Studies of CP violation in $B_s^0 \rightarrow J/\psi + \phi/f_0$ decay

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Motivation

- The mass eigenstates of the $B_s^0$ system have sizeable mass and decay width difference $\Delta M_s$ and $\Delta \Gamma_s$
- The CP-violating mixing phase is predicted to be $\phi_{s}^{J/\psi \phi} = -2\beta_s = -2 \arg[-V_{tb}V_{ts}^*/V_{cb}V_{cs}^*] = -0.038 \pm 0.002$
- New phenomena may alter the phase $\phi_{s}^{J/\psi \phi} \equiv -2\beta_s + \phi_s^\Delta$
- We measure $\Delta \Gamma_s$ and $\phi_{s}^{J/\psi \phi}$
Event distribution

- $B_s \rightarrow J/\psi \Phi$ admixture of CP-even/odd states
- Can be described by 3 polarization amplitudes
- Transversity basis $\vec{\omega} = (\psi, \theta, \phi)$:
  - CP-odd ($l=1$): $A_\perp$
  - CP-even ($l=0,2$): $A_0, A_\parallel$
DØ Detector

- Excellent muon detection to $|\eta| < 2.2$, low punch-through
- Fiber and Silicon Tracker in 2T Solenoid

- Single and dimuon triggers
Data Samples

Run II Integrated Luminosity

19 April 2002 - 17 July 2011

90% efficient

8 fb^{-1}

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Event Selection

- We require two reconstructed muons of opposite charge.
- Form $J/\psi$ candidates
- Form $\Phi$ candidates from opposite charged tracks assuming the tracks are kaons.
- Form $B_s$ candidates from $J/\psi$ and $\Phi$ candidates.
- Make cuts in the kinematic and the mass windows:
  - $P_t(K^\pm) > 0.4 \text{GeV}$
  - $2.84 < M(\mu^+\mu^-) < 3.35 \text{GeV}$
  - $0.98 < M(K^+K^-) < 1.04 \text{GeV}$
  - $5.0 < M(\mu^+\mu^-K^+K^-) < 5.8 \text{GeV}$
Background suppression

- BDT used to suppress background.
  - Prompt $p\bar{p} \rightarrow J/\psi X$

- b-inclusive $p\bar{p} \rightarrow b\bar{b} \rightarrow J/\psi X$

- Simple-Cut as in 2008 PRL, for cross-check and systematic uncertainties.
Optimizing selection

- Tight cuts implies better signal significance but less signal events
- Optimized selection cuts using toy montecarlo studies
Probability Distribution Function

\[ \epsilon(\vec{\omega}) \times \left( B_s(\lambda; t, \vec{\omega}) \frac{1 - D}{2} + \overline{B}_s(\lambda; t, \vec{\omega}) \frac{1 + D}{2} \right) \otimes R(t) \]

where:

- \( \vec{\omega} = (\psi, \theta, \varphi) \) — angles
- \( D \) — initial flavor tagging dilution
- \( \epsilon(\vec{\omega}) \) — acceptance
- \( R(t) \) — resolution.

\[ B_s = \left| \sqrt{1 - F_s g(\mu)} A + e^{-i\delta_s} \sqrt{F_s h(\mu)} B \right| \times \hat{n} \]

- \( A(\lambda; t, \omega) \) — P-Wave
- \( B(\lambda; t, \omega) \) — S-Wave.
- \( \lambda = (\tau_s, \Delta \Gamma_s, \phi_s^{J/\Psi\phi}, |A_0|^2, |A_\perp|^2, F_s, \delta_s, \delta_\parallel, \delta_\perp, \Delta m_s) \)
Real Measurables

- Two constraints:
- $\Delta m_s \equiv 17.77 \pm 0.12$
- $\cos(\delta_{\perp}) < 0$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>A_0</td>
</tr>
<tr>
<td>$</td>
<td>A_\parallel</td>
</tr>
<tr>
<td>$\bar{\tau}_s \text{ (ps)}$</td>
<td>$B_s^0$ mean lifetime</td>
</tr>
<tr>
<td>$\Delta \Gamma_s \text{ (ps}^{-1})$</td>
<td>Heavy-light decay width difference</td>
</tr>
<tr>
<td>$F_S$</td>
<td>$K^+K^-$ $S$-wave fraction</td>
</tr>
<tr>
<td>$\phi_s^{J/\psi\phi}$</td>
<td>CP-violating phase</td>
</tr>
<tr>
<td>$\delta</td>
<td>$</td>
</tr>
<tr>
<td>$\delta$</td>
<td>$\text{arg}(A_{\perp}/A_0)$</td>
</tr>
<tr>
<td>$\delta_s$</td>
<td>$\text{arg}(A_s/A_0)$</td>
</tr>
</tbody>
</table>
• Data selection criteria were applied to flat MC
• 2D $\cos(\theta)$, $\phi$ acceptance

• Event-by-Event resolution width
• Distribution of proper decay time resolution
  • MC - Dots
  • Data - Crosses

• Opposite Flavor tagging using:
  • Muon
  • Electron
  • Jet Charge
Maximum Likelihood Fit
Maximum Likelihood Fit (Signal Enriched)

Proper Decay Time (ps)

N(events) / 0.075 ps

10
210
310
410

Proper Decay Time (ps)

N(events) / 0.075 ps

10
210
310
410

Run II, 8 fb⁻¹

Preliminary

ψ

θ

φ

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CP Violation on $B_s \rightarrow J/\Psi + \phi / f_0$

PANIC 11 July, 25
## Fit Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BDT Sample</th>
<th>Simple Cut Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_s$</td>
<td>$1.426^{+0.035}_{-0.032}$ ps</td>
<td>$1.444^{+0.041}_{-0.033}$ ps</td>
</tr>
<tr>
<td>$\Delta \Gamma_s$</td>
<td>$0.129^{+0.076}_{-0.053}$ ps$^{-1}$</td>
<td>$0.179^{+0.059}_{-0.060}$ ps$^{-1}$</td>
</tr>
<tr>
<td>$\phi_s$</td>
<td>$-0.49^{+0.48}_{-0.40}$</td>
<td>$-0.56^{+0.36}_{-0.32}$</td>
</tr>
<tr>
<td>$</td>
<td>A_0</td>
<td>^2$</td>
</tr>
<tr>
<td>$</td>
<td>A_\parallel</td>
<td>^2$</td>
</tr>
<tr>
<td>$\delta_\parallel$</td>
<td>$-3.15 \pm 0.27$</td>
<td>$-3.15 \pm 0.19$</td>
</tr>
<tr>
<td>$\cos(\delta_\perp - \delta_s)$</td>
<td>$-0.06 \pm 0.24$</td>
<td>$-0.20^{+0.26}_{-0.027}$</td>
</tr>
<tr>
<td>$F_S(\text{eff})$</td>
<td>$0.146 \pm 0.035$</td>
<td>$0.176 \pm 0.036$</td>
</tr>
</tbody>
</table>
Independent determination of $F_s$

- The invariant mass distribution of $B^0_s$ candidates with $ct > 0.02\text{cm}$ in two slices of $M(K^+K^-)$
- Fits to a sum of a Gaussian function and a polynomial are used to extract the $B^0_s$ yield in each slice.
- $F_s = 0.14 \pm 0.01$
Systematic Uncertainties

- Acceptance systematic from differences between BDT and Simple-cut samples
- Variation in resolution parameters
  - Random variations in the resolution parameters
- Different widths of $\Phi$
  - Different resolution for the $\Phi$ mass, important since s-wave is around 15%
- Variation OST calibration curve
- Markov Chain thechique for contours and systematics
$B_s^0 \to J/\psi \phi$ Result

<table>
<thead>
<tr>
<th>$P$</th>
<th>$\chi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_s$</td>
<td>$1.443^{+0.038}_{-0.035}$ ps</td>
</tr>
<tr>
<td>$\Delta \Gamma_s$</td>
<td>$0.163^{+0.065}_{-0.064}$ ps$^{-1}$</td>
</tr>
<tr>
<td>$\phi_s^{J/\psi \phi}$</td>
<td>$-0.55^{+0.38}_{-0.36}$</td>
</tr>
<tr>
<td>$</td>
<td>A_0</td>
</tr>
<tr>
<td>$</td>
<td>A_\parallel</td>
</tr>
<tr>
<td>$\delta_\parallel$</td>
<td>$-3.15 \pm 0.22$</td>
</tr>
<tr>
<td>$(\delta_\perp - \delta_s)$</td>
<td>$-0.11^{+0.027}_{-0.025}$</td>
</tr>
<tr>
<td>$F_S(\text{eff})$</td>
<td>$0.173 \pm 0.036$</td>
</tr>
</tbody>
</table>

\[ \Delta M_s \equiv 17.77 \pm 0.12 \text{ ps}^{-1} \]

SM $p$-value $= 29.8\%$

DØ Run II, 8 fb$^{-1}$

Preliminary

68% CL

90% CL

95% CL

$\phi_s^{J/\psi \phi}$ (rad)

$\phi_s^{J/\psi \phi}$ (rad)

$\phi_s^{J/\psi \phi}$ (rad)
$B^0_s \rightarrow J/\psi f_0(890)$

- CP-odd final state, no angular analysis
- Independent information on $\Delta \Gamma_s$
- First step is measure the branching ratio
$B_s^0 \rightarrow J/\psi f_0(890)$ Branching ratio

- Muon trigger
- Identical selection criteria for $J/\psi f_0$ and $J/\psi \Phi$
- BDT to reduce background
- $478 \pm 76 J/\psi f_0(980)$ events

Branching Ratio:

$$R = \frac{\mathcal{B}(B_s^0 \rightarrow J/\psi f_0(980); f_0 \rightarrow \pi^+\pi^-)}{\mathcal{B}(B_s^0 \rightarrow J/\psi \Phi; \Phi \rightarrow K^+K^-)} = 0.210 \pm 0.032 (\text{stat}) \pm 0.036 (\text{sys})$$
Summary

- Measurement of $B_s^0$ mixing parameters, polarization amplitudes and phases in the $B_s^0 \rightarrow J/\psi \phi$ analysis using 8$fb^{-1}$ data sample.
  - Inclusion of $K^+K^-$ s-wave
- Measurement of the branching fraction of $B_s^0 \rightarrow J/\psi f_0(980)$ in agreement with other experiments.
  - Next step is to use in CP-Violation measurements
- **Combination with other DØ measurements** of CP-Violation parameters will be performed soon

Stay tuned!
Backup Slides
Markov Chain technique

- Since $\phi_s$ is very correlated with $\Delta \Gamma_s$ we want to know how the likelihood depends on these variables.
- Start from some point $\mu$. I use the minimum obtained from the fit.
- Generate a multivariate gaussian $(e^{-\frac{1}{2}(x-\mu)\cdot\Sigma^{-1}\cdot(x-\mu)})$ point $x'$
- Where $\Sigma$ is the covariance matrix.
- Calculate $\alpha = L(x')/L(\mu)$
- Generate a random number $r = U(0,1)$
- If $r < \alpha$ accept the new point $\mu = x$
- And continue until reach the amount of points desired.
- We generate 1M events for each Markov Chain