CP Violation Results from DØ

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for the DØ Collaboration

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The DØ Detector

Tracker:
- Excellent coverage $|\eta| < 3$
- 2T solenoid
- New layer 0 silicon close to beam pipe in 2006, improves impact parameter resolution

Muon system:
- Coverage and triggering: $|\eta| < 2$
- Includes toroid magnets

Polarity flip of both magnets every two weeks
- Reduces detector asymmetries
**B_s \rightarrow J/\psi \phi: CPV via B_s Mixing**

\[ B_s^0 \leftrightarrow \bar{B}_s^0 \]

Schrödinger Equation:

\[
\frac{i}{d} \begin{pmatrix} |B_s^0\rangle \\ |\bar{B}_s^0\rangle \end{pmatrix} = \begin{pmatrix} M - i \frac{\Gamma}{2} & M_{12} - i \frac{\Gamma_{12}}{2} \\ M_{12}^* - i \frac{\Gamma_{12}^*}{2} & M - i \frac{\Gamma}{2} \end{pmatrix} \begin{pmatrix} |B_s^0\rangle \\ |\bar{B}_s^0\rangle \end{pmatrix}
\]

- In the SM:
  - \( \Gamma_{12} \) from long-distance contributions
  - \( M_{12} \) dominated by top quark box diagram
    - Suppressed by four powers of \( g \) and two powers of \( |V_{ts}| \approx 0.04 \)
- CPV phase very small in SM, \( \sim 0.04 \)
- New Physics could easily enhance it
  - Look for non-zero phase as indicator of new physics: \( \phi_s^{NP} \)
  - \( \phi_s^{SM} = -2\beta_s = -2 \arg \left( \frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*} \right) \approx 0.04 \)

Mass eigenstates:

\[
|B_L\rangle = p |B_s^0\rangle + q |\bar{B}_s^0\rangle \approx CP \text{ even}
\]

\[
|B_H\rangle = p |B_s^0\rangle - q |\bar{B}_s^0\rangle \approx CP \text{ odd}
\]

CPV: \( |q/p| \neq 1 \), or interference between direct/mixed decays

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John Ellison, UCR

July 31, 2008
$B_s \to J/\psi(\to \mu^+ \mu^-) \phi(\to K^+ K^-)$

- Pseudoscalar $\to$ Vector Vector, i.e. spin 0 $\to$ 1 + 1
  - L = 0, 2 (amplitudes $A_0$, $A_\perp$): CP even
  - L = 1 ($A_{||}$): CP odd
  - CP-even and CP-odd components have different angular distributions

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

- Initial state flavor tag improves sensitivity and removes sign ambiguity on $\phi_s$ for a given $\Delta \Gamma_s$ present in previous analysis
$B_s \rightarrow J/\psi \phi$ Sample

1967 ± 65 $B_s$ decays

Use a maximum likelihood fit to mass, lifetime, 3 decay angles
- $\Delta M_s$ constrained to measured value (CDF) and strong phases constrained to values measured for $B_d$ at B-factories, allowing some degree of violation of SU(3) symmetry

$B_s$ flavor at production determined using opposite-side + same-side tagging
CP Violation in $B_s \rightarrow J/\psi \phi$: Results

Results:

$$\tau(B_s^0) = 1.52 \pm 0.05 \text{ (stat)} \pm 0.01 \text{ (syst)} \text{ ps}$$

$$\Delta \Gamma_s = 0.19 \pm 0.07 \text{ (stat)} \pm 0.02 \text{ (syst)} \text{ ps}^{-1}$$

$$\phi_s = -0.57 \pm 0.24 \text{ (stat)} \pm 0.07 \text{ (syst)}$$

- Probability of SM = 6.6% $\Rightarrow \sim 1.8\sigma$

(strong phases constrained)

John Ellison, UCR
July 31, 2008

arXiv:0802.2255
Submitted to PRL
New DØ + CDF Combined Result

- Combination of results, *without constraints on strong phases*

\[ \Delta \Gamma_s [\text{ps}^{-1}] \]

**DØ**

- 68% CL
- 95% CL
- 99% CL
- 99.7% CL

\[ \phi_s^{J/\psi \phi} \text{ [rad]} \]

- 68% CL
- 95% CL
- 99% CL
- 99.7% CL

- \( p\)-value = 0.085
- 1.72\( \sigma \) from SM

**CDF**

\[ \Delta \Gamma_s [\text{ps}^{-1}] \]

\[ \phi_s^{J/\psi \phi} \text{ [rad]} \]

\( \phi_s = -2.37^{+0.38}_{-0.27} \text{ rad}, \quad -0.75^{+0.27}_{-0.38} \text{ rad} \)

\( \Delta \Gamma_s = -0.150^{+0.066}_{-0.059} \text{ ps}^{-1}, \quad 0.150^{+0.059}_{-0.066} \text{ ps}^{-1} \)

90% C.L. 1-d regions:

- \( \phi_s \in [-2.85, -1.65] \), \([-1.47, -0.29] \)
- \( \Delta \Gamma_s \in [-0.265, -0.036] \), \([0.036, 0.265] \)

- 1.35 fb\(^{-1}\) + DØ 2.8 fb\(^{-1}\)

- 68% CL
- 95% CL
- 99% CL
- 99.7% CL

**New Result for ICHEP08!**

- \( p\)-value = 0.031
- 2.2\( \sigma \) from SM

- 2.8 fb\(^{-1}\)

- 2.37\( \pm 0.38 \) rad
- \(-0.75 \pm 0.27 \) rad

- 0.150\( \pm 0.066 \) ps\(^{-1}\)
- \(0.150 \pm 0.059 \) ps\(^{-1}\)

- \( \phi_s \) from the DØ and CDF collaborations.

John Ellison, UCR July 31, 2008
Constraint from $A_{SL}$

- From measurements of $A_{SL}^s = \frac{N(B_s \rightarrow \ell^+ X) - N(B_s \rightarrow \ell^- X)}{N(B_s \rightarrow \ell^+ X) + N(B_s \rightarrow \ell^- X)} = \frac{\Delta \Gamma_s}{\Delta M_s} \tan \phi_s$
  - Fix $\Delta M_s$ to measured value and constrain $\Delta \Gamma_s \tan \phi_s$
  - World Average $A_{SL} = 0.0016 \pm 0.0085$
    - (Does not include new DØ measurement – see later)

\[\begin{align*}
\text{HFAG} \\
2008
\end{align*}\]
Direct CP Violation in $B^\pm \rightarrow J/\psi \ K^{\pm}(\pi^{\pm})$

- Search for direct (i.e. not via mixing) CP violation
- Measure charge asymmetry in $B^\pm \rightarrow J/\psi \ K^{\pm}$ and $B^\pm \rightarrow J/\psi \ \pi^{\pm}$
- Charge asymmetry defined by

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

- CP violation $\Rightarrow$ non-zero $A_{CP}$

- In SM, $A_{CP}(B^+ \rightarrow J/\psi \ K^+) \approx 0.003^1$, $\sim 0.01^2$ for $J/\psi \ \pi^+$
  - Due to interference of tree-level and penguin decay diagrams

- New physics may significantly enhance $A_{CP}$

J/$\psi$ K$^{\pm}(\pi^{\pm})$ Mass Distribution

- Fit to sum of contributions from $B \rightarrow J/\psi K$, $B \rightarrow J/\psi \pi$, and $B \rightarrow J/\psi K^*$, as well as combinatorial background (BKG).

- From fit we find
  - $\sim$40k $B \rightarrow J/\psi K$ events
  - $\sim$1.6k $B \rightarrow J/\psi \pi$ events
Asymmetry Measurement

- Divide sample into 8 subsamples according to:
  - Solenoid polarity, $\beta$; sign of pseudorapidity of $J/\psi K$ system, $\gamma$; charge of $K$ candidate, $q$

- Number of events in each subsample:

$$n_{q}^{\beta\gamma} = \frac{1}{4}N\epsilon^{\beta}(1 + qA_{raw})(1 + \gamma A_{det})(1 + q\gamma A_{fb})(1 + q\beta A_{q\beta})(1 + \beta\gamma A_{\beta\gamma})(1 + q\beta\gamma A_{\rho_0})$$

  where
  - $N$ - number of signal events in the sample
  - $\epsilon^{\beta}$ - fraction of integrated luminosity with magnet polarity $\beta$ ($\epsilon^{+} + \epsilon^{-} = 1$)
  - $A_{raw}$ - integrated raw charge asymmetry we want to measure
  - $A_{fb}$ - forward-backward asymmetry (more kaons go in proton direction)
  - $A_{det}$ - north-south asymmetry of the detector
  - $A_{q\beta\gamma}$ - decrease of acceptance of kaons bent by the magnet
  - $A_{\beta\gamma}$ - detector forward-backward asymmetry remaining after magnet polarity flip
  - $A_{q\beta}$ - change in kaon reconstruction efficiency after magnet polarity flip

- $\chi^2$ fit to number of events in each subsample yields asymmetries
**A_{CP}(B^\pm \rightarrow J/\psi \ K^\pm(\pi^\pm)) Results**

<table>
<thead>
<tr>
<th></th>
<th>$J/\psi K$</th>
<th>$J/\psi \pi$</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>40217±243</td>
<td>1577±118</td>
<td>33189±424</td>
</tr>
<tr>
<td>$\epsilon^+$</td>
<td>0.5060±0.0030</td>
<td>0.5060±0.0030</td>
<td>0.5010±0.0064</td>
</tr>
<tr>
<td>$A^{raw}$</td>
<td>-0.0070±0.0060</td>
<td>-0.0887±0.0807</td>
<td>-0.0205±0.0128</td>
</tr>
<tr>
<td>$A_{fb}$</td>
<td>0.0013±0.0060</td>
<td>0.0453±0.0890</td>
<td>-0.0170±0.0128</td>
</tr>
<tr>
<td>$A_{det}$</td>
<td>-0.0033±0.0060</td>
<td>0.2061±0.0826</td>
<td>-0.0158±0.0128</td>
</tr>
<tr>
<td>$A_{ro}$</td>
<td>-0.0050±0.0060</td>
<td>-0.0207±0.0873</td>
<td>-0.0024±0.0128</td>
</tr>
<tr>
<td>$A_{\beta\gamma}$</td>
<td>0.0001±0.0060</td>
<td>-0.1896±0.0823</td>
<td>0.0274±0.0128</td>
</tr>
<tr>
<td>$A_{q\beta}$</td>
<td>-0.0030±0.0060</td>
<td>0.0499±0.0801</td>
<td>-0.0145±0.0128</td>
</tr>
</tbody>
</table>

- **Correct $A^{raw}$ for kaon asymmetry**
  - Reaction $K^- + N \rightarrow$ hyperon + $\pi$ has no $K^+ + N$ analog, so that $N(K^+) > N(K^-)$

- **Results:**
  - $A_{CP}(B^+ \rightarrow J/\psi \ K^+) = +0.0075 \pm 0.0061$ (stat.) $\pm 0.0027$ (syst.)
  - $A_{CP}(B^+ \rightarrow J/\psi \ \pi^+) = -0.09 \pm 0.08$ (stat.) $\pm 0.03$ (syst.)

- **Consistent with world averages**
  - Factor of 2.5 improvement in precision for $A_{CP}(B^+ \rightarrow J/\psi \ K^+)$
  - Competitive precision for $A_{CP}(B^+ \rightarrow J/\psi \ \pi^+)$
CP Violation in Semileptonic $B_s$ Decays

- New search for CP Violation in $B^0_s \rightarrow D^- \mu^+\nu X$, $(D^- \rightarrow \phi\pi^-, \phi \rightarrow K^+K^-)$ by measurement of the charge asymmetry using a time-dependent analysis with flavor tagging
  - Technique similar to $B_s$ oscillation analysis (PRL 97, 021802, 2006), modified to include CPV and study of detector asymmetries

- Flavor at production
  - Opposite-side + same-side flavor tagging

- Flavor at decay from muon charge

- Proper decay length:
  \[ c\tau_{B^0_s} = x^M K, \quad \text{where} \quad x^M = \left[ \frac{\vec{d}^B_s \cdot \vec{p}^{\mu D_s^-}}{(p_T^{\mu D_s^-})^2} \right] cM_{B^0_s} \]

  $K$-factor: $K = \frac{p_T^{\mu D_s^-}}{p_T^{B^0_s}}$ determined from MC

  $x^M$ = Visible Proper Decay Length (VPDL)
Data Sample

Data sample and mass and decay length fits:

\[
\int L \, dt = 2.8 \text{ fb}^{-1} \\
N_{D_s} = 53592 \pm 718
\]

\[\mu^+ D^- : 53592 \pm 718 \text{ events}\]

Divide sample into 8 subsamples according to:

- Solenoid polarity \( \beta \); sign of pseudorapidity of \( D_s \) \( \mu \) system \( \gamma \); muon charge \( q \)
- Construct probabilities, allowing for non-zero asymmetries \( a_{sl}^s, a_{sl}^d, a_{sl}^{bkg} \)

\[
p(x, K, d_{pr}; a_{sl}) = p_{VPDL}(x, K, d_{pr}; a_{sl}) \cdot \varepsilon^\beta (1 + q_\mu \gamma_\mu A_{fb})(1 + \gamma_\mu A_{det})(1 + q_\mu \beta_\gamma_\mu A_{ro})(1 + \beta_\gamma_\mu A_{s_\gamma})(1 + q_\mu \beta A_{q_\beta})
\]

- Unbinned likelihood fit yields asymmetries
Asymmetry Results

- Fit results from Run IIa and Run IIb data combined

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Run II, $\int L dt = 2.8 \text{ fb}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_{sl}^s$</td>
<td>$-0.0024 \pm 0.0117$</td>
</tr>
<tr>
<td>$a_{sl}^d$</td>
<td>$-0.0787 \pm 0.0371$</td>
</tr>
<tr>
<td>$a_{bg}$</td>
<td>$-0.0182 \pm 0.0271$</td>
</tr>
<tr>
<td>$A_{fb}$</td>
<td>$0.0000 \pm 0.0021$</td>
</tr>
<tr>
<td>$A_{det}$</td>
<td>$0.0001 \pm 0.0021$</td>
</tr>
<tr>
<td>$A_{ro}$</td>
<td>$-0.0323 \pm 0.0021$</td>
</tr>
<tr>
<td>$A_{\beta\gamma}$</td>
<td>$-0.0005 \pm 0.0021$</td>
</tr>
<tr>
<td>$A_{q\beta}$</td>
<td>$0.0029 \pm 0.0021$</td>
</tr>
</tbody>
</table>

- Systematic errors due to uncertainties in:
  - $c\bar{c}$ contribution; efficiency vs. VPDL; $B_s \rightarrow D_s^{(*)}\mu\nu$ branching fractions

**Final Result:** $a_{sl}^s = -0.0024 \pm 0.0117 \text{ (stat.)}^{+0.0015}_{-0.0024} \text{ (syst.)}$

**New Result for ICHEP08!** most precise direct measurement to date

DØ Run II Preliminary
Summary

Our recent results in B-Physics include three new measurements on CP violation:

- **CP Violating phase in $B_s \to J/\psi \phi$:**
  
  \[ \phi_s = -0.57^{+0.24}_{-0.30} \text{(stat)} \pm 0.07_{-0.02} \text{(syst)} \text{ rad} \]

- **New DØ+CDF combined results with no strong-phase constraints:**
  
  \[ \sim 2.2\sigma \text{ deviation from SM, intriguing!} \]
  
  \[ \phi = -2.37^{+0.38}_{-0.27} \text{ rad}, \quad -0.75^{+0.27}_{-0.38} \text{ rad} \]

- **Searches for direct CP violation**

  - **Charge asymmetries in $B^+ \to J/\psi K^+ (\pi^+)$**
    
    \[ A_{CP}(B^+ \to J/\psi K^+) = +0.0075 \pm 0.0061 \text{ (stat.)} \pm 0.0027 \text{ (syst.)} \]
    
    \[ A_{CP}(B^+ \to J/\psi \pi^+) = -0.09 \pm 0.08 \text{ (stat.)} \pm 0.03 \text{ (syst.)} \]

  - **Charge asymmetry in $B_s \to D_s \mu \nu X$**
    
    \[ a_{s\ell}^s = -0.0024 \pm 0.0117 \text{ (stat.)}^{+0.0015}_{-0.0024} \text{ (syst.)} \]
    
    DØ Run II Preliminary

- **Note:** due to time constraints CPV in $B_s^0 \to D_s^{(*)} D_s^{(*)}$ is covered in talk by D. Buchholz in tomorrow’s session