Beauty physics with $B_s$ and $\Lambda_b$

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Selected topics

- Masses
- Lifetimes
- $B_s$ lifetime difference
- Charmless $B_s$ and $\Lambda_b$ decays
- $B_s$ oscillations

*Rare decays covered today by YoungJoon Kwon*

*CP violation covered today by Emmanuel Olaiya*
The B hadron family

weakly decaying beauty hadrons (PDG 2003)

Not yet unambiguously observed:

- $\Xi_b^-$ bds
- $\Xi_b^0$ bus
- $\Omega_b^-$ bss
What's so special about spectator quarks?

1. The spectator quarks makes or breaks a CP-Eigen state

\[ B_d \rightarrow D_s^+D^- \quad (CP \text{ mixed}) \quad \text{vs} \quad B_s \rightarrow D_s^+D_s^- \quad (CP \text{ even}) \]

\[ \Rightarrow \text{sizable lifetime difference in } B_s \]

2. The spectator quark can exchange with the b

\[ B^0 \quad \text{vs} \quad B^0_S \]

\[ \Rightarrow B_s \text{ oscillates } >25 \text{ times faster than } B_d \]

3. The spectator quark can annihilate the b

\[ \text{Br}(B_s \rightarrow \mu^+\mu^-) \gg \text{Br}(B_d \rightarrow \mu^+\mu^-) \]

\[ \Rightarrow \text{heavy B-hadrons provide unique window on B-physics} \]
Producing heavy B hadrons

Y(4S): B⁺ / B⁰ only

- Bₛ at Y(5S): ≈ 10x smaller cross-section than B₃d at Y(4S)

→ e⁺ e⁻ above Bₛ threshold:
  • LEP ≈ 880k b̅b events/experiment
  • SLC ≈ 85k b̅b events

→ Fixed target Eₘₑ > 2m(Bₛ)
  • Tried unsuccessfully at HERA-B \( \sigma(b\bar{b})/\sigma(total) \approx 10^{-6} \)

→ Hadron colliders:
  • Operational: Tevatron, Chicago, 1.96 TeV pp \( \sigma_{bb}/\sigma_{tot} \approx 10^{-3} \)
  • Startup 2007: LHC, Geneve 14TeV pp \( \sigma_{bb}/\sigma_{tot} \approx 10^{-2} \)

Production ratio at high energy:

\( B^0 : B^- : B_s : \Lambda_b : B_c \approx 4 : 4 : 1 : 1 : 0.01 \)
Reconstructing B-decays

Generally 3 types of B-decays accessible at hadron collider:

- Semi-leptonic B decays
  - Pro: large branching ratios → large yields
  - Con: missing neutrino

- B decays to J/ψ
  - Pro: muon provides easy trigger
  - Con: small branching fractions

- Fully hadronic B decays
  - Pro: ≈80% of branching fraction
  - Con: requires silicon track trigger
**Tevatron detectors: CDF and DØ**

**CDF:**
- Displaced track trigger
- PID: TOF and dE/dx
- Better mass resolution

**DØ:**
- Larger muon coverage
- Better forward tracking

Strong in J/ψ modes
Strong in semi-leptonic modes

Strong in fully hadronic modes
Forward is the future

**LHCb: startup 2007**

- pp collisions at $E_{cm}=14\text{TeV}$

**BTeV: startup 2009**

- $p\bar{p}$ collisions at $E_{cm}=1.96\text{TeV}$

**Forward region:**
- High cross-sections
- High boost $\Rightarrow$ longer lifetimes
- Often both B's in acceptance
- Ring Imaging Cherenkov for $\pi, K, p$ identification
Mass measurements

Best mass measurements from fully reconstructed decays

100 events with 10MeV resolution give a 1 MeV mass measurement

CDF Run II Preliminary 220 pb⁻¹

\( \Lambda_B \rightarrow J/\psi \Lambda \) 

\( N(\Lambda_b) = 88.6 \pm 10.3 \) 

Prob: 22.3% chisquare: 1.17

\( B_c \) only observed in semileptonic decay \( \Rightarrow \) large uncertainty on mass

CDF Run I: \( m(B_c) = 6.39 \pm 0.39 \pm 0.26 \) GeV

look forward to fully reconstructed \( B_c \rightarrow J/\psi \pi^+ \) signal

\( B_s^0 \rightarrow J/\psi + \phi \)

\( N = 403 \pm 28 \)
New CDF $m(B_s)$ and $m(\Lambda_b)$ results

Dramatic improvements w.r.t to PDG2004:

Little physics motivation to go below 1MeV level.
Beauty hadron lifetimes

To first order: lifetime determined by fastest decaying quark

\[ \tau(B^+) \approx \tau(B^0) \approx \tau(B_s) \approx \tau(\Lambda_b) \gg \tau(B_c) \]

Spectator effects can be calculated in Heavy Quark Expansion

*Dominated by \((\Lambda_{QCD}/m_b)^3\) contributions*

\[
\frac{\tau(B^+)}{\tau(B_d)} = 1.06 \pm 0.02
\]
\[
\frac{\tau(B_s)}{\tau(B_d)} = 1.00 \pm 0.01
\]
\[
\frac{\tau(\Lambda_b)}{\tau(B_d)} = 0.90 \pm 0.05
\]
Bs and Λb lifetime measurements

Best B⁺, B⁰ lifetimes from Y(4S): ≈1% accuracy
Best Bₚ, Λb results from semi-leptonic decays at CDF1, LEP:

\[
\begin{align*}
\tau(B_s) &= 1.46 \pm 0.06 \text{ps} \\
\tau(Λ_b) &= 1.23 \pm 0.08 \text{ps}
\end{align*}
\]

Needs correction for the missing neutrino.
⇒ irreducible systematics from:
  • decay model
  • production model

Fully reconstructed modes allow model-independent lifetime measurement

\[
\frac{\tau(Λ_b)}{\tau(B_d)} = 0.80 \pm 0.05: \\
\text{shorter than predicted } 0.90 \pm 0.05
\]
Latest DØ and CDF fully reconstructed lifetimes approach competitive precision:

CDF 220pb\(^{-1}\): \(\tau(B_s \rightarrow J/\psi \phi) = 1.37 \pm 0.10 \pm 0.01\)ps
DØ 115pb\(^{-1}\): \(\tau(B_s \rightarrow J/\psi \phi) = 1.19 \pm 0.19 \pm 0.14\)ps
CDF 65pb\(^{-1}\): \(\tau(\Lambda_b \rightarrow J/\psi \Lambda) = 1.25 \pm 0.26 \pm 0.10\)ps

Look forward this summer:
- \(B_s, \Lambda_b\) lifetime with more data
- semi-leptonic modes
- hadronic modes: \(B_s \rightarrow D_s \pi, \Lambda_b \rightarrow \Lambda_c \pi\)
**B_s lifetime difference**

B_s has a large branching fraction to CP eigenstates

Dominated by b→c\bar{c}s transition: B_s → D_s(*)^+ + D_s(*)^-

for B_d : b→c\bar{c}d : Cabibbo suppressed → 20× smaller

SM prediction \( \Delta \Gamma_s/\Gamma_s = \Gamma_L-\Gamma_H = 0.074\pm0.024 \)

World average: \( \Delta \Gamma_s/\Gamma_s = 0.07^{+0.09}_{-0.07}( < 0.29 \text{ at } 95\% \text{ CL}) \)

SLD, LEP, CDFI results + \( \tau(B_s) = \tau(B_d) \) constraint

**Three ways to measure:**

- Fit CP-mixed decay distribution to double exponential
  *Only sensitive to \((\Delta \Gamma)^2 \rightarrow \text{poor at low } \Delta \Gamma\)*

- Compare \( \tau(B_s \rightarrow \text{CP even}) \) to \( \tau(B_s \rightarrow \text{CP mixed or CP odd}) \)
  *Angular analysis of \( B_s \rightarrow J/\psi \phi \) separates CP even and CP odd
  Semileptonic \( B_s \rightarrow D_s \mu \nu \) and hadronic \( B_s \rightarrow D_s \pi \) are CP mixed*

- Indirect: measure \( \text{Br } ( B_s \rightarrow D_s(*)^+D_s(*)^-) \)
\( \mathcal{B}_s \rightarrow \mathcal{J/\psi} \phi \) angular analysis

Pseudoscalar → Vector Vector decay
\( \Rightarrow 3 \) invariant angles: \( \Theta_K, \Theta_T, \Phi_T \)

\[
\mathcal{G} = \frac{9}{32\pi} \left\{ 2 \cos^2 \Theta_K \ast (1 - \sin^2 \Theta_T \cos^2 \Phi_T) |A_0|^2 \\
+ \sin^2 \Theta_K \ast (1 - \sin^2 \Theta_T \sin^2 \Phi_T) |A_\parallel|^2 \\
+ \sin^2 \Theta_K \ast \sin^2 \Theta_T |A_\perp|^2 \\
- \sin^2 \Theta_K \ast \sin 2\Theta_T \sin \Phi_T \text{Im}(A_\parallel^* A_\perp) \zeta \\
+ \frac{1}{\sqrt{2}} \sin 2\Theta_K \ast \sin^2 \Theta_T \sin 2\Phi_T \text{Re}(A_0^* A_\parallel) \\
+ \frac{1}{\sqrt{2}} \sin 2\Theta_K \ast \sin 2\Theta_T \cos \Phi_T \text{Im}(A_0^* A_\perp) \zeta \right\}
\]

\( \Rightarrow 3 \) (complex) amplitudes: \( A_0, A_\parallel, A_\perp \)
CDF angular analysis

Using $\approx 180 \, B_s \to J/\psi \phi$ in $180 \text{pb}^{-1}$ CDF finds:

$$A_0 = 0.767 \pm 0.045 \pm 0.017$$

$$A_{||} = (0.424 \pm 0.118 \pm 0.013)e^{(2.11\pm0.55\pm0.29)i}$$

$$|A_{\perp}| = 0.482 \pm 0.104 \pm 0.014$$

$B_s \to J/\psi \phi$ is $\approx 80\%$ CP-even

$\Rightarrow$ expect $\tau(B_s \to J/\psi \phi) < \tau(B_s \to D_s \mu \nu)$

$$\begin{cases}
\text{CP even} \\
\text{short-lived}
\end{cases}$$

$$\begin{cases}
\text{CP odd} \\
\text{long-lived}
\end{cases}$$

$\Delta \Gamma_s$ is imminent
Charmless decays

Rare $b \to u$ transitions probe $|V_{ub}|$ and its phase $\gamma$

In practice: spoiled by penguin transitions

Compare $B_s$, $B_d$ decays to disentangle penguin, $V_{ub}$ contributions

2-body decays challenging: $B_d \to K^+\pi^-$ overlaps $B_s \to K^+K^-$

CDF measures in 65pb$^{-1}$:

$\text{Br}(B_s \to K^+K^-)/(B_d \to K^+\pi^-) = 2.71 \pm 0.73 \pm 0.88$

Statistical separation with $1.15\sigma$ dE/dx and kinematics

SM OK!
New CDF search for $\Lambda_b \rightarrow pK,p\pi$

Prediction: *Mohanta, Giri, Khanna 2001*

- $\text{Br}(\Lambda_b \rightarrow pK) = (1.4-1.9) \times 10^{-6}$
- $\text{Br}(\Lambda_b \rightarrow p\pi) = (0.8-1.2) \times 10^{-6}$

Previous best limit from ALEPH:

$\text{Br}(\Lambda_b \rightarrow p\pi+pK) < 50 \times 10^{-6}$ @90%CL

Optimized search in the high-mass region of $B \rightarrow \pi\pi$ plot

767 events in signal region
772 background events
no signal observed

$\text{Br}(\Lambda_b \rightarrow p\pi+pK) < 22 \times 10^{-6}$ @90%CL

*Compare to $\text{Br}(B^0 \rightarrow K^+\pi) = (18 \pm 1) \times 10^{-6}$*
First observation of $B_s \rightarrow \phi \phi$

$B \rightarrow s\bar{s}s$ penguin transition,

*The $B_s$ equivalent of $B_d \rightarrow \phi K^0_S$*

Predicted $\text{BR}(B_s \rightarrow \phi \phi)$:

- Factorization: $(0.4-25) \times 10^{-6}$
  
  Chen, Chen, Tseng 2003

- QCD factorization: $(18-37) \times 10^{-6}$
  
  Li, Lu, Yang 2003

Blind search: cuts optimized on signal MC and $\phi$ sidebands

12 observed, $1.95 \pm 0.62$ background

$\text{BR}(B_s \rightarrow \phi \phi) = (14 \pm 6(\text{stat.}) \pm 2(\text{syst.}) \pm 5(\text{BR's})) \times 10^{-6}$

Wonderful channel with bright future for:

- Angular analyses
- $\Delta \Gamma_s$ measurement
- CP violation
Bs oscillations

Bd oscillations are sensitive to |Vtd|
Compromised by hadronic uncertainties

Most cancel in Bd/Bs oscillation ratio:

\[ \frac{\Delta m_s}{\Delta m_d} = \frac{m_s}{m_d} (1.15 \pm 0.06^{+0.12}_{-0.00})^2 \left| \frac{V_{ts}}{V_{td}} \right|^2 \]

Double motivation:

New physics may affect \( \Delta m_s/\Delta m_d \)
\( \Delta m_s \) measurement prerequisite for time-dependent CP violation measurements with Bs
Current status of $B_s$ mixing

Heavy Flavor Averaging group: Combined LEP, SLD, CDF1

Most analyses used partially reconstructed decays

Poor sensitivity at high $\Delta m_s$

$$\sigma(A) \propto e \frac{(\sigma(ct) \Delta m_s)^2}{2}$$

⇒ for $\Delta m_s > 15\text{ps}^{-1}$

$\sigma(ct)$ above 67fs hurts!

$\Delta m_s > 14.5\text{ps}^{-1} \rightarrow$ more than 3 full oscillations per lifetime

From CKM fit: $\Delta m_s < 30\text{ps}^{-1} @95\%\text{CL}$
Towards $B_s$ oscillations

DØ has the largest yields in semileptonic modes:

CDF has fully reconstructed hadronic decays

The race is on!
Flavor tagging at hadron colliders

For oscillations: compare flavor at production with flavor at decay

"opposite" side

Jet charge

"opposite" side

Vertexing side

Opposite Kaon

fragmentation Kaon

Soft lepton

Jet charge

b-hadron

Soft lepton

D_{S}^{-}

B_{S}

\pi^{+}

Measure efficiency $\varepsilon$ and dilution factor $D$

<table>
<thead>
<tr>
<th>$\varepsilon D^2$ [%]</th>
<th>CDF</th>
<th>DØ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft muon</td>
<td>0.7 ± 0.1</td>
<td>1.6 ± 1.1</td>
</tr>
<tr>
<td>Soft electron</td>
<td>in progress</td>
<td>in progress</td>
</tr>
<tr>
<td>Jet charge</td>
<td>0.43 ± 0.03</td>
<td>3.3 ± 1.7</td>
</tr>
<tr>
<td>Same side (B^+)</td>
<td>2.8 ± 0.5</td>
<td>5.5 ± 2.0</td>
</tr>
<tr>
<td>Opp. side kaon</td>
<td>in progress</td>
<td></td>
</tr>
<tr>
<td>Same side kaon</td>
<td>in progress</td>
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Compare to B factories: $\varepsilon D^2 \approx 30\%$
Proof of principle: $B_d$ mixing

- $26k \, B^0 \rightarrow D^*-\mu^+\nu$
- Opposite side muon tag

- $6k \, B^0 \rightarrow D^-\pi^+, \, J/\psi \, K^{*0}$
- Same-side pion tag

$\Delta m_d = 0.506 \pm 0.055 \pm 0.049 \, \text{ps}^{-1}$

Both consistent with world average $\Delta m_d = 0.502 \pm 0.007$

Rudolf Oldeman (INFN Roma 1 ‘La Sapienza’) Physics in Collision 2004, Boston  
June 27, 2004
Conclusion

$\Lambda_b$ and especially $B_s$ gives unique window on B physics

CDF, DØ improved mass, lifetime using up to $> 2\times$ Run1 data

$B_s \to J/\psi \phi$ mostly CP even. $\Delta \Gamma_s$ measurements imminent

New modes:
• Charmed hadronic: $B_s \to D_s \pi, \Lambda_b \to \Lambda_c \pi$
• Charmless hadronic: $B_s \to K^+K^-, B_s \to \phi\phi$, new limit $\Lambda_b \to pK,p\pi$

Ingredients for $B_s$ mixing getting ready…

The future for $B_s$ looks strange but beautiful
New results on $B_s \to \mu^+\mu^-$

Experimental limits @90%CL:

<table>
<thead>
<tr>
<th></th>
<th>$B_s \to \mu^+\mu^-$</th>
<th>$B_d \to \mu^+\mu^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDFI</td>
<td>$20 \times 10^{-7}$</td>
<td>$6.8 \times 10^{-7}$</td>
</tr>
<tr>
<td>DØ</td>
<td>$16 \times 10^{-7}$</td>
<td></td>
</tr>
<tr>
<td>CDF</td>
<td>$5.8 \times 10^{-7}$</td>
<td>$1.5 \times 10^{-7}$</td>
</tr>
<tr>
<td>Belle</td>
<td>$1.6 \times 10^{-7}$</td>
<td></td>
</tr>
<tr>
<td>Babar</td>
<td>$2.0 \times 10^{-7}$</td>
<td></td>
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Expected limit with $180\,pb^{-1}$: $11 \times 10^{-7}$ @95%CL
Mass scale calibration

Critical: calibration of momentum scale to $<1 \times 10^{-4}$ level

Two components:
- B field calibration
- Material calibration

use $\approx 5 \times 10^5 \text{ J/} \psi \rightarrow \mu^+ \mu^-$ decays
Tevatron performance

Record initial luminosity:
- $8.3 \times 10^{31}$ on June 21, 2004
- $8.5 \times 10^{31}$ on June 22, 2004

Delivered luminosity in 2004 already surpassed 2003 total

High luminosity has a dark side:
- Less trigger bandwidth for B-physics
- Overlapping events degrade performance