Measurements of the $B_s$ Mixing Phase at CDF

Robert Harr
Wayne State University

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Outline

• Status of the CP violation in $B_s \rightarrow J/\psi \phi$ analysis
• $B_s \rightarrow J/\psi f_0(980)$ branching fraction and lifetime
• Measurement of $\chi_b$
• CP violation in $B_s \rightarrow \phi \phi$
• Summary
The CDF Detector

- Central tracker
- 1.4T solenoid
- Vertex detector
- Muons: $0.6 < |\eta| < 1.0$
- Muons: $|\eta| < 0.6$
$B_s \rightarrow J/\psi \phi$
CP Violation in $B_s \rightarrow J/\psi \phi$ Decays

- Dominant contribution from top quark.
- Decay rate $\sim$.
- New Physics particles?

New Physics can have a detectable effect.

SM predicts tiny CP violation in $B_s$ mixing.
CDF and D0 originally had $\sim 2\sigma$ inconsistencies with SM prediction, were more consistent with each other.

CDF 5.2 fb$^{-1}$ result (summer 2010) is more consistent with SM, difference is $\sim 1\sigma$

An update with $(7+)$ fb$^{-1}$ data set is in progress.
$B_s \rightarrow J/\psi f_0(980)$
Interest in $B_s \rightarrow J/\psi f_0(980)$

- This is a $P \rightarrow V S$ decay.
- The decay is S-wave
  - may effect the $B_s \rightarrow J/\psi \phi$ analysis when $f_0 \rightarrow K^+K^-$.  
- Measure the B.F. to help constrain effects in $J/\psi \phi$.
- Additionally, this final state is CP odd, and neglecting direct CP violation, comes only from $B_H$ eigenstate.
  - Lifetime gives $\tau_H$.
  - Can be used to measure CP violation without angular analysis.
CDF Observation of $B_s \rightarrow J/\psi f_0(980)$

$R_{f_0/\phi} = 0.257 \pm 0.020\text{(stat)} \pm 0.014\text{(syst)}$

$\mathcal{B}(B_s^0 \rightarrow J/\psi f_0(980))\mathcal{B}(f_0(980) \rightarrow \pi^+\pi^-) = (1.63 \pm 0.12\text{(stat)} \pm 0.09\text{(syst)} \pm 0.50\text{(pdg)}) \times 10^{-4}$
Lifetime in $B_s \rightarrow J/\psi f_0(980)$

In the absence of CP violation, measures the lifetime of $B_H$ state.

Simultaneous fit to mass, decay time, and decay time error.
First Lifetime Measurement

\[ \tau(B_s^0 \to J/\psi f_0(980)) = 1.70^{+0.12}_{-0.11}\text{(stat)} \pm 0.03\text{(syst)} \text{ ps} \]

- Interpret as first direct measurement of \( \tau_H \)
- Compares well to indirect measurements of \( \tau_H \), and theoretical predictions.
MEASUREMENT OF $\chi_B$
• $\bar{\chi}$ is the average mixing probability

$$\bar{\chi}_b = \frac{\Gamma(B^0 \to \bar{B}^0 \to \ell^+X)}{\Gamma(B \to \ell^{\pm}X)} = f_d\chi_d + f_s\chi_s$$

• And is related to R:

$$R = \frac{N^{++} + N^{--}}{N^{OS}}$$

• Difference in average $\bar{\chi}$ from LEP (0.1259±0.0042) and Tevatron (0.147±0.011)

CDF Run I: PRD 69, 012002 (2004)
Relation of $R$ to $\bar{\chi}$

- $R$ has contributions from mixing, and other decay processes such as
  - $b \to c \to \mu$ decays
  - $b \to \psi X$, $b \to \chi_c X$, and other $b \to c\bar{c} q$ decays
- We account for these effects with a parameter $f$, determined from simulation to be $f=0.176\pm0.011$
- We obtain the relation:

$$R = \frac{f \left[ \bar{\chi}^2 + (1 - \bar{\chi})^2 \right] + 2\bar{\chi}(1 - \bar{\chi})(1 - f)}{(1 - f) \left[ \bar{\chi}^2 + (1 - \bar{\chi})^2 \right] + 2\bar{\chi}(1 - \bar{\chi}) f}$$
\( \bar{\chi} \) Measurement

• Use dimuon triggered data from 1.44/fb of int. lumi.
• Same selection requirements as described for \( A_{SL} \) measurement.
• Require that both muons have a hit in one of the two innermost silicon layers
  – Removes a large fraction of poorly understood events
  – Reduces overall statistics.
• Fit the OS, ++, and – impact parameter distributions simultaneously
• Determine R from \( b\bar{b} \) component of the fit.
Fit Results

1D projections of 2D fits

Fit probability 78.5%
**Result**

- $R = 0.467 \pm 0.008$ (stat only)
- Varying the templates within their uncertainties yields a systematic error of 0.007
- $R = 0.467 \pm 0.011$ (stat and syst)
- Yields $\overline{\chi} = 0.126 \pm 0.008$
  (0.005 is due to $R$ and 0.006 to $f$)
- Compare to LEP average $\overline{\chi} = 0.1259 \pm 0.0042$
$B_s \rightarrow \phi \phi$
Angular Variables

• This is a $P \rightarrow V V$ decay
  – We use the helicity frame with variables $\phi, \theta_1, \theta_2$
Fit Data from 2.9 fb\(^{-1}\) of Lumi.

• Combined fit to mass and angular variable dists.

\[
\begin{align*}
|A_0|^2 &= 0.348 \pm 0.041 \text{ (stat)} \pm 0.021 \text{ (syst)} \\
|A_{||}|^2 &= 0.287 \pm 0.043 \text{ (stat)} \pm 0.011 \text{ (syst)} \\
|A_{\text{perp}}|^2 &= 0.365 \pm 0.044 \text{ (stat)} \pm 0.027 \text{ (syst)} \\
\cos\delta_{||} &= -0.91^{+0.15}_{-0.13} \text{ (stat)} \pm 0.009 \text{ (syst)} \\
f_L &= 0.348 \pm 0.041 \text{ (stat)} \pm 0.021 \text{ (syst)} \\
f_T &= 0.652 \pm 0.041 \text{ (stat)} \pm 0.021 \text{ (syst)}
\end{align*}
\]

arXiv: 1107.4999
**Triple Product Asymmetries**

- TP asym. is T odd $\rightarrow$ violates CP under CPT cons.
- NP enters in interfer. betwn CP even and odd amplitudes
- Result is consistent with zero (SM expectation)

$$A_u = -0.007 \pm 0.064 \text{ (stat)} \pm 0.018 \text{ (syst)}$$
$$A_v = -0.120 \pm 0.064 \text{ (stat)} \pm 0.016 \text{ (syst)}$$

Summary

• The new $\overline{\chi}$ result is in agreement with the LEP measurements, possibly settling a long standing difference.

• First measurement of triple products in $B_s \rightarrow \phi\phi$ decays, consistent with SM expectation of zero.

• First measurement of lifetime in $B_s$ decay to CP odd eigenstate $B_s \rightarrow J/\psi f_0$

• Update in progress for $B_s \rightarrow J/\psi \phi$ analysis
The Fit Function (for completeness)

\[
L = \prod_i \prod_j \left[ \ell_{ij}^{n(i,j)} \frac{e^{-\ell_{ij}}}{n(i,j)!} \right]
\]

\[
\ell_{ij} = BB^{xs} \cdot S_b^{xs}(i) \cdot S_b^{xs}(j) + BB_{FK}^{xs} \cdot S_b(i) \cdot S_b(j)
+ (CC + CC_{FK}^{xs}) \cdot S_c(i) \cdot S_c(j) + PP^{xs} \cdot S_p(i) \cdot S_p(j)
+ \frac{1}{2} [BP^{xs} \cdot (S_b(i) \cdot S_b(j) + S_p(i) \cdot S_b(j))]
+ CP^{xs} \cdot (S_c(i) \cdot S_p(j) + S_p(i) \cdot S_c(j))
+ BC^{xs} \cdot (S_b(i) \cdot S_c(j) + S_c(i) \cdot S_b(j))]
\]

\[
\frac{1}{2} \left[ \frac{(CP - BP)^2}{CP + BP + (0.14 \cdot BP)^2} + \frac{(BC - 0.046 \cdot BB)^2}{BC + (0.046)^2 \cdot BB + (0.013 \cdot BB)^2} \right]
\]

\[
CP^{LS} = (1.05 \pm 0.05) \cdot CP^{OS}
CP^{++} = (1.2 \pm 0.1) \cdot CP^{--}
BP^{LS} = (0.87 \pm 0.07) \cdot BP^{OS}
BP^{++} = (1.15 \pm 0.05) \cdot BP^{--}
BC^{LS} = BC^{OS}
BC^{++} = BC^{--}
\]
Fit Results

$|A_0|^2 = 0.348 \pm 0.041$ (stat) $\pm 0.021$ (syst)
$|A_{||}|^2 = 0.287 \pm 0.043$ (stat) $\pm 0.011$ (syst)
$|A_{perp}|^2 = 0.365 \pm 0.044$ (stat) $\pm 0.027$ (syst)
$\cos\delta_{||} = -0.91^{+0.15}_{-0.13}$ (stat) $\pm 0.009$ (syst)

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