Searches for CP Violation in the $B^0_s$ System Using $B^0_s \rightarrow J/\psi + (\varphi/f_0/f_2)$ Decays

Dmitri Tsybychev
Stony Brook University
on behalf of D0 Collaboration

XXXVI International Conference on High Energy Physics
July 4–11 Melbourne, Australia
CP Violation in $B^0_s$

- $B^0_s$ is one of the least explored systems
- Study of CP violation in $B^0_s$ mixing may help explain the observed CP violation in Universe and lead to possible new physics
- Predicted CP rated is very small in SM - search for large deviations
- Mixing induced CP violation
  - Assume no CP in decays
  - 2 observables phases
  - $\phi_s$ - accessible through semileptonic decays
  - $\beta_s$- accessible through $B^0_s \rightarrow J/\psi + X$ decays
- Contribution of new particles in the box diagrams may enhance both

$2\beta_s = 2\beta_{SM}^s - \phi_{NP}^s$
$\phi_s = \phi_{SM}^s - \phi_{NP}^s$ with $\phi_{NP}^s >> \phi_{SM}^s$, $2\beta_{SM}^s$

$-2\beta_s \sim \phi_s \sim \phi_{NP}^s$
CP Violation in $B^0_s \to J/\psi + X$

- Study $B^0_s \to J/\psi + X$ decays
- $X$ may be a (non)resonant final state and affect the CP measurements
  - For example S-wave contributions
- $X=\phi(K^+K^-)$ golden mode, used to measure CP-violating phase
- Study additional channels
- $X=f_0(980)(\pi^+\pi^-)$ also used to measure CP-violating phase
- Analysis of decay $B^0_s \to J/\psi K^+K^-$ for $1.35 < M(K^+K^-) < 2.0$
  - Measurement of branching ratio and study of spin have been performed for the resonant decay
B^{0}_{s} \to J/\psi + K^{+}K^{-} Selection

- Study $B^{0}_{s} \to J/\psi + K^{+}K^{-}$ decays
  - For each J/$\psi$ candidate find K$^{+}$K$^{-}$ pair with common vertex
    - assign kaon mass
    - require m(K$^{+}$K$^{-}$) > 1.35 GeV
  - Reconstruct $B^{0}_{s}$ candidate by forming a vertex for J/$\psi$ and K$^{+}$K$^{-}$ pair
- Enhance signal by requiring $1.45 < m(K^{+}K^{-}) < 1.60$ GeV and $|\cos \psi| < 0.8$ (see later)
- Signal + Background model fit yields $578 \pm 100$ events with fit probability 0.338
- Background only fit probability $4.5 \times 10^{-5}$
J/ψK⁺K⁻ Sample Composition

- Decays attributed to f'₂(1525)
  - PDG mass 1525±5 MeV, width 73⁺6₋5 MeV
  - BR to KK: 89%, ππ: 1%
- Other possible contributions due f₂(1270)
  - BR to 2π/4π: 87.6%, KK: 4.6%
- f₀(1500)
  - BR to 2π/4π: 85%, KK: 8%
- No peak observed under J/ψπ⁺π⁻ hypothesis
- Additional contribution possible due to B⁰ → J/ψK⁺K⁻(→Kπ)
Decays $B^0 \rightarrow J/\psi K^*_2(1430)$ contribute to the signal due to $\pi$ misidentification as $K$.

Contribution estimated in the fit using templates of $B^0 \rightarrow J/\psi K^* J$ in steps of $m(K^+K^-)$ of 50 MeV from MC.

Signal and background templates are fitted with double Gaussian.

Extract $B^0_s$ yield as a function of $m(K^+K^-)$.
J/$\psi K^+ K^-$ Signal Yield

- Extract signal in 50 MeV bin of m(K$^+ K^-$)
- Relative normalization of two K*J(1430) states are allowed to vary
  - Normalization of Signal and all background are not constrained to be positive for unbiased rates close to zero
- Event yield versus m(K$^+ K^-$) distributions is fitted with signal (convoluted with Relativistic Breit-Wigner(J=2)) and a constant non-resonant term assumed to be S-wave
  - Signal: 669 ± 158
  - S-wave (in m(K$^+ K^-$) 1.4 to 1.7 GeV): 331 ± 73
- Measure BR relative to $B^0 \rightarrow J/\psi \phi$:

$$R_{f_2'}/\phi = \frac{B(B_s^0 \rightarrow J/\psi f_2'(1525); f_2'(1525) \rightarrow K^+ K^-)}{B(B_s^0 \rightarrow J/\psi \phi; \phi \rightarrow K^+ K^-)} = \frac{N_{B_s^0 \rightarrow J/\psi f_2'(1525)} \times \varepsilon_{\text{reco}}^{B_s^0 \rightarrow J/\psi f_2'(1525)}}{N_{B_s^0 \rightarrow J/\psi \phi} \times \varepsilon_{\text{reco}}^{B_s^0 \rightarrow J/\psi \phi}}$$

- **D0**: 0.22 ± 0.05(stat) ± 0.04(syst)
- **LHCb**: 0.264 ± 0.027(stat) ± 0.024(syst)
Spin Study

• Study spin configuration J=0⁺,1⁻,2⁺
• Decay amplitude is given by:

\[ \frac{d\Gamma}{d\cos\theta d\phi d\cos\psi} \propto \sum_m A_m Y^m_l(\cos\theta_H, \phi_H) Y^{-m}_j(\cos\psi, 0) |D(\cos\theta_H, \phi_H, \psi)|^2 \]

• \( \theta, \phi \) and \( \psi \) are angles in helicity basis and sum extends over equal helicities \( m \) of the J/\( \psi \) and the spin J of \( (K^+K^-) \) system
• D is acceptance for event reconstruction
• Decay amplitude is obtained in helicity angle \( \psi \), integrate out other two angles
• D0 data favor spin=2
• D0 data also accommodate a fit of coherent superposition of J=0 and J=2, with S-wave fraction 0.17±0.14
• Submitted to Phys. Rev. D
\[ \Phi^{J/\psi \Phi_s} \text{ and } \Delta \Gamma_s \text{ in } B^0_s \to J/\psi \Phi \]

- Measure \( \Phi^{J/\psi \Phi_s}(\beta_s) \) and \( \Delta \Gamma_s \) by studying time evolution of flavor tagged \( B_s \to J/\psi(\mu^+\mu^-\Phi(K^+K^-)) \) decays
  - Pseudoscalar → Vector Vector
  - 3 possible angular momentum states
- The mass eigenstates are expected to be almost pure CP-eigenstates
  - \( S, D \) (CP even): linear combination of \( A_0, A_\parallel \)
  - \( P \) (CP odd): \( A_\perp \)

\[
\Gamma(t) \approx \left| A_{\text{even}}(\theta, \psi, \varphi, t) \right|^2 + \left| A_{\text{odd}}(\theta, \psi, \varphi, t) \right|^2 + A^* A(\text{CPC}) \quad \text{CP-conserving interference}
\]

\[
+ A^* A(\text{CPV})(e^{-\Gamma_{L,t}} - e^{-\Gamma_{H,t}}) \sin \phi_s^{J/\psi \Phi} \quad \text{CP-violating interference}
\]
$B^0_s \rightarrow J/\psi \phi$ Event Selection

- $B^0_s \rightarrow J/\psi \phi$ selection criteria are designed to minimize measurement uncertainties on $\phi_{J/\psi \phi}^s$ and $\Delta \Gamma_s$
- Based on Boosted Decision Tree multivariate technique
- Square cuts as a cross check and systematics

![Graphs showing mass and proper decay time distributions](image)
• Use event-by-event resolution
  • Approximated as sum of several Gaussians
  • Variation for systematics

• Use combined OST
  • Muon
  • Electron
  • Jet vertex charge
  • Dilution calibrated using $B^0_d$ decays

• Correct for acceptance 2D acceptance in $\cos(\theta), \varphi$
• Data selection criteria applied to MC generated uniform in all angles
$\phi_{J/\psi\phi_s}$ and $\Delta \Gamma_s$ Fit Results

- Use Markov chain technique to draw contours in $\Delta \Gamma_s$ vs $\phi_{J/\psi\phi_s}$ parameter space
- Sample randomly likelihood using Metropolis-Hasting algorithm
- Use sampled likelihood to obtain contours and combine systematic uncertainties
- Combine BDT and cut based results

<table>
<thead>
<tr>
<th>P</th>
<th>x</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\tau}_s$</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>$\phi_{J/\psi\phi_s}$</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>

Additional Channels for $\beta_s$ Measurements

- $J/\psi f_0(980)$ final state corresponds to a $CP$-odd eigenstate of $B^0_s$
  - Could be used in studies of $CP$ violation

$$R_{f_0/\phi} = \frac{N_{B^0_s \rightarrow J/\psi f_0(980)}}{N_{B^0_s \rightarrow J/\psi \phi}} \cdot \frac{\varepsilon_{\text{reco}}^{B^0_s \rightarrow J/\psi \phi}}{\varepsilon_{\text{reco}}^{B^0_s \rightarrow J/\psi f_0(980)}}$$

- Use BDT selection
- Normalize to $B^0_s \rightarrow J/\psi \phi$


$$R_{f_0/\phi} = 0.275 \pm 0.041 \text{ (stat)} \pm 0.061 \text{ (syst)}$$
Summary

- Mature experiment still producing exciting results
  - Sizeable $B^0_s$ sample has been accumulated
  - Almost full 10 fb$^{-1}$ data sample analyzed
  - Adding new channels
  - Measured relative branching fraction of $B^0_s \rightarrow J/\psi f'_2(1525)$ to $B^0_s \rightarrow J/\psi \phi$ and spin of the $K^+K^-$ system
    - Consistent with $J=2$ or superposition of $J=0,2$ states
  - Measured of $B^0_s$ mixing parameters, polarization amplitudes and phases in the $B^0_s \rightarrow J/\psi \phi$ decay channel using 8 fb$^{-1}$ data sample
  - Measured relative branching fraction of $B^0_s \rightarrow J/\psi f_0(1525)$ to $B^0_s \rightarrow J/\psi \phi$
  - Plan to use for phase measurement with full dataset
BACKUP