Suppressed Decays of $B_s$ Mesons

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On behalf of the CDF collaboration

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Motivation

- Most of the $B_s$ suppressed decays have not been observed yet

$$\Rightarrow B_s \rightarrow J/\psi K^*(892), B_s \rightarrow J/\psi K_S, B_s \rightarrow J/\psi f^0, \ldots$$

- Only difference is the $V_{cd}$ contribution vs the $V_{cs}$

- All of these modes have the possibility of providing further information on lifetime difference and CP asymmetries in $B_s$ decays.

$$\Rightarrow B_s \rightarrow J/\psi K_S$$ is a CP eigenstate, measurement of the lifetime in this mode is a direct measurement of $\tau_{B_s}$ (Heavy)

$$\Rightarrow B_s \rightarrow J/\psi K_S$$ can be used to extract the angle $\gamma$ of unitary triangle (R. Fleischer, Eur.Phys. J.C10:299-306,1999)

$$\Rightarrow B_s \rightarrow J/\psi K^*$$ contains an admixture of CP final states, an angular analysis can be done to extract $\sin(2\beta_s)$ (complementary to $B_s \rightarrow J/\psi \phi$)
B production at Tevatron

- Tevatron is a source of all B-hadron species: $B_d$, $B_u$, $B_c$, $B_s$ and $\Lambda_b$.
  
  ⇒ At CDF the $\sigma_b = 29.4 \pm 0.6 \pm 6.2 \text{ } \mu b$ ($|\eta| < 1$)

- Some of them are not produced at the B-factories
  
  ⇒ $B_s$, $B_c$, $B^{**}$, $B_s^{**}$, $\Lambda_b$, $\Sigma_b$, $\Xi_b$,

- More decays are accessible thanks to the amount of luminosity collected
  
  ⇒ CDF has more than 7.5 fb$^{-1}$ on tape

- CDF has excellent mass resolution, vertex resolution and trigger system for flavor physics
Measurements

- Branching ratio measurement
  \[
  \frac{\text{Br}(B_s \rightarrow J/\psi \ h)}{\text{Br}(B^0 \rightarrow J/\psi \ h)} = \frac{N(B_s \rightarrow J/\psi \ h)}{N(B^0 \rightarrow J/\psi \ h)} \times \frac{f_d}{f_s} \times A_{\text{rel}}
  \]
  where \( h = K_S \) or \( K^* \)

  - Branching ratio of \( B_s \) relative to \( B^0 \)
  - Yield of \( B_s \) and \( B^0 \) events (from data)
  - Fragmentation fractions (from CDF result)
  - Relative Acceptance (from MC)

- Analysis strategy
  ⇒ Reconstruct \( B \rightarrow J/\psi \ K^* \) and \( B \rightarrow J/\psi \ K_S \) from a large sample of di-muon
  \((J/\psi \rightarrow \mu^+ \mu^- \text{ decays})\)
  ⇒ Apply specific optimization cuts to remove backgrounds
  ⇒ Likelihood fit to the invariant mass distribution to get the ratio of yields
Reconstruction

- Data from di-muon triggers
  \[ J/\psi \text{ triggers, mainly looking for:} \]
  - two low $p_T$ muons: $p_T > 1.5$ GeV/$c^2$
  - two muons have opposite charge
  - $\Delta\phi$ (between 2 muons) $< 120$ degrees

- Reconstruction
B→J/ψ K_s Analysis

- **Advantage**: K_s has a long life (cτ ~ 2.5 cm) and is a narrow resonance
  - easy to get a pure K_s sample
- **Disadvantage**: expecting small B_s signal
  - important to suppress combinatorial background contribution

- A Neural Network is used to discriminate between signal and combinatorial background
  - 22 different kinematic variables: p_T, d0, cτ, helicity angles, mass, ...
  - Trained using B_s MC for Signal and data sideband for BKG
  - Optimization procedure geared towards maximizing efficiency/(1.5 + √B)
The invariant mass distribution is fitted with binned Likelihood. The fit contributions for $B \to J/\psi K_S$ include a binned Likelihood fit to the data. 

- **Signal**
  - $B^0$ and $B_s$ decays

- **Background**
  - Partial reconstruction multibody decays where $\pi$, $K$ or $\gamma$ missing
  - Combinatorial background
  - $\Lambda_b \to J/\psi \Lambda$ contribution
    - Negligible after specific cut

The fit uses an Argus function convoluted with a Gaussian. A 3 Gaussian template extracted from $B^0$ simulation is used. The mass difference $m(B_s) - m(B^0)$ is used for extrapolation.
First observation of $B_s \rightarrow J/\psi K_S$ !!!

\[
\frac{\text{Br}(B_s \rightarrow J/\psi K_S)}{\text{Br}(B^0 \rightarrow J/\psi K_S)} = \frac{N(B_s \rightarrow J/\psi K_S)}{N(B^0 \rightarrow J/\psi K_S)} \times \frac{f_d}{f_s} \times A_{\text{rel}}
\]

- $N(B^0) = 5954 \pm 79$ ; $N(B_s) = 64 \pm 14$ ; $N(B_s)/N(B^0) = 0.0108 \pm 0.0019$

- The p-value for $B_s$ signal compared to the background hypothesis
  
  \[
p\text{-value} = 3.85 \times 10^{-13} \text{ or } 7.2\sigma
  \]
**B→J/ψ K* Analysis**

- **Disadvantage:** $K^*$ is not a long-lived particle and is a wider resonance
  $\Rightarrow$ more background contributions to deal with

- **Advantage:** expecting bigger $B_s$ signal
  $\Rightarrow$ not necessary sophisticated tools to remove combinatorial background

- Rectangular cuts optimization to maximize efficiency
  
  $p_T(B) > 6 \text{ GeV/c}$
  
  Flight distance $L_{xy}(B) > 300 \mu m$
  
  Impact parameter $d_{xy}(B) < 50 \mu m$
  
  Fit vertex Probability $(B) > 0.01$
  
  $p_T(K^+, \pi^-) > 1.5 \text{ GeV/c}$
Fit contributions for $B \to J/\psi K^*$

- Same contributions than in the $B \to J/\psi K_S$ analysis plus additional backgrounds

**Signal**
- $B^0$ and $B_s$ decays

**Background**
- Partial reconstruction
- Combinatorial background
- $B_s \to J/\psi \phi$ contribution
- $B_s \to J/\psi f^0$ contribution

The last one is negligible.

- $B_s \to J/\psi \phi$ modeled by 2 Gaussians template
- Extracted from simulation but contribution constrained using data
First observation of $B_s \rightarrow J/\psi K^*$ !!!

$N(B^0) = 9530 \pm 110$ ; $N(B_s) = 151 \pm 25$ ; $N(B_s)/N(B^0) = 0.0159 \pm 0.0022$

- The $p$-value for $B_s$ signal compared to the background hypothesis

\[ p\text{-value} = 8.9 \times 10^{-16} \text{ or } 8\sigma \]
Systematic uncertainties

Difference sources of systematic uncertainties have been considered

<table>
<thead>
<tr>
<th>Sources</th>
<th>$B \to J/\psi K^*$</th>
<th>$B \to J/\psi K_S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal modeling</td>
<td>4.4 %</td>
<td>4.6%</td>
</tr>
<tr>
<td>Mass difference ($B_s - B^0$)</td>
<td>~0.1%</td>
<td>~0.1%</td>
</tr>
<tr>
<td>Combinatorial background (different modeling)</td>
<td>1.25%</td>
<td>5.6%</td>
</tr>
<tr>
<td>Combinatorial background (fixing the contribution)</td>
<td>31%</td>
<td>5.6%</td>
</tr>
<tr>
<td>$B_s \to J/\psi \phi$</td>
<td>1.25%</td>
<td>-</td>
</tr>
</tbody>
</table>

$B \to J/\psi K^*$

$N(B_s)/N(B^0) = 0.0159 \pm 0.0022 \text{ (stat.)} \pm 0.0050 \text{ (sys.)}$

$B \to J/\psi K_S$

$N(B_s)/N(B^0) = 0.0108 \pm 0.0019 \text{ (stat.)} \pm 0.0010 \text{ (sys.)}$
Relative Acceptance Calculation

\[
\frac{Br(B_s \to J/\psi \ h)}{Br(B^0 \to J/\psi \ h)} = \frac{N(B_s \to J/\psi \ h)}{N(B^0 \to J/\psi \ h)} \times \frac{f_d}{f_s} \times A_{rel}
\]

- **Relative Acceptance evaluation using simulation**
  \[
  A_{rel} = \frac{N(B^0 \to J/\psi K_s \text{ passed})}{N(B^0 \to J/\psi K_s \text{ generated})} \times \frac{N(B_s \to J/\psi K_s \text{ passed})}{N(B_s \to J/\psi K_s \text{ generated})}
  \]

\[
B \to J/\psi K^* \quad A_{rel} = 1.057 \pm 0.010 \text{ (stat)} \pm 0.263 \text{ (sys.)}
\]

\[
B \to J/\psi K_S \quad A_{rel} = 1.012 \pm 0.010 \text{ (stat)} \pm 0.042 \text{ (sys.)}
\]

- **Systematic uncertainties**

<table>
<thead>
<tr>
<th>Source</th>
<th>B (\to J/\psi \ K^*)</th>
<th>B (\to J/\psi \ K_S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(c_T) in (B^0) and (B_s) MC</td>
<td>0.9%</td>
<td>2.8%</td>
</tr>
<tr>
<td>(p_T) spectrum</td>
<td>2.7%</td>
<td>3%</td>
</tr>
<tr>
<td>polarization</td>
<td>24.6%</td>
<td>-</td>
</tr>
</tbody>
</table>
Recap of all numbers

$$\frac{\text{Br}(B_s \to J/\psi \ h)}{\text{Br}(B^0 \to J/\psi \ h)} = \frac{N(B_s \to J/\psi \ h)}{N(B^0 \to J/\psi \ h)} \times \frac{f_d}{f_s} \times A_{\text{rel}} \quad \text{where } h = K_S \text{ or } K^*$$

$$\Rightarrow N(B_s \to J/\psi \ h)/N(B^0 \to J/\psi \ h):$$

<table>
<thead>
<tr>
<th>$B \to J/\psi K^*$</th>
<th>$0.0159 \pm 0.0022 \ (\text{stat.}) \pm 0.0050 \ (\text{sys.})$</th>
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<tr>
<td>$B \to J/\psi K_S$</td>
<td>$0.0108 \pm 0.0019 \ (\text{stat.}) \pm 0.0010 \ (\text{sys.})$</td>
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</table>

$$\Rightarrow f_s/f_d \text{ from CDF( Phys.Rev. D77, 072003 (2008))}$$

combined with new PDG value for $\text{Br}(D_s \to \phi \pi)$

$$0.269 \pm 0.033$$

$$\Rightarrow A_{\text{rel}}:$$

| $$1.057 \pm 0.010 \ (\text{stat}) \pm 0.263 \ (\text{sys})$$ |
|--------------------------|-------------------------------------------------|
| $$1.012 \pm 0.010 \ (\text{stat}) \pm 0.042 \ (\text{sys})$$ |


\[
\frac{\text{Br}(B_s \rightarrow J/\psi K^*)}{\text{Br}(B^0 \rightarrow J/\psi K^*)} = 0.062 \pm 0.009 \text{ (stat.)} \pm 0.025 \text{ (sys.)} \pm 0.008 \text{ (frag.)}
\]

\[
\frac{\text{Br}(B_s \rightarrow J/\psi K_S)}{\text{Br}(B^0 \rightarrow J/\psi K_S)} = 0.041 \pm 0.007 \text{ (stat.)} \pm 0.004 \text{ (sys.)} \pm 0.005 \text{ (frag.)}
\]

⇒ Using PDG values:

\[
\text{Br}(B^0 \rightarrow J/\psi K^*) = (1.33 \pm 0.06) \times 10^{-3}
\]

\[
\text{Br}(B^0 \rightarrow J/\psi K^0) = (8.71 \pm 0.32) \times 10^{-4}
\]

\[
\text{Br}(B_s \rightarrow J/\psi K^*) = (8.3 \pm 1.2 \text{ (stat.)} \pm 3.3 \text{ (sys.)} \pm 1.0 \text{ (frag.)} \pm 0.4 \text{ (PDG)}) \times 10^{-5}
\]

\[
\text{Br}(B_s \rightarrow J/\psi K^0) = (3.5 \pm 0.6 \text{ (stat.)} \pm 0.4 \text{ (sys.)} \pm 0.4 \text{ (frag.)} \pm 0.1 \text{ (PDG)}) \times 10^{-5}
\]
Two new Cabibbo and color suppressed decays of $B_s$ mesons have been observed by CDF: $B_s \rightarrow J/\psi K^*$ and $B_s \rightarrow J/\psi K_S$

⇒ significance greater than $7\sigma$

A preliminary measurement of their Branching Ratios relative to the $B^0$ decays have been done

⇒ For $K^*$: $0.062 \pm 0.009$ (stat.) $\pm 0.025$ (sys.) $\pm 0.008$ (frag.)

⇒ For $K_S$: $0.041 \pm 0.007$ (stat.) $\pm 0.004$ (sys.) $\pm 0.005$ (frag.)

These modes are going to provide further information on lifetime difference and CP asymmetries in $B_s$ decays

CDF is collecting a lot of more events every hour...so stay tuned because more decays are coming soon
Back up
Signals and Background Contributions

Both analysis have some common Background contributions and signals

- Signals (B^0 and Bs) templates are obtained from simulation (B^0 MC)

\[
f_{B^0} = N_{B^0} \cdot \left( \frac{f_1}{\sigma_1 \sqrt{2\pi}} e^{-(x-\mu_1)^2/2\sigma_1^2} + \frac{f_2}{\sigma_2 \sqrt{2\pi}} e^{-(x-\mu_2)^2/2\sigma_2^2} + \frac{f_3}{\sigma_3 \sqrt{2\pi}} e^{-(x-\mu_3)^2/2\sigma_3^2} \right)
\]

The same template for B^0 and Bs taking into account \( \Delta m = 86.8 \text{ MeV/c}^2 \)

- Combinatorial background

\[
f_{\text{comb}}(x) = N_0 \cdot e^{C_0 x}
\]

Exponential function

(Float in the final fit)

- Partial reconstruction contribution for 5 bodies B^0 decays

\[
f_{\text{ARGUS}}(x) = N_1 \cdot \sqrt{1 - \frac{x^2}{m_0^2}} \cdot e^{-C_1 \frac{x^2}{m_0^2}}
\]

Argus function

m_0 cut off \~ 5.14

mass (B^0)-mass (\pi^0)
More Backgrounds

**B→J/ψ K** analysis has more backgrounds that need to be modeled

- **Bs →J/ψ φ**
  - Templates are obtained from simulation: 2 Gaussians *(Fixed in the final fit)*
  - Contribution constrained using Bs →J/ψ φ data sample
  
- Partial reconstruction contribution for 5 bodies Bs decays
  - Modeled with another ARGUS function
    - $m_0$ cut off at 5.22 GeV/c² : mass (Bs)-mass($π^0$)
  - Exponential constant constrained to be identical to the previous one

Background studied but considered negligible contributions

- In **B→J/ψ K** analysis: B →J/ψ $f_0$
- In **B→J/ψ Ks** analysis: $Λ_b$ →J/ψ $Λ$