \text{ (syst.)} \mu m$$

$$= 1.593 \pm 0.083 \text{ (stat.)} \pm 0.033 \text{ (syst.)} \text{ ps}$$

Three completely independent analysis implementations within our group have confirmed these results.
Conclusions

Using our $\Lambda_b$ lifetime and the PDG 2004 $B^0$ lifetime, we get

$$\tau (\Lambda_b) / \tau (B^0) = 1.041 \pm 0.057 \text{ (stat.+syst.)}$$

This result is inconsistent with PDG 2004 world average $\tau (\Lambda_b)$ @ 3.2$\sigma$ level

Our $\tau(\Lambda_b)$ measurement is the world's most precise measurement → best by far in a fully reconstructed decay channel

and consistent with theory
The New D0 1fb⁻¹ Result

$$\tau(\Lambda_b) = 1.298 \pm 0.137 \text{(stat.)} \pm 0.050 \text{(syst.)} \text{ ps (D0 1fb}^{-1})$$

Note different x-axis scale!
Current experimental situation:

\[ \tau(\Lambda_b) \text{ in } \Lambda_b \to \Lambda_c \pi \text{ from CDF is the next step!} \]
Thanks from the Authors!

Many thanks to our **godparents**:
- Rick Field (chair), Farrukh Azfar, Fabrizio Scuri

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- HEP Korea, MIT, Barcelona, Illinois, IPP-Canada, SPRG, Beate, Joe Kroll

**B physics group conveners**:
- Matthew Herndon and Kevin Pitts

**Lifetime and Mixing sub-group conveners**:
- Guillelmo Gomez-ceballos and Sinead Farrington
Extras
From talk by Alexey Petrov @ ICHEP 2006
(the overlay of our result in black is mine)