Study of CP Violation in $B_s \rightarrow J/\psi \phi$ Decays at CDF

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Dedication

To the memory of our dear friend and colleague,

Michael Perry Schmidt.
A man said to the Universe:
“Sir, I exist!”
“However,” replied the Universe,
“The fact has not created in me
A sense of obligation.”

- Stephen Crane
Beyond the Standard Model

- The search for physics beyond the standard model is pursued through a broad program of physics at the Tevatron
  - High $p_T$ physics
    - Direct searches for evidence of new physics (SUSY, Technicolor, ???)
  - Flavor physics
    - New physics through participation in loop processes could contribute additional CP violating phases
- CP violation in $B_s^0$ meson system is an excellent way to search for new physics
  - Predicted to be extremely small in the SM, so any large CP phase is a clear sign of new physics!
What Is CP Violation?

- CP violation is the non-conservation of charge and parity quantum numbers

\[ B_s^0 \neq \bar{B}_s^0 \]
CP Violation in the Standard Model

- Described within framework of the CKM mechanism

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix} =
\begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
\]

\(V_{\text{CKM}} =\)

\[
\begin{pmatrix}
  1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4 \\
  -\lambda + \frac{1}{2}A^2\lambda^5[1 - 2(\rho + i\eta)] \\
  A\lambda^3[1 - (1 - \frac{1}{2}\lambda^2)(\rho + i\eta)]
\end{pmatrix}
\begin{pmatrix}
  \lambda \\
  1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4(1 + 4A^2) \\
  -A\lambda^2 + \frac{1}{2}A\lambda^4[1 - 2(\rho + i\eta)]
\end{pmatrix}
\begin{pmatrix}
  1 - \frac{1}{2}A^2\lambda^4 \\
  A\lambda^2 \\
  1 - \frac{1}{2}A^2\lambda^4
\end{pmatrix}
\]

where \(\lambda \approx 0.23\)

- Imaginary terms give rise to CP violation
Unitarity of CKM Matrix

- By construction, CKM matrix must be unitary
  - $V^*V = 1$
- Important to check this experimentally!
  - Evidence of non-unitarity would suggest presence of unknown physics contributions
- Can construct six unitarity relations between distinct columns or rows of CKM matrix
Unitarity Relations in $B^0/B_{s}^0$ Mesons

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix} = 
\begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
\]

\[V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0\]
\[V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0\]
CP Violation in $\mathcal{B}_s^0 \rightarrow J/\psi \phi$

- CP violation arises from interference between mixing and decay amplitudes
  - $J/\psi K_s^0$ is CP even final state
  - $J/\psi \phi$ final state is an admixture of CP even ($\sim 75\%$) and CP odd ($25\%$)

$\Rightarrow \sin(2 \beta)$

$\Rightarrow \sin(2 \beta_s)$
Mixing and Decay in $B_s^0$

Mixing between particle and anti-particle occurs through the loop processes

Oscillations are very fast—\(~3\) trillion times per second!
Mixing in $B_s^0$ Decays

Schrodinger equation governs $\bar{B}_s^0$- $B_s^0$ transitions

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

Mass eigenstates $B_s^H$ and $B_s^L$ are admixtures of flavor eigenstates

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

where

\[
\Delta m_s = m_H - m_L \approx 2 |M_{12}|
\]

Frequency of oscillation between $B_s^0$ and $\bar{B}_s^0$

\[
\Delta \Gamma = \Gamma_L - \Gamma_H \approx 2 |\Gamma_{12}| \cos(\phi_s), \text{ where } \phi_s = \text{arg}(-M_{12}/\Gamma_{12})
\]

Width difference between heavy and light is related to the phase of the mixing

\[
q/p = \frac{V_{tb}V_{ts}^*}{V_{tb}^*V_{ts}}
\]
Standard Model CPV in $B_s^0$ Decays

- CP violation in $B_s^0 \to J/\psi \phi$

  CP observable: $\lambda_{J/\psi\phi} = e^{i2\beta_s}$

  Assume $|\lambda_{J/\psi\phi}| = 1 \rightarrow$ no direct CPV

  The CP phase in $B_s^0 \to J/\psi \phi$ in the standard model is

  $\beta_s = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) \sim 0.02$  \hspace{1cm} \text{Very small CP phase!}

  Note: $\text{Im}(\lambda_{J/\psi\phi}) = \sin(2\beta_s) \approx 0,$
  
  Compared to $\sin(2\beta) \approx 0.70$ ($B^0 \to J/\psi K_s^0$)
New Physics in $B_s^0$ Decays

- $B_s^0 - \bar{B}_s^0$ oscillations recently observed by CDF
- Mixing frequency $\Delta m_s$ now very well-measured
- Precisely determines $|M_{12}|$ - in good agreement w/SM pred.
- Phase of mixing amplitude is still very poorly determined!
- Both are needed to constrain new physics

\[ M_{12} = |M_{12}|e^{i\phi_s}, \]
where $\phi_s^{SM} \sim 0.004$

New physics could produce large CP phase!
New Physics CPV in $B_s^0$ Decays

- If large new physics phase present in mixing amplitude
  - $\varphi_s = \varphi_s^{SM} + \varphi_s^{NP} \sim \varphi_s^{NP}$
  - Can measure $\varphi_s$ directly from asymmetry in $B_s^0$ semileptonic decays

- Same new physics phase $\varphi_s^{NP}$ would add to $\beta_s$
  - In $B_s^0 \rightarrow J/\psi\phi$, we would then measure $(2\beta_s - \varphi_s^{NP}) \sim -\varphi_s^{NP}$
  - Would also be sensitive to NP effects in $M_{12} = |M_{12}| e^{-i2\beta_s}$

- Observation of large CP phase in $B_s^0 \rightarrow J/\psi\phi$
  \[ \Rightarrow \text{unequivocal sign of new physics} \]
Measurement Overview

“Men's activities are occupied in two ways -- in grappling with external circumstances and in striving to set things at one in their own topsy-turvy mind.”

-William James
Properties of $B_s^0 \rightarrow J/\psi \phi$ Decays

- Overview of decay
  - $B_s^0$ travels $\sim 450$ $\mu$m before decaying into $J/\psi$ and $\phi$
  - Spin-0 $B_s^0$ decays to spin-1 $J/\psi$ and spin-1 $\phi$
    \[ \Rightarrow \text{final states with } l=0,1,2 \]
  - Properties of decay depend on decay time, CP at decay, and initial flavor of $\bar{B}_s^0/B_s^0$

\[ t = m(B_s^0) * L_{xy}(B_s^0 \rightarrow J/\psi \phi)/p_T(B_s^0) \]
Experimental Strategy

- Reconstruct $B_s^0 \rightarrow J/\psi(\rightarrow \mu^+\mu^-) \varphi(\rightarrow K^+K^-)$
- Use angular information from $J/\psi$ and $\varphi$ decays to separate angular momentum states which correspond to CP eigenstates
  - CP-even ($l=0,2$) and CP-odd ($l=1$) final states
- Identify initial state of $B_s$ meson (flavor tagging)
  - Separate time evolution of $B_s^0$ and $\bar{B}_s^0$ to maximize sensitivity to CP asymmetry ($\sin 2\beta_s$)
- Perform un-binned maximum likelihood fit to extract signal parameters of interest (e.g. $\beta_s$, $\Delta \Gamma$)
Related Measurements

- $B_s^0 \to J/\psi \, \phi$ decays without flavor tagging
  - $B_s^0$ mean lifetime ($\tau = 1/\Gamma$)
    - $\Gamma = (\Gamma_L + \Gamma_H)/2$
  - Width difference $\Delta \Gamma$
  - Angular properties of decay

- Decay of $B^0 \to J/\psi(\to \mu^+\mu^-) \, K^*0(\to K^-\pi^+)$
  - No width difference ($\Delta \Gamma \approx 0$)
  - Check measurement of angular properties of decay
Current Experimental Results

Dotted line indicates 39% CL

- D0 measurement of CP phase made without flavor tagging
  - Four-fold ambiguity in determination of $\phi_s$

$$\tau(B_s^0) = 1.52 \pm 0.08 \text{ (stat)} ^{+0.01}_{-0.03} \text{ (syst) ps}$$

$$\Delta \Gamma = 0.17 \pm 0.09 \text{ (stat)} \pm 0.02 \text{ (syst) ps}^{-1}$$
Signal Reconstruction

“Begin at the beginning and go on till you come to the end: then stop.”

-Alice in Wonderland
$B_s^0 \rightarrow J/\psi \phi$ Signal Selection

- Use an artificial neural network (ANN) to efficiently separate signal from background
- ANN training
  - Signal from Monte Carlo reconstructed as it is in data
  - Background from $J/\psi \phi$ sidebands
    - $m(J/\psi \phi) \in [5.1820, 5.2142] \text{ GeV}/c^2$
    - $\cup [5.3430, 5.3752] \text{ GeV}/c^2$
B_{s}^{0} \rightarrow J/\psi \phi \ Neural \ Network

Variables used in network

- $B_{s}^{0}$: $p_T$ and vertex probability
- $J/\psi$: $p_T$ and vertex probability
- $\phi$: mass and vertex probability
- $K^{+},K^{-}$: $p_T$ and PID (TOF, dE/dx)

Optimization of ANN selection: \[
\frac{S}{\sqrt{S + B}}
\]
$\text{B}_{s}^0 \rightarrow \text{J}/\psi \phi$ Signal

$N(\text{B}_{s}^0) \sim 2000 \text{ in } 1.35 \text{fb}^{-1}$ (with flavor tagging)

$2500 \text{ in } 1.7 \text{ fb}^{-1}$ (without flavor tagging)
$B^0 \rightarrow J/\psi K^{*0}$ Signal

CDF Run II Preliminary \hspace{1cm} L = 1.3 fb$^{-1}$

N($B^0$) $\sim$ 7800 in 1.35 fb$^{-1}$
Angular Analysis of Final States

“[In this business] everybody’s got an angle.”

- Bing Crosby in “White Christmas”
Identifying CP of Final States

- J/ψ, ϕ vector mesons
  - definite angular distributions for CP-even (S- or D-wave) and CP-odd (P-wave) final states
- Use transversity basis to describe angular decay
  - Express angular dependence in terms of linear polarization
  - Transversely polarized: \( A_\perp(t) \) and \( A_\parallel(t) \)
  - Longitudinally polarized: \( A_0(t) \)
- Can determine initial magnitude of polarizations and their phases relative to each other
  - \( |A_\perp(0)|^2 + |A_\parallel(0)|^2 + |A_0(0)|^2 = 1 \)
  - \( \delta_\parallel = \arg(A_\parallel(0)A_0^*(0)) \), \( \delta_\perp = \arg(A_\perp(0)A_0^*(0)) \)
Definition of Transversity Angles

VV final state defines 3D coordinate system
Flavor Tagging

“Time is a sort of river of passing events, and strong is its current; no sooner is a thing brought to sight than it is swept by and another takes its place, and this too will be swept away.”

- Marcus Aurelius Antonius
Basics of Flavor Tagging

- b quarks generally produced in pairs at Tevatron
- Tag either b quark which produces J/ψφ, or other b quark
Combined Tags

- **OST**
  - $\epsilon = (96 \pm 1)\%$, average $D = (11 \pm 2)\%$

- **SSKT**
  - $\epsilon = (50 \pm 1)\%$, average $D = (27 \pm 4)\%$
  - Calibrated only for first 1.35 fb$^{-1}$ of data
“Like stones, words PDFs are laborious and unforgiving, and the fitting of them together, like the fitting of stones, demands great patience and strength of purpose and particular skill.”

- Edmund Morrison (paraphrased)
Observables and Parameters in Fit

- Measured quantities that enter fit function
  - $B_s^0$ decay time and its error, transversity angles, reconstructed mass of $B_s^0$ and its error, flavor tag decision, dilution $D$

- Fit for parameters of interest ($\beta_s, \Delta \Gamma$) plus many nuisance parameters (e.g. mean width $\Gamma = (\Gamma_L + \Gamma_H)/2$,
  $|A_\perp(0)|^2, |A_\parallel(0)|^2, |A_0(0)|^2, \delta_\parallel, \delta_\perp \ldots$)

- Simultaneous fit to mass (separate signal from background) and lifetime distributions (separate CP even and odd terms with angular dependence and time evolution with flavor tagging)
Signal Probability Distribution

- Signal PDF for a single tag

\[ P_s(t, \vec{\rho}, \xi | \mathcal{D}, \sigma_t) = \frac{1 + \xi \mathcal{D}}{2} P(t, \vec{\rho} | \sigma_t) \epsilon(\vec{\rho}) + \frac{1 - \xi \mathcal{D}}{2} \bar{P}(t, \vec{\rho} | \sigma_t) \epsilon(\vec{\rho}) \]

- Signal probability depends on
  - Tag decision \( \xi = \{-1, 0, +1\} \)
  - Event-per-event dilution \( \mathcal{D} \)
  - Sculpting of transversity angles due to detector acceptance, \( \epsilon(\rho) \)
    - \( \rho = \{\cos \theta_T, \varphi_T, \cos \psi_T\} \)
  - Convolve time dependence with Gaussian proper time resolution function with mean of 0.1 ps and RMS of 0.04 ps
Signal Probability Distribution

- General relation for $B \rightarrow VV$

\[
\begin{align*}
\mathbf{B}_s^0 : \quad & \frac{d^4 P(t, \rho)}{dtd\rho} \propto |A_0(0)|^2 \mathcal{T}_+ f_1(\rho) + |A_\parallel(0)|^2 \mathcal{T}_+ f_2(\rho) \\
& + |A_\perp(0)|^2 \mathcal{T}_- f_3(\rho) + |A_\parallel(0)||A_\perp(0)| \mathcal{U} f_4(\rho) \\
& + |A_0(0)||A_\parallel(0)| \cos(\delta_\parallel) \mathcal{T}_+ f_5(\rho) \\
& + |A_0(0)||A_\perp(0)| \mathcal{V} f_6(\rho)
\end{align*}
\]

\[
\begin{align*}
\mathbf{B}_s^0 : \quad & \frac{d^4 \bar{P}(t, \rho)}{dtd\bar{\rho}} \propto |A_0(0)|^2 \mathcal{T}_+ f_1(\rho) + |A_\parallel(0)|^2 \mathcal{T}_+ f_2(\rho) \\
& + |A_\perp(0)|^2 \mathcal{T}_- f_3(\rho) + |A_\parallel(0)||A_\perp(0)| \mathcal{U} f_4(\rho) \\
& + |A_0(0)||A_\parallel(0)| \cos(\delta_\parallel) \mathcal{T}_+ f_5(\rho) \\
& + |A_0(0)||A_\perp(0)| \mathcal{V} f_6(\rho)
\end{align*}
\]

Time dependence appears in $\mathcal{T}_\pm$, $\mathcal{U}_\pm$, $\mathcal{V}_\pm$. Different for $\mathbf{B}_s^0$ and $\mathbf{B}_s^0$!
Time-evolution with Flavor Tagging

- Separate terms for Bs, Bs-bar

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

where \( \eta = +1 \) for \( P \) and \( -1 \) for \( \bar{P} \)

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

Dependence on \( \cos(\Delta m_s t) \)

\[ V_{\pm} = \pm e^{-\Gamma t} \times \left[ \sin(\delta_{\perp}) \cos(\Delta m_s t) - \cos(\delta_{\perp}) \cos(2\beta_s) \sin(\Delta m_s t) \right. \\
\left. \quad \pm \cos(\delta_{\perp}) \sin(2\beta_s) \sinh \left( \frac{\Delta \Gamma t}{2} \right) \right] . \]
Time-evolution without Flavor Tagging

- Separate terms for Bs, Bs-bar

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

where \( \eta = +1 \) for \( P \) and \(-1\) for \( \bar{P} \)

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

\[ V_\pm = \pm e^{-\Gamma t} \times \left[ \sin(\delta_\perp) \cos(\Delta m_s t) - \cos(\delta_\perp) \cos(2\beta_s) \sin(\Delta m_s t) \right. \\
\left. \pm \cos(\delta_\perp) \sin(2\beta_s) \sinh \left( \frac{\Delta \Gamma t}{2} \right) \right] . \]
$B_s^0$ Lifetime Projection

No flavor tagging, $2\beta_s$ fixed to SM value
Detector Sculpting of Angles

- Use Monte Carlo passed through detector simulation and reconstruction as in data to determine angular sculpting

Deviation from flat distribution indicates detector effects!
$B_s^0$ Angular Fit Projections

Uncorrected for detector sculpting effects.
Corrected $B_s^0$ Angular Fit Projections

Corrected for detector sculpting.
Compare $B^0$ Angular Fit Projections

Acceptance corrected distributions - fit agrees well!

Validates treatment of detector acceptance!
Cross-check with $B^0$ Decays

• Fit results for $B^0 \rightarrow J/\psi \ K^{*0}$

\[ c\tau = 456 \pm 6 \text{ (stat)} \pm 6 \text{ (syst) } \mu \text{m} \]
\[ |A_0(0)|^2 = 0.569 \pm 0.009 \text{ (stat)} \pm 0.009 \text{ (syst)} \]
\[ |A_\parallel(0)|^2 = 0.211 \pm 0.012 \text{ (stat)} \pm 0.006 \text{ (syst)} \]
\[ \delta_\parallel = -2.96 \pm 0.08 \text{ (stat)} \pm 0.03 \text{ (syst)} \]
\[ \delta_\perp = 2.97 \pm 0.06 \text{ (stat)} \pm 0.01 \text{ (syst)} \]

• Results are in good agreement with BABAR and errors are competitive!

\[ |A_0(0)|^2 = 0.556 \pm 0.009 \text{ (stat)} \pm 0.010 \text{ (syst)} \]
\[ |A_\parallel(0)|^2 = 0.211 \pm 0.010 \text{ (stat)} \pm 0.006 \text{ (syst)} \]
\[ \delta_\parallel = -2.93 \pm 0.08 \text{ (stat)} \pm 0.04 \text{ (syst)} \]
\[ \delta_\perp = 2.91 \pm 0.05 \text{ (stat)} \pm 0.03 \text{ (syst)} \]
Additional Complications

- Two exact symmetries are present in $B_s^0 \to J/\psi \phi$ untagged analysis
  - $2\beta_s \to -2\beta_s$, $\delta_\perp \to \delta_\perp + \pi$
  - $\Delta\Gamma \to -\Delta\Gamma$, $2\beta_s \to 2\beta_s + \pi$
  - Gives four equivalent solutions in $\beta_s$ and $\Delta\Gamma$!
- Also observe biases in pseudo-experiments for fit parameters under certain circumstances
Biases in Untagged Fits

- Can still reliably quote some point estimates with $2\beta_s$ fixed to standard model prediction
  - Mean lifetime, $\Delta \Gamma$, $|A_0(0)|^2$, $|A_\parallel(0)|^2$, $|A_\perp(0)|^2$
- When $2\beta_s$ floats freely in fit, see significant biases in pseudo-experiments
Untagged $B_s^0$ Decays

- Fit results with $2\beta_s$ fixed to SM value (w/ 1.7 fb$^{-1}$ of data)
  \[ \tau(B_s^0) = 1.52 \pm 0.04 \pm 0.02 \text{ ps} \]
  \[ \Delta \Gamma = 0.076 \pm 0.059 - 0.063 \pm 0.006 \text{ ps}^{-1} \]

- Best measurement of width difference, mean $B_s^0$ lifetime
  - 30-50% improvement on previous best measurements
  - Good agreement with D0 results (Phys. Rev. D 76, 031102, (2007))
    \[ \tau(B_s^0) = 1.52 \pm 0.08 \text{ (stat)} \pm 0.01 \text{ (syst)} \text{ ps} \]
    \[ \Delta \Gamma = 0.17 \pm 0.09 \text{ (stat)} \pm 0.02 \text{ (syst)} \text{ ps}^{-1} \]

- Also measure angular amplitudes
  \[ |A_0(0)|^2 = 0.531 \pm 0.020 \text{ (stat)} \pm 0.007 \text{ (syst)} \]
  \[ |A_\parallel(0)|^2 = 0.230 \pm 0.026 \text{ (stat)} \pm 0.009 \text{ (syst)} \]
  \[ |A_\perp(0)|^2 = 0.239 \pm 0.029 \text{ (stat)} \pm 0.011 \text{ (syst)} \]
Untagged $2\beta_s$-$\Delta\Gamma$ Confidence Region

- Quote instead Feldman-Cousins confidence region
- Use likelihood ratio to determine probability of result to fluctuate above a given value of input parameters (p-value)

$$\Delta\Gamma = 2|\Gamma_{12}| \cos(2\beta_s)$$

p-value at standard model point is 22%
Exact Symmetries in Tagged Decays

- With flavor tagging, exact symmetry is present in signal probability distribution

\[
2\beta_s \rightarrow \pi - 2\beta_s \\
\Delta\Gamma \rightarrow -\Delta\Gamma \\
\delta_\parallel \rightarrow 2\pi - \delta_\parallel \\
\delta_\perp \rightarrow \pi - \delta_\perp
\]

- Leads to two equivalent solutions in $\beta_s$ and $\Delta\Gamma$!

- Can remove exact symmetry by boxing one of the parameters
Check Fit with Pseudo-Experiments

- Check $\beta_s - \Delta\Gamma$ likelihood profile on Toy MC with exact symmetry removed
- Approximate symmetry is still significant with current level of signal statistics!

Likelihood profile is not parabolic; cannot reliably separate the two minima!

Generated with $\beta_s = 0.40$
More Pseudo-Experiments

Generated with $\beta_s = 0.40$

Can see residual four-fold symmetry in some cases!

$2\Delta \ln \mathcal{L} = 2.31 \approx 68\% \text{ CL}$

$2\Delta \ln \mathcal{L} = 5.99 \approx 95\% \text{ CL}$

Generated with $\beta_s = 0.80$
Fits with Flavor Tagging

- Don’t have parabolic minima → can’t quote point estimate!
- Again quote confidence regions using Feldman-Cousins likelihood ratio ratio ordering method
- 2D profile of $2\beta_s$ vs $\Delta \Gamma$
- 1D intervals in $2\beta_s$
  - Quote results with and without external theory constraints
“Happiness is a butterfly, which, when pursued, is always just beyond your grasp, but which, if you will sit down quietly, may alight upon you.”

- Nathaniel Hawthorne
Flavor Tagged $2\beta_s - \Delta \Gamma$ Confidence Region

Probability of fluctuation from SM to observation is 15% ($1.5\sigma$)
Improvement from Flavor Tagging

With flavor tagging, phase space for $2\beta_s$ is half that without flavor tagging!
**$\beta_s$ 1D Intervals**

- One-dimensional Feldman-Cousins confidence interval
  - $2\beta_s \in [0.32, 2.82]$ at 68% CL
- Constraining $\Delta \Gamma = 2 |\Gamma_{12}| \cos(2\beta_s)$, where $|\Gamma_{12}| = 0.048 \pm 0.018$
  - $2\beta_s \in [0.24, 1.36] \cup [1.78, 2.90]$ at 68% CL
- Constraining $\Delta \Gamma = 2 |\Gamma_{12}| \cos(2\beta_s)$, $\Gamma$ to PDG $B^0$ lifetime, and $\delta_\parallel = -2.92 \pm 0.11$ and $\delta_\perp = 2.72 \pm 0.09$ (BABAR results, hep-ex/0411016)
  - $2\beta_s \in [0.40, 1.20]$ at 68% CL
Future Sensitivity

Projected Confidence Regions in 6 fb$^{-1}$ assuming same yield per fb$^{-1}$ in future and same tagging efficiency and dilution

Pseudo-experiments generated with $\beta_s = 0.02$

Pseudo-experiments generated with $\beta_s = \pi / 8$
Conclusions

“Congratulations, you are one step closer to hitting bottom.”

-Brad Pitt in “Fight Club”
Significant Improvement in CP Phase

- CDF significantly improves knowledge of $\beta_s / \varphi_s^{NP}$
  - $1.5\sigma$ consistency with SM predicted phase
  - Have reduced space available for new physics by factor of two!
    - Provide significantly tighter constraints on NP
- CDF also provides best measurement of mean $B_s^0$ lifetime, width difference in context of standard model
- Two exciting new results submitted to PRL today!
  - arXiv:0712.2348 (untagged measurement)
  - arXiv:0712.2397 (tagged measurement)