CP Violation and Suppressed $B_s$ Decays at CDF

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Outline

- Suppressed $B_s$ Decays
  - $B_s \rightarrow J/\psi \ f_0(980)$ (New for LaThuile)
  - $B_s \rightarrow J/\psi \ K_S^0$
- Fragmentation Fractions (New)
- CP Violation
  - $B^+ \rightarrow D^0 \ h^+$: ADS Method
  - $D^0 \rightarrow K^+K^-, \pi^+\pi^-$ (New)
\[ B_s \rightarrow J/\psi \ f_0(980) \]

- CP=-1 eigenstate
  - Unambiguous measure of lifetime \( 1/\Gamma_H \)
  - Clean measure of CP violating parameter \( \beta_s \) (weak phase)
    - \( B_s \rightarrow J/\psi \phi \) requires complex angular analysis for vector-vector final state
  - Understand S-wave contributions to \( \beta_s \) measurement in \( B_s \rightarrow J/\psi \phi \)

- New result from Belle
  - \[ \text{Br}(B_s \rightarrow J/\psi \ f_0, f_0 \rightarrow \pi^+\pi^-) = 0.34^{+0.11+0.03+0.08}_{-0.14-0.02-0.05} \times 10^{-4} \]

- Observation by LHCb
  - \[ R = \frac{\text{Br}(B_s \rightarrow J/\psi \ f_0, f_0 \rightarrow \pi^+\pi^-)}{\text{Br}(B_s \rightarrow J/\psi \phi, \phi \rightarrow K^+K^-)} = 0.252^{+0.046+0.027}_{-0.032-0.033} \]
CDF Analysis

- Start with loose selection of $\mu\mu\pi\pi$ candidates
  - $f_0$ is wide, so $0.85 < M(\pi\pi) < 1.2$ GeV

- Neural Net Selection
  - Kinematic variables, track & vertex displacement, isolation
  - High-mass sideband only for background model
  - Use identical selection for $B_s \rightarrow J/\psi \phi$ reference mode

- Physics backgrounds from Monte Carlo
Fit

- Simultaneous log-likelihood fit to signal and normalization channels

\[ N(J/\psi f_0) = 571 \pm 37 \]

\[ N(J/\psi \phi) = 2302 \pm 49 \]
Confirmation of $f_0(980)$

- Helicity angles consistent with $P \rightarrow SV$ decay
- After efficiency correction

- Dipion mass distribution consistent with $f^0$
- Shape parameters consistent with BES, CLEO

CDF Run 2 Preliminary | $L=3.8 \text{ fb}^{-1}$

Candidates per 10 MeV/c$^2$

<table>
<thead>
<tr>
<th>$m(\pi^+\pi^-)$ [GeV/c$^2$]</th>
<th>0</th>
<th>1</th>
<th>1.1</th>
<th>1.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability per 0.1</td>
<td>0.02</td>
<td>0.04</td>
<td>0.06</td>
<td>0.08</td>
</tr>
</tbody>
</table>

$\cos(\theta_\pi)$
Result:

\[
R = \frac{\text{Br}(B_s \rightarrow J/\psi f_0, f_0 \rightarrow \pi^+\pi^-)}{\text{Br}(B_s \rightarrow J/\psi \varphi, \varphi \rightarrow K^+K^-)} = 0.290 \pm 0.020(\text{stat}) \pm 0.017(\text{sys})
\]

- Systematics
  - Fit model
  - Background
  - Relative Efficiency

- For details see public note CDF/10404
$B_s \rightarrow J/\psi \ K_S^0$

- CKM suppressed decay mode
  - Expect
    \[ \frac{\text{Br}(B_s \rightarrow J/\psi \ K_S^0)}{\text{Br}(B_d \rightarrow J/\psi \ K_S^0)} \approx 0.05 \]
- CP=-1 eigenstate
  - In large samples, measure $1/\Gamma_H$ and $\beta_s$
- Reference mode is CKM favored $B_d \rightarrow J/\psi \ K_S^0$
- Relative efficiency from Monte Carlo
- Also used to derive signal template
  - Same shape for $B_d$ and $B_s$, offset by known splitting
Mass Fit

- Binned Log Likelihood
- Include combinatorial backgrounds and partially reconstructed B hadrons

$N(B_s) = 64 \pm 14$
Results

- **Significance**
  - Compare to null hypothesis
  - Interpret change in $-2\log(L)$ as $\Delta\chi^2$
  - Probability of background fluctuation $4 \times 10^{-13}$ or 7.2$\sigma$

- **Branching Ratio:**

$$\frac{Br(B_s^0 \rightarrow J/\psi K_s^0)}{Br(B_d^0 \rightarrow J/\psi K_s^0)} = 0.041 \pm 0.007 \text{(stat.)} \pm 0.004 \text{(syst.)} \pm 0.005 \text{(frag.)}$$

- **First observation of CKM suppressed $B_s$ decay**
Fragmentation Fractions: $f_s/f_d$

- Two methods
  - Count semileptonic decays and assume $SU(3)$
    - $\Gamma(B^- \rightarrow D^0 \mu^- \nu) = \Gamma(B^0 \rightarrow D^+ \mu^- \nu) = \Gamma(B_s^0 \rightarrow D_s^+ \mu^- \nu)$
  - Use time-integrated average mixing parameter:
    \[ \tilde{\chi} = f_d \chi_d + f_s \chi_s \]
  - Derived from
    \[ R = \frac{[N(l^+l^+) + N(l^-l^-)]}{N(l^+l^-)} \]
  - Discrepancies in $\tilde{\chi}$ from previous measurements
    - CDF Run 1: $0.152 \pm 0.013$
    - D0: $0.132 \pm 0.024$
    - LEP Average: $0.126 \pm 0.004$
  - Are fractions different in $p\bar{p}$ vs. $e^+e^-$?
**\( \bar{\chi} \): New CDF Measurement**

- Dimuon data sample
  - 1.4 fb\(^{-1}\)
- Use impact parameter to identify source of muons: \( b, c, \) prompt
  - Same technique as \( b\bar{b} \) cross-section measurement
  - 2D fit of \( d_0 \) using templates from Monte Carlo
  - Constraints on \( b,c \rightarrow K,\pi \rightarrow \mu \) also from MC
    - Fake rates from \( D^0 \rightarrow K\pi^+ \) data
  - Much tighter selection than earlier measurements
    - Requires hit in silicon layer 1.7cm from beam

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\[ R_{bb,\text{raw}} = 0.472 \pm 0.011 \pm 0.007 \]

- Systematic from fake muon contributions
Extracting $\bar{\chi}$

- Many sources of dimuons in $b\bar{b}$ events
  - $b$ semileptonic decay
  - $b \rightarrow c \rightarrow \mu$ sequentials
  - $b \rightarrow \psi \rightarrow \mu \mu$
  - Hadron fakes
- Use MC to derive wrong-charge fraction
- Result: $\bar{\chi} = 0.126 \pm 0.008$
  - Includes systematic uncertainty on wrong-charge correction
  - Compare to LEP average: $0.1259 \pm 0.0042$
Further Agreement

- HFAG average at the Z:
  - $f_s/f_d = 0.256 \pm 0.022$

- CDF result from semileptonics from PRD 77, rescaled for updated $D_s \to \phi \pi$ branching ratio:
  - $f_s/f_d = 0.269 \pm 0.033$

- Maybe fragmentation is universal after all
ADS Method: Interference of two suppressed amplitudes

- Color-suppressed $b \rightarrow u$ diagram with Cabibbo-allowed $\bar{D}^0$ decay

- Color-allowed diagram with doubly Cabibbo-suppressed $D^0$ decay
ADS Observables

- DCS fraction and asymmetry:

\[
R_{ADS}(K) = \frac{\text{Br}(B^- \rightarrow [K^+\pi^-]_D K^-) + \text{Br}(B^+ \rightarrow [K^-\pi^+]_D K^-)}{\text{Br}(B^- \rightarrow [K^-\pi^+]_D K^-) + \text{Br}(B^+ \rightarrow [K^+\pi^-]_D K^+)}
\]

\[
A_{ADS}(K) = \frac{\text{Br}(B^- \rightarrow [K^+\pi^-]_D K^-) - \text{Br}(B^+ \rightarrow [K^-\pi^+]_D K^-)}{\text{Br}(B^- \rightarrow [K^+\pi^-]_D K^-) + \text{Br}(B^+ \rightarrow [K^-\pi^+]_D K^+)}
\]

- These are a function of CKM angle \(\gamma\)
  - \(R_{ADS} = r_B^2 + r_D^2 + r_B r_D \cos \gamma \cos (\delta_B + \delta_D)\)
  - \(A_{ADS} = 2r_B r_D \sin \gamma \sin (\delta_B + \delta_D) / R_{ADS}\)
  - Where
    - \(r_B = |A(b \rightarrow u)/A(b \rightarrow c)|\)
    - \(\delta_B = \text{Arg}[A(b \rightarrow u)/A(b \rightarrow c)]\)
    - And similar for \(r_D\) and \(\delta_D\)

CDF Signals

- Optimize cuts using Cabibbo-favored modes to limit combinatorial background
  - Kinematic variables
  - B candidate isolation
  - Vertexing
- Likelihood fit using mass and dE/dx to separate D$^0$K$^-$ and D$^0$π$^-$ signals
  - B backgrounds constrained from Cabibbo favored modes
Results

- Correction to raw asymmetry for K⁺ vs. K⁻ efficiency
- Systematic uncertainties from fit model, physics backgrounds and dE/dx
- First application of ADS method at a hadron collider
  - Details in public note CDF/10309
Search for CP Violation in
$D^0 \rightarrow K^+K^- \& \pi^+\pi^-$

- Negligible penguin contribution to charm decays in SM
  - CPV in charm would point to new physics
- Asymmetry:
  \[ A_{CP} = \frac{\Gamma(D^0 \rightarrow h^+h^-) - \Gamma(\bar{D}^0 \rightarrow h^+h^-)}{\Gamma(D^0 \rightarrow h^+h^-) + \Gamma(\bar{D}^0 \rightarrow h^+h^-)} \]
- In the usual mixing formalism:
  \[ A_{CP}(t) = \frac{\eta_{CP}}{2} \frac{t}{\tau} \left[ y \left( \left| \frac{p}{q} \right| - \left| \frac{q}{p} \right| \right) \cos \varphi + x \left( \left| \frac{p}{q} \right| + \left| \frac{q}{p} \right| \right) \sin \varphi \right] \]
- Time-Integrated Asymmetry:
  \[ A_{CP} = a_{CP}^{\text{Direct}} + \left\langle \frac{t}{\tau} \right\rangle a_{CP}^{\text{Indirect}} \]
D* Tagged Analysis

- Asymmetry of signal sample:
  - \( A(h^+h^-,\pi^*) = A_{CP}(h^+h^-) + \delta(\pi^*) \)

- Retrieve asymmetry of D* tag in CKM favored mode:
  - \( A(K^-\pi^+,\pi^*) = A_{CP}(K^-\pi^+) + \delta(K^-\pi^+) + \delta(\pi^*) \)

- Now need asymmetry from \( D^0 \to K^-\pi^+ \)
  - \( A(K^-\pi^+) = A_{CP}(K^-\pi^+) + \delta(K^-\pi^+) \)

- Now we solve:
  - \( A_{CP}(h^+h^-) = A(h^+h^-,\pi^*) - A(K^-\pi^+,\pi^*) + A(K^-\pi^+) \)
  - Measure these three asymmetries
Data Samples

- Key assumptions:
  - Soft pion efficiency independent of $D^0$ decay mode
    - Confirmed in data
  - No production charge asymmetry for $D^0$ or $D^*$
    - QCD
  - No variation of acceptance with rapidity
    - Confirmed in data

- All collected with displaced-vertex trigger
  - Nearly identical kinematics
  - MC checked for small differences
ACP(D⁰ → π⁺π⁻) = +0.22 ± 0.24 ± 0.11 %

ACP(D⁰ → K⁺K⁻) = -0.24 ± 0.22 ± 0.10 %
Conclusions

- $B_s \rightarrow J/\psi \ f_0(980)$: $R_{f/\phi} = 0.313 \pm 0.021 \pm 0.020$
- $Br(B_s \rightarrow J/\psi \ K_S^0)/Br(B_d \rightarrow J/\psi \ K_S^0) = 0.041 \pm 0.009$
- $\chi = 0.127 \pm 0.008$
- $B^+ \rightarrow D^0 \ h^+$: ADS Analysis
  - $R(K) = 22.5 \pm 8.4 \pm 7.9 \times 10^{-3}$
  - $A(K) = -0.63 \pm 0.40 \pm 0.23$
  - $R(\pi) = 4.1 \pm 0.8 \pm 0.4 \times 10^{-3}$
  - $A(\pi) = 0.22 \pm 0.18 \pm 0.06$
- $A_{CP}(D^0 \rightarrow \pi^+\pi^-) = +0.22 \pm 0.24 \pm 0.11 \%$
- $A_{CP}(D^0 \rightarrow K^+K^-) = -0.24 \pm 0.22 \pm 0.10 \%$
Final Thought:
“*I’m not dead yet*”

Many more results expected for summer