Mixing and CP violation at DØ

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On behalf of DØ collaboration

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In this talk...

- Introduction
- The Flavor Oscillation Frequency of $B_s$.
- The time-dependent angular analysis for the decay $B_s \rightarrow J/\psi \phi$
- New measurement of $\Delta \Gamma_s$ from $\text{Br}(B_s \rightarrow D_s^{(*)} D_s^{(*)})$
- CP asymmetry in $B^\pm \rightarrow J/\psi K^\pm$
One of the hypothesis for the current baryon asymmetry in the Universe is the CP violation.

SM predicts that there exist CPV effects, but they are relatively small.

A measurement of large CPV contributions from $B_s \to J/\psi\phi$ and/or $B^\pm \to J/\psi K^\pm$ decays can give us signs of New Physics.

The $B_s$ has an “identity crisis”: it changes from particle to antiparticle.

GOOD REASONS TO DO DETAILED STUDIES IN $B$ MESONS!!!
The DØ Detector

- Silicon and fiber trackers immersed into 2 T solenoid, coverage $|\eta| < 3$
  - Precise vertexing and tracking
  - New Layer 0 silicon on beam pipe in 2006 improves impact parameter resolution
- Muon system (central + forward), coverage $|\eta| < 2$
  - Includes its own magnet-toroid
- Two magnets- solenoid and toroid- flip polarities every two weeks
  - Unique feature of DØ
  - Diminishes detector asymmetries
\[ V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4) \]

In SM CP-violation is governed by only one parameter: \( \eta \).

**Unitary triangle in the \( B_s \) system**

\[ V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0 \]

\[ \frac{V_{us}V_{ub}^*}{V_{cs}V_{cb}^*} = (\bar{\rho}, \bar{\eta}) \quad \frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*} = \beta_s \]

Area \( \propto \) level of CP violation

CP violation phase \( \beta_s^{SM} \) is predicted to be small:

\[ 2\beta_s^{SM} = 2 \arg \left( -\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*} \right) \approx 0.04 \pm 0.01 \text{ rad} \]
CKM matrix

\[ V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4) \]

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The $B_s$'s identity crisis

Neutral B mesons can spontaneously transform in the corresponding antiparticle

The Schrodinger for $B_s$ system

$$i \frac{d}{dt} \begin{pmatrix} |\bar{B}_s(t)\rangle \\ |B_s(t)\rangle \end{pmatrix} = \left( M - \frac{i}{2} \Gamma \right) \begin{pmatrix} |\bar{B}_s(t)\rangle \\ |B_s(t)\rangle \end{pmatrix}$$

$$|B^L_s(t)\rangle = p |B_s(t)\rangle + q |\bar{B}_s(t)\rangle$$

$$|B^H_s(t)\rangle = p |B_s(t)\rangle - q |\bar{B}_s(t)\rangle$$

- Mixing oscillation frequency
  $$\Delta m_s = M_H - M_L = 2|M_{12}| \approx (19.3 \pm 6.7) \text{ ps}^{-1}$$

- Decay width difference
  $$\Delta \Gamma_s = \Gamma_L - \Gamma_H = 2|\Gamma_{12}| \cos \phi_s \approx (0.096 \pm 0.039) \text{ ps}^{-1}$$

- CPV phase
  $$\phi^{SM}_s = \text{arg} \left( -\frac{M_{12}}{\Gamma_{12}} \right) \approx 0.004$$

NP may introduce a new phase such that

$$\phi_s = \phi^{SM}_s + \phi^{NP}_s, \ 2\beta_s = 2\beta^{SM}_s - \phi^{NP}_s$$

If the phase $\phi^{NP}_s$ dominates

$$\phi_s \approx \phi^{NP}_s \approx -2\beta_s$$

1Lenz,Nierste hep-ph/0612167
The **$B_s$'s identity crisis**

Neutral B mesons can spontaneously transform in the corresponding antiparticle

### The Schrödinger for $B_s$ system

\[
\frac{id}{dt} \left( \begin{array}{c} |\bar{B}_s(t)\rangle \\ |B_s(t)\rangle \end{array} \right) = \left( M - \frac{i}{2} \Gamma \right) \left( \begin{array}{c} |\bar{B}_s(t)\rangle \\ |B_s(t)\rangle \end{array} \right)
\]

\[
|B^L_s(t)\rangle = p|B_s(t)\rangle + q|\bar{B}_s(t)\rangle
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- **Mixing oscillation frequency**
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  \Delta m_s = M_H - M_L = 2|M_{12}| \quad [(19.3 \pm 6.7) \text{ ps}^{-1}]_{\text{theory}}
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\[
\phi_s \approx \phi_s^{\text{NP}} \approx -2\beta_s
\]

---

\(^1\)Lenz,Nierste hep-ph/0612167
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\frac{i}{dt} \begin{pmatrix} \bar{B}_s(t) \\ B_s(t) \end{pmatrix} = \begin{pmatrix} M - \frac{i}{2} \Gamma \end{pmatrix} \begin{pmatrix} \bar{B}_s(t) \\ B_s(t) \end{pmatrix}
\]

\[
|B_{sL}(t)\rangle = p|B_s(t)\rangle + q|\bar{B}_s(t)\rangle
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\]

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\[1\] Lenz, Nierste hep-ph/0612167
Flavor tagging and the frequency oscillation $\Delta m_s$
We need to determine (tag) $B_s/\bar{B}_s$ initial- and final-state flavors.

**Two main tagging methods:**
- **Same-side tagging (SST):**
  - It is based on the sign of an associated charged particle.
- **Opposite-side tagging:**
  - Does not depend on the $B-$meson flavor

**Tagging parameters**
- $\eta_s = \frac{N_{corr \ tagged \ evts}}{N_{tot}}$
- $D = 2\eta_s - 1$
- $\varepsilon = \frac{N_{tot \ tagged \ evts}}{N_{total \ evts}}$
- $d = \frac{1 - y}{1 + y}$. $d > 0 \Rightarrow b$ quark; $d < 0 \Rightarrow \bar{b}$ quark
- $P = \varepsilon D^2 = (4 - 5)\%$
New features

- Fully reconstructed hadronic mode.
- Partially reconstructed hadronic and semileptonic modes.
- Combined SST and OST flavor-tagging.
- Improved decay length resolution.
- K-factor: correction for missing particles.
- Scale factor

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

**DØ RunII Preliminary**

![Graph showing dilution vs. $|d_{COMB}|$](image)
The Frequency Oscillation $\Delta m_s$ @ DØ

Preliminary results

$\Delta m_s = 18.53 \pm 0.93\text{(stat)} \pm 0.30\text{(syst)}$ ps$^{-1}$

Significance 2.9$\sigma$

The measurement is in good agreement with CDF$^a$:

$17.77 \pm 0.10\text{(stat)} \pm 0.07\text{(syst)}$ ps$^{-1}$

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CPV in the $B_s \rightarrow J/\psi \phi$?
CPV in the decay $B_s \to J/\psi \phi$? The **tagged angular analysis**

- It is necessary to separate the different parity contributions.
- We use the Combined flavor-tagging method.
- Upper (lower) sign for pure $B_s (\bar{B}_s)$ at $t = 0$.

$$|A_0(t)|^2 = |A_0(0)|^2 \left[ T_+ \pm e^{-\Gamma t} \sin \phi_s \sin(\Delta M_{s} t) \right] ,$$

$$|A_\parallel(t)|^2 = |A_\parallel(0)|^2 \left[ T_+ \pm e^{-\Gamma t} \sin \phi_s \sin(\Delta M_{s} t) \right] ,$$

$$|A_\perp(t)|^2 = |A_\perp(0)|^2 \left[ T_+ \mp e^{-\Gamma t} \sin \phi_s \sin(\Delta M_{s} t) \right]$$

where

$$T_\pm = (1/2) \left[ (1 \pm \cos \phi_s) e^{-\Gamma_L t} + (1 \mp \cos \phi_s) e^{-\Gamma_H t} \right] .$$

$$\Re(A_0(t)A_\parallel(t)) = |A_0(0)||A_\parallel(0)| \cos(\delta_2 - \delta_1) [T_+ \pm e^{-\Gamma t} \sin \phi_s \sin(\Delta M_{s} t)] ,$$
CPV in the decay $B_s \rightarrow J/\psi \phi$? The results

**Results with flavor tagging**

$\tau_s = 1.51 \pm 0.06 \pm 0.01$ ps

$N_{sig} = 1,967 \pm 65$

**Angular analysis**

mass mean = $5361.5 \pm 1.0$ MeV/$c^2$
CPV in the decay $B_s \rightarrow J/\psi \phi$? The results

\[ \Delta \Gamma_s = 0.19 \pm 0.07^{+0.02}_{-0.01} \text{ ps}^{-1} \]
\[ \phi_s = -0.57^{+0.24+0.07}_{-0.30-0.02} \text{ rad} \]
\[ \Delta m_s \equiv 17.77 \text{ ps}^{-1} \text{ fixed} \]
\[ \delta_1 = -0.46 \text{ Gaussian constrained} \]
\[ \delta_2 = 2.92 \text{ Gaussian constrained} \]

New physics or only fluctuations?
To be continued...

References:

- hep-ex/0802.2255, Submitted to PRL
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- $\delta_2 = 2.92$ Gaussian constrained

New physics or only fluctuations?
To be continued…
$\Delta \Gamma_s$ from $\text{Br}(B_s \rightarrow D_s^{(*)} D_s^{(*)})$
In the $B_s$ system, $\Delta \Gamma_s = \Gamma_L - \Gamma_H = 2|\Gamma_{12}| \cos \phi_s$.

From previous experiments, $\Delta \Gamma_s$ is sizable.

From theory $D_s^{(*)} D_s^{(*)}$ is purely CP even.

$$2\text{Br}(B_s \rightarrow D_s^{(*)} D_s^{(*)}) = \Delta \Gamma_s^{CP} \left[ \frac{1+\cos \phi_s}{\Gamma_L} + \frac{1-\cos \phi_s}{\Gamma_H} \right]$$

In SM ($\phi_s = 0$)

$$\frac{\Delta \Gamma_s}{\Gamma_s} \approx \frac{2\text{Br}(B_s \rightarrow D_s^{(*)} D_s^{(*)})}{1 - \text{Br}(B_s \rightarrow D_s^{(*)} D_s^{(*)})}$$

We look for $D_s \rightarrow \phi_1 \pi$; $D_s \rightarrow \phi_2 \mu \nu$; $\phi_i \rightarrow K^+ K^-$

D0 Run II Preliminary (2.8 fb$^{-1}$)
\[ \Delta \Gamma_s \text{ from } \text{Br}(B_s \to D_s^{(*)} D_s^{(*)}) \]

\[
\frac{N(B_s \to D_s^{(*)} D_s^{(*)})}{N(B_s \to D_s^{(*)} \mu \nu)} = 2R \frac{\epsilon(B_s \to D_s^{(*)} D_s^{(*)})}{\epsilon(B_s \to D_s^{(*)} \mu \nu)}
\]

\[ R \equiv \frac{\text{Br}(B_s \to D_s^{(*)} D_s^{(*)}) \text{Br}(D_s \to \phi \mu \nu) \text{Br}(\phi \to K^+ K^-)}{\text{Br}(B_s \to D_s^{(*)} \mu \nu)} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N(B_s \to D_s^{(<em>)} D_s^{(</em>)}) )</td>
<td>27.5 ± 9.8</td>
</tr>
<tr>
<td>( N(B_s \to D_s^{(*)} \mu \nu) )</td>
<td>28680 ± 288</td>
</tr>
<tr>
<td>( \epsilon(B_s \to D_s^{(<em>)} D_s^{(</em>)}) )</td>
<td>8.7 ± 1.5%</td>
</tr>
<tr>
<td>( \epsilon(B_s \to D_s^{(*)} \mu \nu) )</td>
<td></td>
</tr>
<tr>
<td>( \text{Br}(D_s \to \phi \mu \nu) )</td>
<td>0.0249 ± 0.0028</td>
</tr>
<tr>
<td>( \text{Br}(\phi \to K^+ K^-) )</td>
<td>0.493 ± 0.006</td>
</tr>
<tr>
<td>( \text{Br}(B_s \to D_s^{(*)} \mu \nu) )</td>
<td>0.079 ± 0.024</td>
</tr>
</tbody>
</table>

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D0 Run II Preliminary (2.8 fb⁻¹)

Candidates / (0.003 GeV/c²)

m(\( \phi \pi \)) (GeV/c²)

D0 Run II Preliminary (2.8 fb⁻¹)

Candidates / (0.0045 GeV/c²)

m(KK) (GeV/c²)
Using all these inputs:

\[
\text{Br}(B_s \rightarrow D_s^{(*)} D_s^{(*)}) = 0.042 \pm 0.015\text{(stat)} \pm 0.017\text{(syst)}
\]

\[
\frac{\Delta \Gamma_s}{\Gamma_s} = 0.088 \pm 0.030\text{(stat)} \pm 0.036\text{(syst)}
\]

In good agreement with

\[
\frac{\Delta \Gamma_s}{\Gamma_s} |_{SM}^{\text{exp}^a} = 0.096 \pm 0.048
\]

\[
\frac{\Delta \Gamma_s}{\Gamma_s} |_{SM}^{\text{theory}^b} = 0.127 \pm 0.024
\]

\[^a\text{Heavy Flavor Averaging Group}\]
\[^b\text{Lenz,Nierste hep-ph/0612167}\]

Conclusions

- \(\text{Br}(B_s \rightarrow D_s^{(*)} D_s^{(*)})\) is a promising method for \(\Delta \Gamma_s\)
- First experimental evidence for \(\Delta \Gamma_s \neq 0\).
- Significance 3.7\(\sigma\)
Using all these inputs:

\[ \text{Br}(B_s \rightarrow D_s^{(*)} D_s^{(*)}) = 0.042 \pm 0.015(\text{stat}) \pm 0.017(\text{syst}) \]

\[ \Delta \Gamma_s / \Gamma_s = 0.088 \pm 0.030(\text{stat}) \pm 0.036(\text{syst}) \]

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Direct CPV in the decay $B^\pm \rightarrow J/\psi K^{\pm}$?
Direct CP-Violation in the decay $B^\pm \to J/\psi K^\pm$?

The decay $B^\pm \to J/\psi K^\pm$ goes via two diagrams:

Their interference produces small asymmetry. We define the charge asymmetry in this decay as

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

From the SM $A_{CP}^{SM} = 0.003$, but $A_{CP}^{NP} = 0.01$

The measurement of $A_{CP}$ is an important way of constraining those new physics models which predict an enhanced value of this asymmetry.

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2. S. Hou et al. hep-ph/0605080
We divide the $J/\psi K$ sample into categories according to solenoid polarity $\beta(=\pm1)$, sign of the kaon pseudorapidity $\gamma(=\pm1)$, and kaon charge $q(=\pm1)$. For each $q\beta\gamma$ subsample:

$$n_{q\beta\gamma}^{N_{\text{sig}}\epsilon^\beta} \propto (1 + qA) (1 + q\gamma A_{fb}) (1 + \gamma A_{det}) (1 + q\beta\gamma A_{q\beta\gamma}) (1 + q\beta A_{q\beta}) (1 + \beta\gamma A_{\beta\gamma})$$

- $\epsilon^\beta$: fraction of integrated luminosity
- $A$: the charge asymmetry to be measured
- $A_{fb}$: forward-backward asymmetric $B$ production
- $A_{det}$: detector asymmetry for kaons
- $A_{q\beta\gamma}$: change in the acceptance of kaons of different sign bent by the solenoid in different directions
- $A_{q\beta}$: detector asymmetry for the change in the kaon reconstruction efficiency
- $A_{\beta\gamma}$: any detector-related f-w asym. that remain after the solenoid polarity flip.

<table>
<thead>
<tr>
<th>Asymmetry</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{sig}}$</td>
<td>$40,127 \pm 243$</td>
</tr>
<tr>
<td>$\epsilon^+$</td>
<td>$0.506 \pm 0.003$</td>
</tr>
<tr>
<td>$A$</td>
<td>$-0.0070 \pm 0.0060$</td>
</tr>
<tr>
<td>$A_{fb}$</td>
<td>$0.0013 \pm 0.0060$</td>
</tr>
<tr>
<td>$A_{det}$</td>
<td>$-0.0033 \pm 0.0060$</td>
</tr>
<tr>
<td>$A_{q\beta\gamma}$</td>
<td>$-0.005 \pm 0.006$</td>
</tr>
<tr>
<td>$A_{q\beta}$</td>
<td>$0.0001 \pm 0.0060$</td>
</tr>
<tr>
<td>$A_{\beta\gamma}$</td>
<td>$-0.0030 \pm 0.006$</td>
</tr>
</tbody>
</table>
Direct CP-Violation in the decay $B^\pm \rightarrow J/\psi K^\pm$

- Take account for the momentum dependence of the kaon cross-section, $A_K = -0.0145 \pm 0.0010$

$$A_{CP}(B^+ \rightarrow J/\psi K^+) = A - A_K = +0.0075 \pm 0.0061\,(\text{stat}) \pm 0.0027\,(\text{syst})$$

This measurement is consistent with the WA value\(^4\): $A_{CP} = +0.015 \pm 0.017$

The achieved precision is of the same level as the expected deviations predicted by the SM.

\(^4\text{Particle Data Group}\)
We have shown four measurements related with CP-violation and mixing in $B$-meson decays at DØ.

Using the combined tagging methods, as a preliminary result from DØ
$\Delta m_s = 18.53 \pm 0.93\text{(stat)} \pm 0.30\text{(syst)} \text{ ps}^{-1}$. Significance $2.9\sigma$.

Consistent with CDF$^a$: $\Delta m_s = 17.77 \pm 0.10\text{(stat)} \pm 0.07\text{(syst)} \text{ ps}^{-1}$.

From the tagged analysis of $B_s \to J/\psi\phi$, we found a possible indication of CPV by measuring the phase $\phi_s = -0.57^{+0.24+0.07}_{-0.30-0.02} \text{ rad}$.

The uncertainty on $\phi_s$ is statistically dominated. More data should be processed to reduce this uncertainty.

From $B_s \to D_s^{(*)} D_s^{(*)}$, we have the first experimental evidence for $\Delta\Gamma_s \neq 0$.
$\Delta\Gamma_s/\Gamma_s = 0.088 \pm 0.030\text{(stat)} \pm 0.036\text{(syst)}$

Consistent with the SM prediction and previous experimental measurements that do not allow CPV.

Direct CPV in the decay $B^+ \to J/\psi K^+$ is consistent with zero.

The uncertainty on this asymmetry is of the order of the SM prediction.

Backup
## Systematic uncertainties for $B_s \to J/\psi \phi$

<table>
<thead>
<tr>
<th>Source</th>
<th>$\bar{\tau}_s$ (ps)</th>
<th>$\Delta \Gamma_s$ (ps$^{-1}$)</th>
<th>$\phi_s$ (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance</td>
<td>$\pm 0.003$</td>
<td>$\pm 0.003$</td>
<td>$\pm 0.005$</td>
</tr>
<tr>
<td>Flavor purity estimate</td>
<td>$\pm 0.001$</td>
<td>$\pm 0.001$</td>
<td>$\pm 0.01$</td>
</tr>
<tr>
<td>Background model</td>
<td>$+0.003$</td>
<td>$\pm 0.02$</td>
<td>$\pm 0.02$</td>
</tr>
<tr>
<td>$\Delta m_s$ input</td>
<td>$\pm 0.01$</td>
<td>$\pm 0.001$</td>
<td>$+0.06, -0.01$</td>
</tr>
</tbody>
</table>
Systematic uncertainties for $B_s \rightarrow D_s^{(*)} D_s^{(*)}$

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
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<tbody>
<tr>
<td>$\text{Br}(B_s \rightarrow D_s^{(*)} \mu \nu)$</td>
<td>0.0127</td>
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<tr>
<td>$\text{Br}(D_s \rightarrow \phi \mu \nu)$</td>
<td>0.0047</td>
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<tr>
<td>$\text{Br}(\phi \rightarrow K^+ K^-)$</td>
<td>0.0006</td>
</tr>
<tr>
<td>Efficiencies ratio</td>
<td>0.0072</td>
</tr>
<tr>
<td>Fitting procedure</td>
<td>0.0071</td>
</tr>
</tbody>
</table>