New Measurement of the $B^0_s$ Mixing Phase at CDF

Elisa Pueschel
University of Massachusetts, Amherst
on behalf of the CDF Collaboration

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CP Violation in $B^0_s \rightarrow J/\psi \phi$

- Analogous to measurement of $\sin 2\beta$
- CPV in the interference between direct decays and decays via mixing

Could have new physics participation in loop process

- Use unitary property of CKM matrix to derive unitary triangles

Large measured $\beta_s$ must be due to new physics participation!

$$\beta_s = arg\left(-\frac{V_{tb}V_{ts}^*}{V_{cb}V_{cs}^*}\right) \approx 0.02$$
CP Violation in $B^0_s$ Mixing

Time evolution of states is given by:

$$i \frac{d}{dt} \left( \begin{array}{c} B^0_s(t) \\ \bar{B}^0_s(t) \end{array} \right) = \left( M - \frac{i}{2} \Gamma \right) \left( \begin{array}{c} B^0_s(t) \\ \bar{B}^0_s(t) \end{array} \right)$$

Flavor eigenstates $\rightarrow$ heavy and light mass eigenstates:

$$| B_s^H \rangle = p | B_s^0 \rangle - q | \bar{B}_s^0 \rangle \quad | B_s^L \rangle = p | B_s^0 \rangle + q | \bar{B}_s^0 \rangle$$

Observables:

$$\Delta m_s = m_H - m_L \approx 2 | M_{12} | \quad \text{Mass difference/oscillation frequency}$$

$$\Delta \Gamma_s = \Gamma_H - \Gamma_L \approx 2 | \Gamma_{12} | \cos(\phi_s) \quad \text{Lifetime/decay width difference}$$

$$\phi_s = \text{arg} \left( \frac{-M_{12}}{\Gamma_{12}} \right) \quad \text{CP Phase}$$

If a new phase, $\phi_s^{NP}$ exists, $\phi_s = \phi_s^{SM} + \phi_s^{NP} - \phi_s^{NP}$, $2\beta_s = 2\beta_s^{SM} - \phi_s^{NP} - \phi_s^{NP}$

For large new physics phase, $2\beta_s = -\phi_s^{NP} = -\phi_s$
Analysis Flow

Reconstruct signal events

Use neural network to suppress background

Simultaneously fit to:

Mass:
Separate signal from background

Angular Distributions:
Separate CP-odd from CP-even contributions

Lifetime:
Determine time dependence

Apply flavor tagging:
Distinguish $B^0_s$ from anti-$B^0_s$ at production

*Must handle: angular efficiencies, flavor tagging calibration*
Likelihood Anatomy

• Probability density as a function of time and angles:

\[
\left(\frac{d^4 P(t, \vec{\rho})}{dtd\vec{\rho}}\right)_{(B_{s,0}^0, \bar{B}_{s,0}^0)} \propto |A_0|^2 T_{(+,+)} f_1(\vec{\rho}) + |A_{||}|^2 T_{(+,+)} f_2(\vec{\rho}) + |A_{\perp}|^2 T_{(-,-)} f_3(\vec{\rho})
+ |A_{||}||A_{\perp}| U_{(+,-)} f_4(\vec{\rho}) + |A_0||A_{||}| \cos(\delta_{||}) T_{(+,+)} f_5(\vec{\rho}) + |A_0||A_{\perp}| V_{(+,-)} f_6(\vec{\rho})
\]

Time dependent terms:

\[
T_\pm = e^{-\Gamma t}\left[\cosh\left(\frac{\Delta \Gamma t}{2}\right) \mp \cos(2\beta_s) \sinh\left(\frac{\Delta \Gamma t}{2}\right) \pm \eta \sin(2\beta_s) \sin(\Delta m_s t)\right]
\]

\[
U_\pm = \pm e^{-\Gamma t}\left[\sin(\delta_- - \delta_{||}) \cos(\Delta m_s t) - \cos(\delta_- - \delta_{||}) \cos(2\beta_s) \sin(\Delta m_s t) \pm \cos(\delta_- - \delta_{||}) \sin(2\beta_s) \sinh\left(\frac{\Delta \Gamma t}{2}\right)\right]
\]

\[
V_\pm = \pm e^{-\Gamma t}\left[\sin(\delta) \cos(\Delta m_s t) - \cos(\delta) \cos(2\beta_s) \sin(\Delta m_s t) \pm \cos(\delta) \sin(2\beta_s) \sinh\left(\frac{\Delta \Gamma t}{2}\right)\right]
\]

• Extract parameters of interest: \(\beta_s, \Delta \Gamma\) (decay width difference), \(\tau(B_{s,0}^0)\) (\(B_{s,0}^0\) average lifetime), \(A_0, A_{||}, A_{\perp}\) (transversity amplitudes), \(\varphi_{||}, \varphi_{\perp}\) (strong phases)
Flavor Tagging and Likelihood Symmetries

- Without flavor tagging, likelihood has two symmetries → four solutions

- \(2\beta_s \rightarrow -2\beta_s, \delta_\perp \rightarrow \pi - \delta_\perp\)

- \(\Delta \Gamma \rightarrow -\Delta \Gamma, \delta_\parallel \rightarrow 2\pi - \delta_\parallel\)

- Flavor tagging removes \(\beta_s \rightarrow -\beta_s\) symmetry → two solutions for \(\beta_s\) and \(\Delta \Gamma\)

Toy Monte Carlo pseudo-experiment

![Graph showing the difference in likelihood distribution between untagged and tagged data, with \(\Delta \Gamma\) and \(2\beta_s\) axes.]
Previous results

CDF: 1.35 fb⁻¹
1.5σ consistency with SM

CDF: 2.8 fb⁻¹
1.8σ consistency with SM

CDF: 2.8 fb⁻¹ + DØ: 2.8 fb⁻¹
2.3σ consistency with SM
The Tevatron and CDF

- p anti-p collisions at a center of mass energy of 1.96 TeV
- ~5 fb\(^{-1}\) data used for this analysis

![Tevatron Diagram]

Analysis relies on

- Mass and decay time resolution (~0.1 ps compared to B lifetime ~1.5 ps)

Particle Identification
Signal Selection

- Suppress background using artificial neural network

- Training variables include $p_T$ of tracks and decay particles, vertex probability for decay particles

- Cut on neural network output is chosen by minimizing $\beta_s$ errors on pseudo-experiments

- Reconstruct $\sim$6500 signal events
OST Calibration

- Calibrate opposite side tagger on $B^+ \rightarrow J/\Psi K^+$ events, which have same opposite side fragmentation behavior as $B_s^0$
- $B^+ \rightarrow J/\Psi K^+$ decays are self-tagging
  - Compare measured to predicted dilution
  - Tagging power $\epsilon D^2 = 1.2\pm0.2\%$

CDF II Preliminary, 5.2 fb$^{-1}$

CDF Run II Preliminary $L = 5.2$ fb$^{-1}$

CDF Run II Preliminary $L = 5.2$ fb$^{-1}$
SSKT Calibration

- Remeasured $B_s^0$ mixing on 5.2 fb$^{-1}$ of data

- $B_s^0\rightarrow D_s^- \pi^+$ and $B_s^0\rightarrow D_s^- (3\pi)^+$ channels

- For amplitude scan of $\Delta m_s$, probability normalized such that $A=1$ at true value of $\Delta m_s$

- Measured amplitude relates measured to predicted dilution

- $A = 0.94 \pm 0.15$ (stat) $\pm 0.13$ (syst)

- $\Delta m_s = 17.79 \pm 0.07$ ps$^{-1}$ (stat) (Consistent with world average)

- Tagging power $\varepsilon D^2 = 3.1\pm1.4\%$
S-wave Contamination

- $B_s^0 \rightarrow J/\Psi K^+K^-$ and $B_s^0 \rightarrow J/\Psi f_0$ could contaminate $B_s^0 \rightarrow J/\Psi \phi$ signal and bias measurement of $\beta_s$
  - Include possibility of non-resonant $KK/f_0$ in likelihood
  - Model $KK$ and $f_0$ as flat in (narrow) $\phi$ mass region
  - Model $\phi$ as relativistic Breit-Wigner
  - Perform mass integration over $\phi$ mass window
  - S-wave terms enter in angular part of likelihood
Angular Analysis

For Standard Model $\beta_s$:

\[ |A_{||}(0)|^2 = 0.231 \pm 0.014\text{(stat)} \pm 0.015\text{(syst)} \]
\[ |A_0(0)|^2 = 0.524 \pm 0.013\text{(stat)} \pm 0.015\text{(syst)} \]
\[ \phi_\perp = 2.95 \pm 0.64\text{(stat)} \pm 0.07\text{(syst)} \]
Lifetime Measurement

CDF Run II Preliminary

L = 5.2 fb⁻¹

For Standard Model $\beta_s$:

(World’s best measurements)

\[ c\tau_s = 458.7 \pm 7.5(stat) \pm 3.6(syst) \mu m \]
\[ \Delta \Gamma_s = 0.075 \pm 0.035(stat) \pm 0.01(syst) \text{ps}^{-1} \]
\( \beta_s - \Delta \Gamma \) Contours

- Profile likelihood ordering technique used to guarantee coverage at 68% and 95% confidence levels
- \( 0.8\sigma \) consistency with SM
- \( \beta_s \in [0.28, 0.52] \) U \([1.08, 1.55]\) at 68% CL
- Similar consistency with SM to 2D case
Comparison to Previous Measurement

Size of contour has decreased significantly with increased statistics and analysis improvements
Effect of S-wave

Likelihood scan of S-wave fraction finds S-wave contamination <7% at 95% CL

A fit to KK invariant mass does not show large S-wave contamination

β_s-ΔΓ contour with S-wave included in fit is not significantly different than fit without S-wave
Tagged versus Untagged Contours

Good agreement between contours with and without flavor tagging included in fit
Conclusions

- Latest measurement of $\beta_s$ using $B_s^0 \rightarrow J/\Psi \phi$ decays
- Errors on $\beta_s$ have decreased significantly from previous measurements
- Consistency with Standard Model expectation has improved from previous measurements
- CDF will double data sample by end of Run II, allowing even more precise measurement
Detector Sculpting

- Account for detector sculpting of transversity angles
- Calculate angular efficiencies on realistic $B_{s}^{0} \rightarrow J/\Psi \phi$ Monte Carlo
- Generate angles flat
- Parameterize after going through full CDF reconstruction

![Graphs showing data distributions](images/graph.png)