Recent CP Violation Results from DØ

Derek A. Strom
Northwestern University

on behalf of the DØ Collaboration

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The DØ Detector

The $B_s^0$ Meson System

Recent CP Violation Results from DØ:

- Flavor-tagged angular analysis in $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decays
- New C.L. contours: adjustments to likelihood value, systematic uncertainties, and constraints from:
  - W.A. value of flavor-specific asymmetry of semileptonic $B_s^0$ decays
  - W.A. value of flavor-specific $B_s^0$ lifetime
  - DØ measurement of $\mathcal{B}(B_s^0 \rightarrow D_s^{(*)}+D_s^{(*)}-)$

Conclusions
The DØ Detector

- Tracker
  - Excellent coverage $|\eta| < 3$
  - 2T solenoid
  - precision secondary vertexing
  - New Layer 0 silicon close to beam pipe

- Muon system
  - Coverage and triggering $|\eta| < 2$
  - Toroid magnet

- Regular polarity flip of both magnets
  - Reduces detector asymmetries
$B_s^0 - \bar{B}_s^0$ mixing governed by the Schrödinger equation

$$i \frac{\partial}{\partial t} \left( \begin{array}{c} |B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle \end{array} \right) = \left( M - \frac{i}{2} \Gamma \right) \left( \begin{array}{c} |B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle \end{array} \right)$$

Unique window into difference between matter and antimatter

Mass eigenstates $B_s^L$ and $B_s^H$ are admixtures of the flavor eigenstates:

Light: $|B_s^L\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle = |B_s^{even}\rangle$ \hspace{1cm} $|p|^2 + |q|^2 = 1$

Heavy: $|B_s^H\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle = |B_s^{odd}\rangle$ \hspace{1cm} if CP is conserved, $p = q$

Quantities measured experimentally:

$\Delta m_s \equiv M_H - M_L \approx 2|M_{12}|$ \hspace{1cm} Mixing frequency ($\Delta m_s^{meas.} = 17.77 \pm 0.12$ ps$^{-1}$)

$\Delta \Gamma_s \equiv \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}| \cos \phi_s$ \hspace{1cm} Width difference ($\Delta \Gamma_s^{SM} = 0.096 \pm 0.039$ ps$^{-1}$)

$\phi_s = \arg \left( -\frac{M_{12}}{\Gamma_{12}} \right)$ \hspace{1cm} CPV weak phase ($\phi_s^{SM} = 0.004$)

$\Gamma_s = \frac{\Gamma_L + \Gamma_H}{2}$; \hspace{1cm} $\bar{\tau} = \frac{1}{\Gamma_s}$ \hspace{1cm} Average width and lifetime
CPV-phase in $B_s^0 \rightarrow J/\psi\phi$

- $B_s^0$ mixing:
  \[
  \begin{array}{c|ccc|c}
  s & V_s & W^- & V_{sb} & b \\
  \hline
  b & V_{bs}^* & W^+ & V_{bs}^* & s \\
  \end{array}
  \]

- $B_s^0$ decays:
  \[
  \begin{array}{c|c|c}
  s & \phi & J/\psi \\
  \hline
  \bar{s} & \bar{c} & J/\psi \\
  \end{array}
  \]

- Direct decay $\iff$ Interference $\iff$ Decay through mixing

- SM prediction of CPV mixing phase in $B_s^0 \rightarrow J/\psi\phi$:
  \[
  \phi_{J/\psi\phi,SM}^s \equiv -2\beta_{J/\psi\phi,SM}^s = -0.04 \pm 0.01
  \]

- New physics may alter the phase ($\phi_{J/\psi\phi,NP}^s$) such that:
  \[
  \phi_{J/\psi\phi}^s = \phi_{J/\psi\phi,SM}^s + \phi_{J/\psi\phi,NP}^s
  \]

- A significantly large observed phase ($\phi_{J/\psi\phi}^s \approx \phi_{J/\psi\phi,NP}^s$) would indicate new physics
Most direct and precise measurements of $\Delta \Gamma_s$ and $\phi_s$ come from the Tevatron

- $B_s^0 \rightarrow J/\psi \phi$ provides a rich decay mode for studies: lifetime, decay width difference, and CP-violating phase

- Pseudoscalar ($S=0$) $\rightarrow$ Vector ($S=1$) + Vector ($S=1$) ($L = 0, 1, 2...$ S, P, D waves)
  - $L=0$ (S wave), 2 (D wave): CP-even $B^0_L$
  - $L=1$ (P wave): CP-odd $B^0_H$

- Fit to time-dependent angular distributions of $B_s^0 \rightarrow J/\psi \phi$ allows separation of CP—even and CP—odd components

- Initial state flavor tag improves sensitivity

- For angular analysis, work in the $J/\psi$ ($\theta, \phi$) and $\phi$ ($\psi$) rest frames
Flavor Tagging

- Flavor tagging uses the combined properties of the $B$ hadron opposite to the reconstructed $B^0_s$ meson (OST) and the properties accompanying the reconstructed $B^0_s$ meson (SST).

- These properties should have different distributions for $B^0_s$ and $\bar{B}^0_s$.

Combined Tag (OST + SST)
$\mathcal{P} \approx 4.7\%$
Reconstruct $B_s^0 \rightarrow J/\psi (\mu^+ \mu^-) \phi (K^+ K^-)$ decay chain

1967 ± 65 $B_s^0$ signal candidates in 2.8 fb$^{-1}$ data sample

Use a maximum likelihood fit to mass, lifetime, 3 decay angles

$\Delta m_s$ fixed to measured value and strong phases constrained to values measured for $B_d$ at B-factories, allowing for some degree of violation of SU(3) symmetry

$B_s^0$ flavor at production determined using opposite-side + same-side tagging
Constraint on strong phases, $\delta_i$

Results (PRL 101 241801 (2008)):

\[
\phi_s^{J/\psi \phi} = -0.57^{+0.24}_{-0.30} \text{ (stat)}^{+0.07}_{-0.02} \text{ (syst)} \text{ rad} \quad \text{SM p-value} = 6.6\% \\
\Delta \Gamma_s = 0.19 \pm 0.07 \text{ (stat)}^{+0.02}_{-0.01} \text{ (syst)} \text{ ps}^{-1} \\
\bar{\tau}(B_s^0) = 1.52 \pm 0.05 \pm 0.01 \text{ ps}
\]
The $\phi_s^{J/\psi\phi}(−2\beta_s)$ vs. $\Delta\Gamma_s$ contour from DØ as of winter 2008 has been presented.

Now we’ll see updated contours taking into account:

- Releasing the constraint on the strong phases, $\delta_i$
- Making adjustments for non-Gaussian uncertainties in the DØ fit parameters and including systematic uncertainties
- Constraint from the W.A. flavor-specific asymmetry in $B^0_s$ semileptonic decays
- Constraint from W.A. flavor-specific $B^0_s$ lifetime
- Constraint from the DØ measurement of $\mathcal{B}(B^0_s \to D^*_s + D^*_s)$

New Physics?
Adjusting for non-Gaussian Behavior

- Ideally, with high statistics and Gaussian behavior, the 2D 68% (95%) C.L. regions correspond to the 2.3 (6) slices of the likelihood profile.

- The DØ result has non-Gaussian behavior of the uncertainties on the fit parameters.

- We correct for non-Gaussian behavior of the uncertainties on the fit parameters using pseudo-experiments to map between C.L. and $2\Delta\log(L)$ (e.g. 95% needs to go up to 8 instead of 6).

- 2000 MC pseudo-experiments generated to determine the statistical coverage.

- Likelihood value at each point in $J/\psi \phi$ vs. $\Delta \Gamma_s$ space is adjusted.

- Allows for combination with CDF results.

![Graph showing the relationship between $2\Delta\log(L)$ and $(1 - C.L.)$]

C.L. value corresponding to a given likelihood ratio value in the 2D likelihood scan.
Some systematic uncertainties (i.e. signal and background models) are included as nuisance parameters in the fit.

Largest effect is the inclusion of the uncertainty on $\Delta m_s = 17.77 \pm 0.12$ ps$^{-1}$.

Effects of the systematics are studied by varying these parameters by $\pm 1\sigma$.

Most conservative value is used, i.e. the largest value of $(1 - CL)$ for a given likelihood ratio.
Adjusted Likelihood Profile in $\phi_s^{J/\psi \phi}$ vs. $\Delta \Gamma_s$ Contours

No constraint on strong phases, $\delta_i$

SM $p$-value = 8.5%

SM $p$-value = 24%

- From publications PRL 101 241801 (2008), DØ Note 5933-CONF
Applying Additional Constraints

- Use other measurements to supply additional constraints on $\phi_{J/\psi}^s$ vs. $\Delta \Gamma_s$

- Flavor-specific Semileptonic Asymmetry
  \[ A_{SL}^s = \frac{N(\bar{B}_s^0(t) \to \ell^+ \nu_\ell X) - N(B_s^0(t) \to \ell^- \bar{\nu}_\ell X)}{N(\bar{B}_s^0(t) \to \ell^+ \nu_\ell X) + N(B_s^0(t) \to \ell^- \bar{\nu}_\ell X)} = \frac{\Delta \Gamma_s}{\Delta m_s} \tan \phi_s \]

- Fix $\Delta m_s$ to measured value and constrain $\Delta \Gamma_s \tan \phi_s$

- $A_{SL}^{s, HF AG} = -0.0027 \pm 0.0066$

- Flavor-specific $B_s^0$ Lifetime
  \[ \tau(B_s^0)^{fs} = \frac{1}{\Gamma_s} \frac{1 + (\frac{\Delta \Gamma_s}{2 \Gamma_s})^2}{1 - (\frac{\Delta \Gamma_s}{2 \Gamma_s})^2} \]

- $\tau(B_s^0)^{WA} = 1.456 \pm 0.030$ ps

- Branching Fraction $\mathcal{B}(B_s^0 \to D_s^{(*)+} D_s^{(*)-})$
  \[ 2\mathcal{B}(B_s^0 \to D_s^{(*)+} D_s^{(*)-}) \approx \frac{\Delta \Gamma_s}{\Gamma_s \cos \phi_s} \left[ \frac{1}{1 - 2x_f} - \frac{\Delta \Gamma_s \cos \phi_s}{2 \Gamma_s} \right] \]

- DØ measurement using $2.8 \text{ fb}^{-1}$, $\mathcal{B}(B_s^0 \to D_s^{(*)+} D_s^{(*)-}) = 0.035 \pm 0.015$
CP Violation in Semileptonic $B_s^0$ Decays

- New search for CP Violation in semileptonic $B_s^0 \rightarrow \mu^+ D_s^- X$

- Similar technique to $B_s^0$ oscillation analysis (PRL 97, 021802, 2006), modified to include CPV and detector asymmetries

- Flavor Tagging
  - Production: Opposite-side
  - Decay: Muon charge

$A_{SL} = -0.0017 \pm 0.0091^{+0.0012}_{-0.0023}$

- Final state samples ($5 \text{ fb}^{-1}$):
  - $\mu^+ \phi \pi^-$ where $\phi \rightarrow K^+ K^-$

- $\mu^+ \phi \pi^-$ where $\phi \rightarrow K^+ K^-$

- DØ magnets flipped regularly; control and measure detector asymmetries

- arXiv.org:0904.3907, submitted to PRL
Constraint from Flavor-Specific Semileptonic Asymmetry

- \( \mathcal{A}_{SL}^{s} = \frac{\Delta \Gamma_s}{\Delta m_s} \tan \phi_s \)
- \( \mathcal{A}_{SL}^{s, HF AG} = -0.0027 \pm 0.0066 \)
- With the constraint to the WA value of \( \mathcal{A}_{SL}^{s} \) we get the following C.L. contours
- SM p-value = 24%

![Diagram showing constraint and contours](image)
Constraint from Flavor-Specific $B^0_s$ Lifetime and $\mathcal{B}(B^0_s \rightarrow D_s^{(*)}+D_s^{(*)}-)$

$$\tau(B^0_s)_{f_s} = \frac{1}{\Gamma_s} \frac{1 + (\frac{\Delta \Gamma_s}{2 \Gamma_s})^2}{1 - (\frac{\Delta \Gamma_s}{2 \Gamma_s})^2}$$

$$\tau(B^0_s)^{WA}_{f_s} = 1.456 \pm 0.030 \text{ ps}$$

$$2\mathcal{B}(B^0_s \rightarrow D_s^{(*)}+D_s^{(*)}-) = 0.035 \pm 0.015$$

PRL 102 091801 (2009)

- World average value of $B^0_s$ flavor-specific lifetime
- $p$-value of SM point = 12%
- $p$-value of SM point = 10%
Conclusions

- DØ’s most recent results on CPV include new C.L. contours taking into account adjustments for non-Gaussian uncertainties from the fit, systematic uncertainties, and constraints from independent measurements.

- Results shown here with the 2.8 - 5.0 fb\(^{-1}\) data sample, but 6 fb\(^{-1}\) already on tape and ready to be analyzed.

- Expect 8 fb\(^{-1}\) by the end of Run 2 in 2010 and possibly 10 fb\(^{-1}\) by the end of 2011.

- If \(\phi_{J/\psi}\) is large the Tevatron has an excellent chance at finding New Physics.

- Updated analyses expected soon. Stay tuned!
Constraints to the Fit

- $\Delta m_s$ is constrained to the CDF measured value:
  \[
  \Delta m_s = 17.77 \pm 0.12 \text{ ps}^{-1} \quad \text{PRL 97, 242003 (2006)}
  \]

- A two-fold ambiguity remains in the fit:
  \[
  \begin{align*}
  \Delta \Gamma_s &> 0, & \cos \phi_s &> 0, & \cos \delta_1 &> 0, & \cos \delta_2 &< 0 \\
  \Delta \Gamma_s &< 0, & \cos \phi_s &< 0, & \cos \delta_1 &< 0, & \cos \delta_2 &> 0
  \end{align*}
  \]

- $\delta_1$ and $\delta_2$ were measured at the $B$ factories in $B_d^0 \to J/\psi K^*$ decays [arXiv:0704.0522]. The solution with $\delta_1 < 0, \delta_2 > 0$ is experimentally and theoretically favored

- $\delta_1$ and $\delta_2$ are constrained to the world average values measured in $B_d^0 \to J/\psi K^*$ decays, and are allowed to vary over a Gaussian width $\pi/5$
  \[
  \begin{align*}
  \delta_1 &= -0.46 \\
  \delta_2 &= 2.92 \\
  \end{align*}
  \]
  [arXiv:0704.3575]
Recent CPV Results from DØ

**Decay Angles**

**DØ, 2.8 fb⁻¹**

$B^0_s \to J/\psi \phi$

5.26 $< M(B^0_s) <$ 5.46 GeV

cτ/σ(ct) $>$ 5

**Events per 0.10**

- Data
- Total Fit
- CP-even
- CP-odd
- Total Signal
- Background

**DØ, 2.8 fb⁻¹**

$B^0_s \to J/\psi \phi$

5.26 $< M(B^0_s) <$ 5.46 GeV

cτ/σ(ct) $>$ 5

**Events per 0.17**

- Data
- Total Fit
- Total Signal
- Background

**DØ, 2.8 fb⁻¹**

$B^0_s \to J/\psi \phi$

5.26 $< M(B^0_s) <$ 5.46 GeV

cτ/σ(ct) $>$ 5

**Events per 0.10**

- Data
- Total Fit
- Total Signal
- Background
Sakharov Conditions (1967)

1. Baryon number violation (proton decay)
2. C and CP discrete symmetry violation
3. Thermal non-equilibrium
### Selection Cuts

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T$ of $\mu^+, \mu^-$</td>
<td>$&gt; 1.5$ GeV/c</td>
</tr>
<tr>
<td>$p_T$ of $K^+, K^-$</td>
<td>$&gt; 0.7$ GeV/c</td>
</tr>
<tr>
<td>$p_T$ of $\phi$</td>
<td>$&gt; 1.5$ GeV/c</td>
</tr>
<tr>
<td>$p_T$ of $B^0_s$</td>
<td>$&gt; 6.0$ GeV/c</td>
</tr>
<tr>
<td>$J/\psi$ candidate mass</td>
<td>$2.9 &lt; M(\mu^+, \mu^-) &lt; 3.3$ GeV/c$^2$</td>
</tr>
<tr>
<td>$\phi$ candidate mass</td>
<td>$1.01 &lt; M(K^+, K^-) &lt; 1.03$ GeV/c$^2$</td>
</tr>
<tr>
<td>$B^0_s$ candidate mass</td>
<td>$5.0 &lt; M(\psi, \phi) &lt; 5.8$ GeV/c$^2$</td>
</tr>
<tr>
<td>Decay length error of $B^0_s$ candidate</td>
<td>$&lt; 0.006$ cm</td>
</tr>
<tr>
<td>SMT hits on track</td>
<td>$&gt; 1$</td>
</tr>
<tr>
<td>$\chi^2$ of $B^0_s$</td>
<td>$&lt; 30.0$</td>
</tr>
</tbody>
</table>
## Summary of Fit Results

<table>
<thead>
<tr>
<th></th>
<th>( f_{\text{sig}} (N_{\text{sig}}) )</th>
<th>( 0.0409 \pm 0.0013 ) (1967±65)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2, 3</td>
<td>( M, \sigma ) (in MeV)</td>
<td>5361.4±1.0, 30.1±1.0</td>
</tr>
<tr>
<td>4</td>
<td>( \bar{\tau} ) (in ( \mu m ))</td>
<td>456±17</td>
</tr>
<tr>
<td>5</td>
<td>( \Delta \Gamma ) (in ( ps^{-1} ))</td>
<td>0.19±0.07</td>
</tr>
<tr>
<td>6, 7</td>
<td>( A_\perp(0),</td>
<td>A_0(0)</td>
</tr>
<tr>
<td>8, 9</td>
<td>( \delta_1, \delta_2 )</td>
<td>-0.52±0.42, 3.17±0.39</td>
</tr>
<tr>
<td>10</td>
<td>( \phi_s )</td>
<td>-0.57^{+0.24}_{-0.30}</td>
</tr>
<tr>
<td>11</td>
<td>( \Delta M_s ) (in ( ps^{-1} ))</td>
<td>( \equiv 17.77 )</td>
</tr>
<tr>
<td>12</td>
<td>( S )</td>
<td>1.24±0.01</td>
</tr>
<tr>
<td>13, 14, 15</td>
<td>( a_{1p}, a_{1l}, a_{2l} )</td>
<td>-0.06±0.03, -1.45±0.08, 0.68±0.11</td>
</tr>
<tr>
<td>16, 17, 18</td>
<td>( f_-, f_+, f_{++} )</td>
<td>0.049±0.004, 0.155±0.004, 0.035±0.003</td>
</tr>
<tr>
<td>19, 20, 21</td>
<td>( b_-, b_+, b_{++} ) (in ( \mu m ))</td>
<td>65±3, 88±3, 399±21</td>
</tr>
<tr>
<td>22, 23</td>
<td>( X_{2p}, X_{4p} )</td>
<td>0.85±0.09, -0.60±0.09</td>
</tr>
<tr>
<td>24, 25</td>
<td>( X_{2l}, X_{4l} )</td>
<td>0.39±0.17, -0.23±0.19</td>
</tr>
<tr>
<td>26, 27</td>
<td>( Y_{1p}, Y_{2p} )</td>
<td>-0.23±0.01, -0.10±0.02</td>
</tr>
<tr>
<td>28, 29</td>
<td>( Y_{1l}, Y_{2l} )</td>
<td>-0.15±0.02, -0.00±0.04</td>
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<tr>
<td>30, 31</td>
<td>( Z_{2p}, Z_{2l} )</td>
<td>0.05±0.02, 0.27±0.06</td>
</tr>
<tr>
<td>31, 32</td>
<td>( \text{Int}_p, \text{Int}_l )</td>
<td>-0.011±0.003, -0.018±0.001</td>
</tr>
</tbody>
</table>
Flavor Tagging: Dilution

Dilution of combined flavor tagging in simulated and real $B^\pm \to J/\psi K^\pm$ events for different values of the $|d|$ variable. All uncertainties are statistical.

| $|d|$ | $\mathcal{D}(B^\pm \to J/\psi K^\pm)$ (%) (MC) | $\mathcal{D}(B^\pm \to J/\psi K^\pm)$ (%) (data) |
|-----|--------------------------------|--------------------------------|
| 0.00 < $|d|$ < 0.10 | $0.029 \pm 0.014$ | $0.024 \pm 0.017$ |
| 0.10 < $|d|$ < 0.20 | $0.127 \pm 0.015$ | $0.154 \pm 0.019$ |
| 0.20 < $|d|$ < 0.35 | $0.261 \pm 0.015$ | $0.275 \pm 0.018$ |
| 0.35 < $|d|$ < 0.45 | $0.302 \pm 0.028$ | $0.397 \pm 0.032$ |
| 0.45 < $|d|$ < 0.60 | $0.483 \pm 0.038$ | $0.545 \pm 0.049$ |
| 0.60 < $|d|$ < 1.00 | $0.544 \pm 0.045$ | $0.573 \pm 0.055$ |

$|\mathcal{D}| = 0.7895 \cdot |d| + 0.3390 \cdot d^2$ if $|d| < 0.55$

$|\mathcal{D}| = 0.5957$ if $|d| > 0.55$. 


The mass of the $B^0_s$ candidates with $\mathcal{D} > 0$ (points) and $\mathcal{D} < 0$ (line).
Comparison to Other Experimental Results

DØ PRL 101 241801 (2008):

Updated CDF Result (2.8 fb\(^{-1}\))

Allowed range at the 90% CL:

\[ \phi_s \in [-1.20, 0.06] \text{ rad} \]

1.7\(\sigma\) disagreement with SM

Deviation seen in same direction!

Allowed range at the 68% CL:

\[ \phi_s = -2\beta_s \in [-1.29, -0.28] \text{ rad} \]

1.8\(\sigma\) disagreement with SM