Recent $B$ Physics Results at DØ

Alexander Rakitin
Lancaster University
Representing the DØ Collaboration

Lake Louise Winter Conference
February 18 – 23, 2008
Lake Louise, Alberta, Canada

- Study of production and properties of heavy-flavor hadrons
- Indirect searches for new physics (NP)
DØ Detector

- Multi-purpose detector
- Silicon and fiber trackers immersed in 2 T solenoid, coverage $|\eta| < 3$
- Muon system (central + forward), coverage $|\eta| < 2$
  - Includes its own magnet – toroid
- Two magnets – solenoid and toroid – flip polarity every two weeks
  - Unique feature of DØ
“Three-Scoop” Baryon $\Xi_b^-(dsb)$

$b$-Baryon 20-plet:

$J = 1/2$ $b$ Baryons

$\Xi_b^- \rightarrow \Lambda \pi^-, \Lambda \rightarrow p \pi^-$:

- $N(\Xi_b^-) = 15.2 \pm 4.4$ (stat.) $\pm 1.9$ (syst.)
- Stat. significance $5.5\sigma$
- $m(\Xi_b^-) = 5.774 \pm 0.011$ (stat.) $\pm 0.015$ (syst.) GeV/$c^2$
- Relative production rate:

$$\frac{f(b \rightarrow \Xi_b^-) \cdot Br(\Xi_b^- \rightarrow J/\psi \Xi^-)}{f(b \rightarrow \Lambda_b) \cdot Br(\Lambda_b \rightarrow J/\psi \Lambda)} = 0.28 \pm 0.09^{+0.09}_{-0.08}$$

- DØ: [PRL99, 1052001 (2007)]
- CDF: [PRL99, 052002 (2007)]
Orbitally Excited $b$ Mesons

- In HQET $Qq$ meson is similar to hydrogen atom
- Predicted: Two broad $jq = \frac{1}{2}$ and two narrow $jq = \frac{3}{2}$ excited states
- Search for narrow states: $B_s^{**} \to B^{(*)}\pi$ (left) and $B_s^{**} \to B^{(*)}K$ (right)
- $B_s^{**} \to B_s^{(*)}\pi$ forbidden by isospin
- Expect 3 peaks: $B_{(s)1} \to B^{*}\pi(K)$, $B_{(s)2}^{*} \to B^{*}\pi(K)$, $B_{(s)2} \to B\pi(K)$
- $B_{(s)1} \to B\pi(K)$ is forbidden

Fit for $B_1$ and $B_2^*$ [PRL 99, 172001 (2007)]

- Stat. significance > 7σ
- All masses and branchings are measured

Fit for $B_{s1}$ and $B_{s2}^*$ [hep-ex/0711.0319, Acc. by PRL]

- $N(B_{s2}^*) = 125 \pm 25$(stat.); Significance $4.8\sigma$
- Mass and branching are measured
- $N(B_{s1}) = 25 \pm 10$(stat.); Significance < $3\sigma$
- More data is required to claim observation of $B_{s1}$
Motivation:

- Semileptonic decays of $B_s$ into $L = 1$ states ($D_s^{**}$) comprise significant part of total $B_s$ width
- Important in inclusive/exclusive decay rates, CKM elements, $B_s$-mixing
- Help us better understand $D_{sJ}$ systems

Analysis: [hep-ex/0712.3789]

- Start reconstruction with $B \to \mu D^0 X, D^0 \to K\pi$
- Add a soft pion $\pi_s$ to get $B \to \mu D^* X, D^* \to D^0 \pi_s$ (top plot)
- Then add $K^0_S \to \pi^+\pi^-$ and get $D_s^{**}$ (bottom plot)

Results:

- $N(D_{s1}) = 45.9 \pm 9.1$ (stat.)
- Statistical significance 6.1$\sigma$
- $m(D_{s1}) = 2535.7 \pm 0.6 \pm 0.5$ GeV/$c^2$ (agrees with PDG)
- $Br(B_s^0 \to D_{s1}\mu\nu X) = 1.03 \pm 0.20$(stat.) $\pm 0.17$(syst.) $\pm 0.14(B\%$
- Largest uncertainty - from $K^0_S$ acceptance
- First $Br$ measurement
- Consistent with predictions: 0.2 – 1.1%

**Lifetimes \((\Lambda_b, B_c)\)**

- Heavy-Quark Expansion is successful for lifetimes of \(B\)-mesons, less successful with \(B\)-baryons
- Same techniques used as for CKM calculations
- Stringent verification needed ⇒ \(\Lambda_b\) lifetime is important

\[
\begin{align*}
\Lambda_b &\to \mu \nu \Lambda_c X, \Lambda_c \to K^0_S p \quad [\text{PRL 99, 182001 (2007)}] \\
& \quad \tau(\Lambda_b) = 1.290^{+0.119+0.087}_{-0.110-0.091} \text{ ps} \\
\Lambda_b &\to J/\psi \Lambda \quad \text{and} \quad B_d \to J/\psi K^0_S \quad [\text{PRL 99, 142001 (2007)}] \\
& \quad \tau(\Lambda_b) = 1.218^{+0.130}_{-0.115} \pm 0.042 \text{ ps} \\
& \quad \tau(B_d) = 1.501^{+0.078}_{-0.074} \pm 0.050 \text{ ps} \\
& \quad \text{Ratio consistent with prediction:} \quad 0.88 \pm 0.05 \text{ ps} \quad [\text{Eur.Phys.J. C33 (2004)}]
\end{align*}
\]

- \(B_c\) - 2 heavy quarks, each can decay
- Shortest lifetime of all \(B\)-hadrons
- Three \(\mu\) final state - take advantage of good DØ muon system
- Main physics bkg: \(B_u \to J/\psi K, K \to \mu \nu \pi\)

**DØ Run II Preliminary 1.3 fb\(^{-1}\)**

\[
\begin{align*}
B_c &\to \mu \nu \mu J/\psi, J/\psi &\to \mu^+ \mu^- \\
\text{[DØ Conf. Note 5524]} \\
& \quad \text{[DØ Conf. Note 5524]}
\end{align*}
\]

- \(B_c\) - 2 heavy quarks, each can decay
- Shortest lifetime of all \(B\)-hadrons
- Three \(\mu\) final state - take advantage of good DØ muon system
- Main physics bkg: \(B_u \to J/\psi K, K \to \mu \nu \pi\)

**DØ Average** \(\tau(\Lambda_b) = 1.251^{+0.102}_{-0.096} \text{ ps} \quad [\text{PRL 99, 182001 (2007)}]\)
Direct CP-Violation

Charge asymmetry in $B \rightarrow J/\psi K$:

$$A_{CP} = \frac{N(B^+ \rightarrow J/\psi K^+) - N(B^- \rightarrow J/\psi K^-)}{N(B^+ \rightarrow J/\psi K^+) + N(B^- \rightarrow J/\psi K^-)}$$

SM: $\sim 0.003$, NP: $\sim 0.01$ [hep-ph/0605080]

- Detector asymmetries cancel because of flipping toroid polarity
- Physics asymmetry for $K^+/K^-$ interaction with detector material: reaction $K^- + \text{nucleon} \rightarrow \pi + \Sigma/\Lambda$ has no $K^+ + \text{nucleon}$ analog
- Finally:
  - $A_{CP}(B \rightarrow J/\psi K) = 0.0067 \pm 0.0074 \pm 0.0026$
  - PDG’06: $A_{CP}(B \rightarrow J/\psi K) = -0.024 \pm 0.014$
CP-Violation in Mixing

Schrödinger equation for $B_s$ system:

$$i \frac{d}{dt} \left( \frac{|B_s(t)\rangle}{|B_s(t)\rangle} \right) = \left( M - \frac{i}{2} \Gamma \right) \left( \frac{|B_s(t)\rangle}{|B_s(t)\rangle} \right) \Rightarrow$$

\[ |B_{S,H}(t)\rangle = p|B_s(t)\rangle - q|\overline{B}_s(t)\rangle \]

\[ |B_{S,L}(t)\rangle = p|B_s(t)\rangle + q|\overline{B}_s(t)\rangle \]

Observables:

\[ \Delta M_s = M_H - M_L = 2|M_{12}^s| \]

and \[ \Delta \Gamma_s = \Gamma_L - \Gamma_H = 2|\Gamma_{12}^s| \cos \phi_s \]

where \[ \phi_s = \text{arg} \left( -\frac{M_{12}^s}{\Gamma_{12}^s} \right) \]

- CP-violating phase

\[ a_{SL}^s = \text{Im} \left( \frac{\Gamma_{12}^s}{M_{12}^s} \right) \tan \phi_s \]

- small and sensitive to NP

Two time-integrated DØ analyses:

**Inclusive muons:**

\[ A_{\mu \mu}^{SL} = \frac{N(b\bar{b} \rightarrow \mu^+ \mu^- X) - N(b\bar{b} \rightarrow \mu^- \mu^+ X)}{N(b\bar{b} \rightarrow \mu^+ \mu^- X) + N(b\bar{b} \rightarrow \mu^- \mu^+ X)} \]

\[ A_{\mu \mu}^{SL} = -0.0064 \pm 0.0101 \] [PRD76, 057101 (2007)]

Consistent with SM [hep-ph/0406300]

**Semileptonic $B_s$ decays**

\[ A_{SL}^s = \frac{N(B_S \rightarrow \mu^+ D_S^- X) - N(B_S \rightarrow \mu^- D_S^+ X)}{N(B_S \rightarrow \mu^+ D_S^- X) + N(B_S \rightarrow \mu^- D_S^+ X)} \]

\[ A_{SL}^s = 0.0123 \pm 0.0097 \pm 0.0017 \] [PRL98, 151801 (2007)]

- SM: \[ 2 \cdot A_{SL}^s = (0.000021 \pm 0.000004) \] [hep-ph/0406300]

- NP may increase this value, up to 0.005

In both analyses detector systematics again cancels by flipping toroid polarity

**Combined:** \[ a_{SL}^s = 0.0001 \pm 0.0090 \] [PRD 76, 057101 (2007)]

Thus, \[ \Delta \Gamma_s \cdot \tan \phi_s = a_{SL}^s \cdot \Delta M_s = 0.02 \pm 0.16 \text{ ps}^{-1} \]
$\Delta \Gamma_s$ and $\phi_s$ from $B_s \rightarrow J/\psi \phi$

- Mostly CP-even final state
- Angular analysis is needed to disentangle small CP-odd component
- Angular momenta: $|J = 0\rangle \rightarrow |J = 1\rangle + |J = 1\rangle$
- Amplitudes:
  - $A_0(t)$ - both V’s longitudinal, CP = +
  - $A_{\parallel}(t)$ - both V’s transverse with polarizations parallel to each other, CP = +
  - $A_{\perp}(t)$ - both V’s transverse with polarizations $\perp$ to each other, CP = −

- Rate $\frac{d^3\Gamma (B_S \rightarrow J/\psi \phi)}{d\cos \theta d\phi d\cos \psi}$ depends on angles $\phi$, $\theta$ and $\psi$ (see plots) and on the amplitudes $A_0(t)$, $A_{\parallel}(t)$ and $A_{\perp}(t)$
- The amplitudes depend on $\Gamma_H$, $\Gamma_L$, $\Delta M_s$, $\phi_s$ etc
- This dependence is different for $B_s$ and $\overline{B}_s$
- For given event the rate is multiplied by probability of $B_s$ or $\overline{B}_s$ flavor (obtained from flavor tagging)

Perform unbinned likelihood fit with function:

$$\mathcal{L} = \prod_{i=1}^{N} [f_{\text{sig}} x_i^{j_{\text{sig}}} + (1 - f_{\text{sig}}) x_i^{j_{\text{bkg}}} ]$$

- Bkg is split into:
  - “Prompt bkg”, where $J/\psi$ comes from PV
  - “Non-prompt bkg”, where $J/\psi$ comes from $b$-hadron

A. Rakitin, Lancaster University, Feb 18 – 23, Lake Louise 2008
\[ \Delta \Gamma_s \text{ and } \phi_s \text{ from } B_s \rightarrow J/\psi \phi \]

Main results:

\[ \Delta \Gamma_s = 0.19 \pm 0.07^{+0.02}_{-0.01} \text{ ps}^{-1}, \quad \phi_s = -0.57^{+0.24}_{-0.30} \pm 0.07 \]

[hep-ex/0802.2255, Sub. to PRL]

There is a small inconsistency with SM...
New Physics?

In $B_s$ system New Physics can be parametrized by complex number $\Delta_s = |\Delta_s| \cdot \exp^{i\phi_s} \text{[hep-ph/0612167]}$

$$M_{12}^s = (M_{12}^s)^{SM} \cdot \Delta_s,$$

$$\Delta M_s = \Delta M_{s}^{SM} \cdot |\Delta_s|,$$

$$\Delta \Gamma_s = 2|\Gamma_{12}| \cos \phi_s, \text{ where } \phi_s = \phi_s^{SM} + \phi_s^\Delta$$

- $\Delta_s = 1$ in SM
- Red: from CDF’s $\Delta M_s$ measurement [PRL 97, 242003 (2006)]
- Yellow: from $\Delta \Gamma_s/\Delta M_s$ with $\Delta \Gamma_s$ from DØ [PRL98, 121801 (2007)] - untagged 1.1 fb$^{-1}$ analysis
- Blue: from DØ’s $\alpha_{SL}^s$ measurement [PRD 76, 057101 (2007)]
- Forward and backward regions: from sign of $\Delta \Gamma_s$ from DØ [PRL98, 121801 (2007)] - untagged 1.1 fb$^{-1}$ analysis
- Dashed wedge: from $\phi_s$ from DØ [PRL98, 121801 (2007)] - untagged 1.1 fb$^{-1}$ analysis

- In SM all regions should intersect in point (1,0)
- Current experimental situation (black area) shows a small deviation which may become significant as the uncertainties go down
$\Delta \Gamma_s$ from $B_s \rightarrow D_s^(*) D_s^(*)$

Motivation:
- Predominantly CP-even final state
- Can extract width difference between CP-even and CP-odd $B_s$ states, $\Delta \Gamma_s^{CP}$, from branching ratio
- Test of SM

Analysis: [PRL99, 241801 (2007)]
- $B_s \rightarrow D_s^{(*)} D_s^{(*)}$, one $D_s \rightarrow \phi(1)\pi$, another $D_s \rightarrow \phi(2)\mu\nu$
- $D_s$ and $D_s^*$ are not distinguished
- Reconstruct $\phi(1)$ (top left plot), then $\mu\phi(1)\pi$ (top right)
- In this sample reconstruct $\phi(2)$ (bottom left) and then add muon to $\phi(2)$ (bottom right)
- Dashed line - disjoint production (bkg)

Results:
- $N(\mu\phi(2)) = 13.4^{+6.6}_{-6.0}$
- Stat. significance $2.2\sigma$
- $Br = 0.039^{+0.019}_{-0.017}(stat.)^{+0.016}_{-0.015}(syst.)$
- $\Delta \Gamma_s^{CP} = 0.079^{+0.038}_{-0.035}(stat.)^{+0.031}_{-0.030}(syst.)$
- Agrees with SM prediction: $0.127 \pm 0.024$

[hep-ph/0612167]
**$B_s$ Mixing**

- Measurement of $\Delta M_s$
- One needs to know
  1) $B_s$-flavor at decay (charges of decay products)
  2) $B_s$-flavor at production ($B_s$-flavor tagging)
  3) Proper decay length

$$\text{Sig}(\Delta M_s) \propto \sqrt{\varepsilon D^2} \frac{S}{\sqrt{S+B}} \exp\left(-\frac{(\Delta M_s \sigma_{ct})^2}{2}\right)$$

- Flavor-tagging: high $\varepsilon D^2 = 4.0\%$

<table>
<thead>
<tr>
<th>Semileptonic and hadronic modes</th>
<th>$N_{\text{sig}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s \to \mu \nu D_s X, D_s \to \phi \pi$</td>
<td>45K</td>
</tr>
<tr>
<td>$B_s \to e \nu D_s X, D_s \to \phi \pi$</td>
<td>1.7K</td>
</tr>
<tr>
<td>$B_s \to \mu \nu D_s X, D_s \to K^{*0}K$</td>
<td>18K</td>
</tr>
<tr>
<td>$B_s \to \mu \nu D_s X, D_s \to K^0 S K$</td>
<td>0.6K</td>
</tr>
<tr>
<td>$B_s \to D_s \pi X, D_s \to \phi \pi$</td>
<td>0.25K</td>
</tr>
</tbody>
</table>

- $\Delta M_s = 18.56 \pm 0.87\,(\text{stat.})$
- Significance $3.1\sigma$
- DØ Conf. Note 5474
FCNC

\[ D \to \mu^+\mu^-\pi \] [hep-ex/0708.2094]

- SM forbids FCNC at tree-level ⇒ sensitive to NP
- Search for \( c \to u\mu^+\mu^- \):
  - \( D/\bar{D}_s \to \phi\pi, \phi \to \mu^+\mu^- \)
  - use \( D^+ \) due to long lifetime and high production rate

\( N(D_s) = 254 \pm 36 \)
\( N(D) = 115 \pm 31 \)
Comb. signif. 8σ
Signif. \( D \) 4.1σ

- Non-\( \phi \) \( m(\mu^+\mu^-) \)
- Sig. reg.: 19 ev.
- Exp. bkg: 25.8 ± 4.6 events
- \( \text{Br}(D \to \mu^+\mu^-\pi^-) < 3.9 \times 10^{-6} \) at 90% CL
- 500x SM
  [PRD66, 014009 (2002)]
- 10x little Higgs
  [PRD73, 054026 (2006)]

\[ B_s \to \mu^+\mu^- \] [DØ Conf. Note 5344]

Run IIa: 1 ev. with 0.8 ± 0.2 exp. bkg

Run IIb: 2 ev. with 1.5 ± 0.3 exp. bkg

\( B_s \to \mu^+\mu^- \) < 7.5 \times 10^{-8} at 90% CL
SM: \( Br = (3.42 \pm 0.54) \times 10^{-9} \) [Phys.Lett.B566, 115 (2003)]
Summary

- Very rich $B$-physics program at DØ
- A few highlights shown today:
  - First observation of $\Xi_b$ + other spectroscopy analyses
  - Precise $\Lambda_b$ and $B_c$ lifetime measurement
  - Search for direct CPV and CPV in mixing
  - Measurement of $B_s$ parameters
  - Search for FCNC

Exciting time to do $B$-physics at DØ!
Backup
A few more plots:

**[Cosine plot]**
- Data
- Total Fit
- CP-even
- CP-odd
- Total Signal
- Background

**[Transversity plot]**
- Data
- Total Fit
- Total Signal
- Background

**[Cosine ψ plot]**
- Data
- Total Fit
- Total Signal
- Background

**Likelihood profile of $\phi_s$**
- $-2\ln(L/L_{\text{max}})$

**Likelihood profile of $\Delta\Gamma_s$**
- $-2\ln(L/L_{\text{max}})$

**$\Delta\Gamma_s$ vs. $\phi_s$**
- $\Delta\Gamma_s = \Delta\Gamma_{\text{SM}} \times |\cos(\phi_s)|$

A. Rakitin, Lancaster University, Feb 18 – 23, Lake Louise 2008
\( \Upsilon(1S) \) and \( \Upsilon(2S) \) Polarization

- Muons in decay \( \Upsilon(nS) \rightarrow \mu^+\mu^- \) are distributed as
  \[ \frac{dN}{d(\cos \theta^*)} \propto 1 + \alpha \cos^2 \theta^* , \]
  where \( \theta^* \) - decay angle, \( \alpha \) - known function of \( p_T(\Upsilon(nS)) \)

Analysis: [DØ Conf. Note 5089]
- Divide sample into 8 \( p_T \) bins and 10 \( \cos \theta^* \) bins \( \Rightarrow N(\Upsilon(1S)) \) and \( N(\Upsilon(2S)) \) \( \Rightarrow \) get \( \alpha(p_T) \)

- Black/Green points: DØ /CDF data
- Yellow band: NRQCD prediction
  [PRD 63, 071501(R)(2001)]
- Magenta: two limiting cases: quark-spin conservation (lower) and full quark-spin depolarization (upper)

- Blue points - DØ data
- Yellow band - NRQCD prediction
- No discrepancy
$B_s \rightarrow \mu^+\mu^-\phi$

- Search for $b \rightarrow s\mu^+\mu^-$ FCNC
- Obtain 0 events in signal region
- Expected bkg $1.6 \pm 0.4$
- Normalize to $B_s \rightarrow J/\psi\phi$ (same cuts)
  
  $\frac{Br(B_s \rightarrow \mu^+\mu^-\phi)}{Br(B_s \rightarrow J/\psi\phi)} < 4.4 \times 10^{-3}$ [DØ Conf. Note 4862]
- $Br(B_s \rightarrow \mu^+\mu^-\phi) < 4.1 \times 10^{-6}$
- Consistent with SM prediction $1.6 \times 10^{-6}$

**$B_S \rightarrow \psi(2S)\phi$**

Similar to $B_S \rightarrow J/\psi \phi$ also can be used for $\Delta \Gamma_{CP}$

Control channel: $B \rightarrow \psi(2S)K$ ($N = 149$)

Normalize to $B \rightarrow J/\psi K$ ($N = 1970$)

Reconstruct $B_S \rightarrow \psi(2S)\phi$

($N = 9$, $\sqrt{-2\ln(L_0/L_{max})} = 3.89\sigma$)

Normalize to $B_S \rightarrow J/\psi \phi$ ($N = 200$)

$$\frac{B(B_S \rightarrow \psi(2S)\phi)}{B(B_S \rightarrow J/\psi \phi)} = 0.54 \pm 0.10 \pm 0.07 \pm 0.06(B)$$

Also,

$$\frac{B(B \rightarrow \psi(2S)K)}{B(B \rightarrow J/\psi K)} = 0.64 \pm 0.05 \pm 0.03 \pm 0.07(B)$$

[DØ Conf. Note 4869]

Consistent with CDF [PRL96, 231801 (2006)] and BABAR [PRD65, 032001 (2002)]

A. Rakitin, Lancaster University, Feb 18 – 23, Lake Louise 2008