Measurement of CP Violation in $B_s \to J/\psi\phi$ Decay at CDF

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Introduction

- *CP* violation means that the laws of nature are not invariant under the simultaneous transformation of Charge and Parity

- Charge conjugation transforms particles into anti-particles

- Parity transformation is a mirror reflection (space inversion)

- Parity conservation was first questioned by T.D. Lee and C.N. Yang in 1956 when they argued that there was no experimental evidence for parity conservation in weak interactions

- Same year, C.S. Wu showed that Parity is violated in beta decays of Cobalt nuclei

- The combined *CP* was soon adopted as the correct symmetry, just to be shown wrong by Cronin and Fitch in 1964 when they showed that *CP* is violated in neutral Kaon decays
- **CP violation enters the Standard Model through complex phases in mixing matrices that connect up-type fermions with down-type fermions via W bosons:**

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

- Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix transforms quark mass eigenstates into weak eigenstates and induces **CP violation in the hadronic sector**

- Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix → induces neutrino oscillations and possibly **CP violation in lepton sector**

\[
\begin{bmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{bmatrix}
\]
CKM Matrix

- Expand CKM matrix in $\lambda = V_{us} = \sin(\theta_{\text{Cabibbo}}) \approx 0.23$

$$
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} \approx
\begin{pmatrix}
1 - \frac{1}{2} \lambda^2 - \frac{1}{8} \lambda^4 & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda + \frac{1}{2} A^2 \lambda^5[1 - 2(\rho + i\eta)] & 1 - \frac{1}{2} \lambda^2 - \frac{1}{8} \lambda^4(1 + 4A^2) & A\lambda^2 \\
A\lambda^3[1 - (1 - \frac{1}{2} \lambda^2)(\rho + i\eta)] & -A\lambda^2 + \frac{1}{2} A^4 \lambda^4[1 - 2(\rho + i\eta)] & 1 - \frac{1}{2} A^2 \lambda^4
\end{pmatrix}
$$

- To conserve probability CKM matrix must be unitary
  $\rightarrow$ Unitary relations can be represented as “unitarity triangles”

unitarity relations:

$$
V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0
$$

unitarity triangles:

$$
\begin{align*}
\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} = |\alpha| = \phi_2 \\
\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = |\beta| = \phi_3 \\
\frac{|V_{us}|}{|V_{cs}|} = \frac{|V_{ts}|}{|V_{cb}|} \sim 1
\end{align*}
$$

Small $CP$ violation phase $\beta_s$ accessible in $B_s \rightarrow J/\psi\Phi$ decays

$$
(0,0) \xrightarrow{\beta_s} (1,0)
$$
Why Look for CPV in $B_s$ System?

- CP violation has been studied in various Kaon and $B$-meson decays
- CKM matrix is well constrained by experimental data

- Within the SM framework, $\bar{\mathcal{CP}}$ violation in the quark sector is too small to explain the matter - antimatter asymmetry in the universe

- Could still find large CP violation within the SM in the lepton sector
  - initial asymmetry between leptons and anti-leptons may induce baryon asymmetry through baryon number violation processes (lepto-genesis)
  - long baseline neutrino experiments will investigate CP violation in neutrino sector

- Alternatively we look for sources of CP violation beyond the SM in the quark sector

- Promising place to look for non-SM CP violation is the neutral $B_s$ meson system
Neutral $B_s$ System

- Time evolution of $B_s$ flavor eigenstates described by Schrodinger equation:

$$i \frac{d}{dt} \left( |B_s^0(t)\rangle \right) = \left( M - \frac{i}{2} \Gamma \right) \left( |B_s^0(t)\rangle \right)$$

- Diagonalize mass ($M$) and decay ($\Gamma$) matrices
  → mass eigenstates:

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

- Flavor eigenstates differ from mass eigenstates and mass eigenvalues are also different:

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

$\rightarrow B_s$ oscillates with frequency $\Delta m_s$

precisely measured by

CDF $\Delta m_s = 17.77 +/\ - 0.12$ ps$^{-1}$

DØ $\Delta m_s = 18.56 +/\ - 0.87$ ps$^{-1}$

- Mass eigenstates have different decay widths

$$\Delta \Gamma = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}| \cos(\Phi_s)$$

where $\phi_s^{SM} = \arg \left( -\frac{M_{12}}{\Gamma_{12}} \right) \approx 4 \times 10^{-3}$
**CP Violation in \( B_s \rightarrow J/\Psi\Phi \) Decays**

- Analogously to the neutral \( B^0 \) system, CP violation in \( B_s \) system is accessible through interference of decays with and without mixing:

  $$\beta_s$$ in SM is predicted to be very small, \( O(\lambda^2) \)

  - New physics particles running in the mixing diagram may enhance \( \beta_s \)
    - large \( \beta_s \) → clear indication of New Physics!

\[ \beta_{s}^{SM} = \arg\left(-V_{ts}V_{tb}^{*}/V_{cs}V_{cb}^{*}\right) \approx 0.02 \]
**B_s → J/ψΦ Decays**

- Measure:
  - $B_s$ lifetime $\tau_s$
  - $B_{sH}, B_{sL}$ decay width difference $\Delta \Gamma_s$
  - $CP$ violating phase $\beta_s$

- Decay of $B_s$ (spin 0) to $J/\Psi$ (spin 1) and $\Phi$ (spin 1) leads to three different angular momentum final states:
  - $L = 0$ (s-wave), 2 (d-wave) → $CP$ even ( = short lived or light $B_s$ if no CPV )
  - $L = 1$ (p-wave) → $CP$ odd ( = long lived or heavy $B_s$ if no CPV )

- Three decay angles $\vec{\rho} = (\theta, \phi, \psi)$ describe directions of final decay products
  - $\mu^+ \mu^- K^+ K^-$
Transversity Basis

- Use “transversity basis” in which the vector meson polarizations w.r.t. direction of motion are either (Phys. Lett. B 369, 144 (1996), 184 hep-ph/9511363):

  - transverse (⊥ perpendicular to each other) → CP odd

  - transverse (∥ parallel to each other) → CP even

  - longitudinal (0) → CP even

- Corresponding decay amplitudes: $A_0$, $A_∥$, $A_⊥$
Decay Rate

- $B_s \rightarrow J/\Psi \Phi$ decay rate as function of time, decay angles and initial $B_s$ flavor:

$$\frac{d^4P(t, \bar{\rho})}{dt d\bar{\rho}} \propto \left| A_0 \right|^2 T_+ f_1(\bar{\rho}) + \left| A_\perp \right|^2 T_+ f_2(\bar{\rho})$$
$$+ \left| A_\perp \right|^2 T_- f_3(\bar{\rho}) + \left| A_\parallel \right| A_\perp U_+ f_4(\bar{\rho})$$
$$+ \left| A_0 \right| A_\parallel \cos(\delta_\parallel) T_+ f_5(\bar{\rho})$$
$$+ \left| A_0 \right| A_\perp V_+ f_6(\bar{\rho}),$$

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

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

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

- Identification of $B$ flavor at production (flavor tagging) $\rightarrow$ better sensitivity to $\beta_s$
Status Before This Update

- Both CDF (public note 9458) and DØ (conference Note 5933-CONF) showed $\sim 1.5\sigma$ deviations from SM in the same direction.
Status Before This Update: CDF + DØ Combination

- CDF + DØ combination done by the Tevatron B Working Group:
  http://tevbwg.fnal.gov/

- Shows intriguing 2.1σ deviation from SM expectation (CDF note 9787)
CDF Detector

High muon acceptance and precise muon ID

Calorimeter for electron ID used in flavor tagging

dE/dx in drift chamber and TOF provide 1.5σ pion/kaon ID crucial in flavor tagging and signal selection

Excellent vertexing (silicon detector)
→ decay time resolution ≈ 0.1 ps

Excellent momentum resolution for improving S/B (large radius drift chamber immersed in 1.4 T B field)
Analysis Components

- Multi-dimensional likelihood fit

\[ f_s P_s (m | \sigma_m) P_s (t, \bar{\rho}, \xi | D, \sigma_t) P_s (\sigma_t) P_s (D) \]

Mass discriminate signal against background

Decay-time determines lifetime of each mass eigenstate

Angles separate CP-even from CP-odd final states

Tagging determines flavor of initial $B_s$ state
Signal Reconstruction

- Reconstruct $B^0_s \rightarrow J/\psi\Phi$ in 5.2 fb$^{-1}$ of data from sample selected by di-muon trigger
- Combine kinematic variables with particle ID information ($dE/dx$, TOF) in neural network to discriminate signal from background
- Yield of $\sim$6500 signal $B_s$ events with $S/B \sim 1$ (compared to $\sim$3150 in 2.8 fb$^{-1}$)
**Flavor Tagging**

- Tevatron: $b$-quarks mainly produced in pairs of *bottom anti-bottom*
  
  $\rightarrow$ flavor of the $B$ meson at production inferred with:

- Opposite Side Tagger (OST): exploits decay products of other $b$-hadron in the event

- Same Side Kaon Tagger (SSKT): exploits correlations with particles produced in fragmentation

- Output of flavor tagger:
  
  - flavor decision ($b$-quark or anti-$b$-quark)
  
  - probability that the decision is correct: $P = (1 + \text{Dilution}) / 2$
Opposite Side Tagging Calibration and Performance

- OST combines in a NN opposite side lepton and jet charge information
- Initially calibrated using a sample of inclusive semileptonic $B$ decays
  - predicts tagging probability on event-by-event basis
- Re-calibrated using $\approx 52,000 B^{+/−} → J/\Psi K^{+/−}$ decays

- OST efficiency = 94.2 +/- 0.4\%, OST dilution = 11.5 +/- 0.2 \% (correct tag probability ~56\%)
- Total tagging power = 1.2\%
Same Side Tagging Calibration

- Event-by-event predicted dilution based on simulation
- Calibrated with 5.2 fb\(^{-1}\) of data
- Simultaneously measuring the \(B_s\) mixing frequency \(\Delta m_s\) and the dilution scale factor \(A\)

\[
P_{Si}(ct|\sigma_{ct}, \xi = \xi_D \cdot \xi_P, D) = \frac{1}{N} \cdot \left[ \frac{1}{\tau} e^{-\xi t/\tau} \cdot (1 + \xi AD \cdot \cos(\Delta m_s \tilde{t})) \right] \otimes \mathcal{G}(ct|\sigma_{ct}) \cdot \epsilon(ct|\sigma_{ct})
\]

- \(D\) – event by event predicted dilution
- \(\xi\) – tagging decision = +1, -1, 0 for \(B_s\), \(\bar{B}_s\) and un-tagged events

- Fully reconstructed \(B_s\) decays selected by displaced track trigger

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B_s^0 \rightarrow D_s^- \pi^+, D_s^- \rightarrow \phi \pi^-)</td>
<td>5613 ± 75</td>
</tr>
<tr>
<td>(B_s^0 \rightarrow D_s^- \pi^+, D_s^- \rightarrow K^* K^-)</td>
<td>2761 ± 53</td>
</tr>
<tr>
<td>(\bar{B}_s^0 \rightarrow D_s^- \pi^+, D_s^- \rightarrow (3\pi)^-)</td>
<td>2652 ± 52</td>
</tr>
<tr>
<td>(B_s^0 \rightarrow D_s^- (3\pi)^+, D_s^- \rightarrow \phi \pi^-)</td>
<td>1852 ± 43</td>
</tr>
<tr>
<td>Sum</td>
<td>12877 ± 113</td>
</tr>
</tbody>
</table>
Same Side Tagging Performance

- $B_s$ oscillation frequency measured: $\Delta m_s = (17.79 \pm 0.07) \text{ ps}^{-1}$ (statistical error only)

- In good agreement with the published CDF measurement with 1 fb$^{-1}$
  PRL 97, 242003 2006,  PRL 97, 062003 2006

  \[ \Delta m_s = 17.77 \pm 0.10 \text{ (stat.)} \pm 0.07 \text{ (syst.)} \text{ ps}^{-1} \]

  used as external constraint in $\beta_s$ measurement

- Dilution scale factor (amplitude) in good agreement with 1:

  \[ A = 0.94 \pm 0.15 \text{ (stat.)} \pm 0.13 \text{ (syst.)} \]

- Largest systematic uncertainty from decay time resolution modeling

- Total SSKT tagging power:

  \[ \varepsilon A^2 D^2 = (3.2 \pm 1.4) \% \]


CDF public note 10108
Detector Angular Efficiency

- **CP even** and **CP odd** final states have different angular distributions
  → use angles $\rho = (\theta, \phi, \psi)$ to statistically separate **CP even** and **CP odd** components

- Detector acceptance distorts the angular distributions
  → determine 3D angular efficiency function from simulation and account for this effect in the fit

CDF Simulation of Detector Angular Sculpting
**B_s Lifetime and Decay Width Difference**

- Assuming no CP violation ($\beta_s = 0$) obtain most precise measurements of lifetime $\tau_s$ and decay width difference $\Delta \Gamma_s$:

\[
\begin{align*}
\tau_s &= 1.53 \pm 0.025 \text{(stat.)} \pm 0.012 \text{(syst.)} \text{ ps} \\
\Delta \Gamma &= 0.075 \pm 0.035 \text{(stat.)} \pm 0.01 \text{(syst.)} \text{ ps}^{-1}
\end{align*}
\]

compared to PDG 2009 averages:

\[
\begin{align*}
\tau_s &= 1.472^{+0.024}_{-0.026} \text{ ps} \\
\Delta \Gamma_s &= 0.062^{+0.034}_{-0.037} \text{ ps}^{-1}
\end{align*}
\]

CP-even ($B_s^{\text{light}}$) and CP-odd ($B_s^{\text{heavy}}$) components have different lifetimes

$\rightarrow \Delta \Gamma \neq 0$
Polarization Amplitudes

Most precise measurement of polarization amplitudes

\[ |A_{\parallel}(0)|^2 = 0.231 \pm 0.014 \text{ (stat)} \pm 0.015 \text{ (syst.)} \]

\[ |A_0(0)|^2 = 0.524 \pm 0.013 \text{ (stat)} \pm 0.015 \text{ (syst.)} \]

\[ \phi_{\perp} = 2.95 \pm 0.64 \text{ (stat)} \pm 0.07 \text{ (syst.)} \]
S-Wave

- As noted in arxiv:0812.2832v3, the KK pair in $B_s \rightarrow J/\Psi \, KK$ decays can be in an s-wave state with $\sim6\%$ contribution in a +/-10 MeV window around the $\Phi$ peak.

- Systematic effects from neglecting such contribution were first investigated by Clarke et al in arxiv:0908.3627v1 where it is shown that:
  - 10% un-accounted s-wave contamination in the $\Phi$ region leads to
    - 10% bias in the measured $2\beta_s$, towards the SM prediction
    - 15% increase in statistical errors

- S-wave contribution can be either non-resonant or from the $f^0(980)$ resonance

- To account for potential s-wave contribution, enhance the likelihood function to account for the s-wave amplitude $A_S$ and interference between s-wave and p-wave

- Time dependence of the s-wave amplitude $A_S$ is $CP$-odd, same as $A_{\perp}$

- Mass and phase of s-wave component are assumed flat (good approximation in a narrow +/- 10 MeV around the $\Phi$ mass)
S-Wave Measurement

- The fitted s-wave fraction is found to be very small in the KK mass range used in this analysis: [1.009, 1.028] GeV
  s-wave fraction < 6.7% at 95% C.L.

- To be compared with expectation from arxiv:0812.2832v3 of 6.3% s-wave contribution in a range of +/- 10 MeV around the Φ peak
CP Violation Phase $\beta_s$ in Tagged $B_s \rightarrow J/\Psi\Phi$ Decays

- Without the s-wave the likelihood function is symmetric under the transformation

\[
2\beta_s \rightarrow \pi - 2\beta_s \quad \Delta \Gamma \rightarrow -\Delta \Gamma
\]

\[
\delta_\parallel \rightarrow 2\pi - \delta_\parallel \quad \delta_\perp \rightarrow \pi - \delta_\perp
\]

- Study expected effect of tagging using pseudo-experiments

- Improvement of parameter resolution is small due to limited tagging power ($\varepsilon D^2 \sim 4.5\%$ compared to B factories $\sim 30\%$)

- However, $\beta_s \rightarrow -\beta_s$ no longer a symmetry
  $\rightarrow$ 4-fold ambiguity reduced to 2-fold ambiguity

- Adding the s-wave “slightly” breaks the symmetry due to asymmetric $\Phi$ mass shape

- Symmetry still valid with good approximation…
CP Violation Phase $\beta_s$ in Tagged $B_s \rightarrow J/\Psi\Phi$ Decays

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$$\delta_\parallel \rightarrow 2\pi - \delta_\parallel \quad \delta_\perp \rightarrow \pi - \delta_\perp$$

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- Symmetry still valid with good approximation
Cross Checks With Pseudo-Experiments

- Generate 10 pseudo-experiments with $\beta_s = 0.3$ and $\Delta \Gamma = 0.2$ corresponding to 1.4 fb$^{-1}$
  - same parameters, just different random seeds

- Large fluctuations expected in shape and size of confidence regions

$2 \Delta \log(L) = 2.3$
$2 \Delta \log(L) = 6.0$
**Non-Gaussian Regime**

- Pseudo-experiments show that we are still not in perfect Gaussian regime
  → *quote confidence regions instead of point estimates*

- In ideal case (high statistics, Gaussian likelihood), to get the 2D 68% (95%) C.L. regions, take a slice through profiled likelihood at 2.3 (6.0) units up from minimum

- In this analysis integrated likelihood ratio distribution (black histogram) deviates from the ideal $\chi^2$ distribution (green continuous curve)

- Using pseudo-experiments establish a “map” between Confidence Level and $2\Delta\log(L)$

- All nuisance parameters are randomly varied within +/- 5$\sigma$ from their best fit values and maps of CL vs $2\Delta\log(L)$ re-derived

- To establish final confidence regions use most conservative case

---

*CDF Run II Preliminary, $L = 5.2 \text{ fb}^{-1}$*
CP Violation Phase $\beta_s$ with 5.2 fb\(^{-1}\) at CDF

- Final confidence regions in $\beta_s$-$\Delta \Gamma_s$ space:

Agreement with SM expectation is at $\sim 0.8 \sigma$ level
Agreement with SM prediction at $\sim 0.8 \sigma$ level
1D Profiled Likelihood for $\beta_s$

- CP violation phase $bs$ is bounded by the ranges:

$[0.02, 0.52] \cup [1.08, 1.55]$ at 68% C.L.

$[-\pi/2, -1.44] \cup [-0.13, 0.68] \cup [0.89, \pi/2]$ at 95% CL

Agreement with SM at $\sim 1\sigma$ level
$\beta_s - \Delta \Gamma$ Contours with and without Including the S-Wave

- Compare likelihood contours with and without including the s-wave
- Very small effect on $\beta_s$ and $\Delta \Gamma$
Comparison Between Different Data Periods

- Divide 5.2 fb$^{-1}$ sample in three sub-samples corresponding to three public releases:
  0 - 1.4 fb$^{-1}$ (initial result released at the end of 2007, PRL 100, 161802 (2008), arXiv:0712.2397)
  1.4 - 2.8 fb$^{-1}$ (added for 2008 ICHEP update)
  2.8 - 5.2 fb$^{-1}$ (added for this update)

- Previous results reproduced with updated analysis
- Clearly, improved agreement with the SM expectation comes from the second half of data (2.8 – 5.2 fb$^{-1}$)
Comparison with Previous Results

- $\beta_s$ and $\Delta \Gamma_s$ allowed parameter space greatly reduced

- Agreement with SM expectation improves with higher statistics

Initial result released at the end of 2007, PRL 100, 161802 (2008)  
arXiv:0712.2397  
~2000 signal events

2008 ICHEP update with preliminary PID and tagging  
~3150 signal events

This update  
~6500 signal events
Conclusions

- Measurement of CP violation in $B_s$ system updated by CDF with 5.2 fb$^{-1}$

- Tightened constraints in $\beta_s$ space:
  
  $[0.02, 0.52] \cup [1.08, 1.55]$ at 68% C.L.

- Improved agreement with SM expectation, at $\sim 1\sigma$ level

- Best measurements of $B_s$ lifetime, decay width difference $\Delta \Gamma_s$ and polarization amplitudes

\[
\begin{align*}
  c\tau_s &= 458.7 \pm 7.5 \text{ (stat)} \pm 3.6 \text{ (syst)} \mu m \\
  \Delta \Gamma_s &= 0.075 \pm 0.035 \text{ (stat)} \pm 0.01 \text{ (syst)} \text{ ps}^{-1} \\
  |A_{||}(0)|^2 &= 0.231 \pm 0.014 \text{ (stat)} \pm 0.015 \text{ (syst)} \\
  |A_0(0)|^2 &= 0.524 \pm 0.013 \text{ (stat)} \pm 0.015 \text{ (syst)}.\end{align*}
\]
Prospects

- Possible analysis improvements:

  - Improve statistics by ~25-30% by adding $B_s \rightarrow J/\psi \Phi$ decays from displaced track trigger (difficult due to trigger effects on decay time)

  - Addition of new decay modes:
    $B_s \rightarrow J/\psi f^0$, with $f^0 \rightarrow \pi \pi$ (less statistics but no angular analysis needed since final state is CP eigen-state)
    $B_s \rightarrow \psi(2s) \Phi$

  - Perform KK mass dependent fit (for more precise determination of s-wave contamination)

- Add more data!

  - 7 fb$^{-1}$ already recorded

  - expect to double sample size (~10 fb$^{-1}$) by end of Tevatron running in 2011
Backup Slides
**B Physics at the Tevatron**

- Mechanisms for $b$ production in $p\bar{p}$ collisions at 1.96 TeV

- At Tevatron, $b$ production cross section is much larger compared to B-factories
  \[\rightarrow\] Tevatron experiments CDF and DØ enjoy rich B Physics program

- Plethora of states accessible only at Tevatron: $B_s$, $B_c$, $\Lambda_b$, $\Xi_b$, $\Sigma_b$...
  \[\rightarrow\] complement the B factories physics program

- Total inelastic cross section at Tevatron is $\sim$1000 larger than $b$ cross section
  \[\rightarrow\] large backgrounds suppressed by triggers that target specific decays
$\beta_s \text{ vs } \phi_s$

- Up to now, introduced two different phases:

$$\phi_s^{SM} = \arg \left( -\frac{M_{12}}{\Gamma_{12}} \right) \approx 4 \times 10^{-3} \quad \text{and} \quad \beta_s^{SM} = \arg \left( -V_{ts}V_{tb}^*/V_{cs}V_{cb}^* \right) \approx 0.02$$

- New Physics affects both phases by same quantity $\phi_s^{NP}$ (arxiv:0705.3802v2):

$$2\beta_s = 2\beta_s^{SM} - \phi_s^{NP}$$

$$\phi_s = \phi_s^{SM} + \phi_s^{NP}$$

- If the new physics phase $\phi_s^{NP}$ dominates over the SM phases $2\beta_s^{SM}$ and $\phi_s^{SM}$ → neglect SM phases and obtain:

$$2\beta_s = -\phi_s^{NP} = -\phi_s$$
Decay Rate

- $B_s \to J/\psi \Phi$ decay rate (A.S. Dighe et al., Phys. Lett. B 369 144 (1996)):

$$P_B(\theta, \phi, \psi, t) = \frac{9}{16\pi} |A(t) \times \hat{n}|^2$$

where: $A(t) = (A_0(t) \cos \psi, -\frac{A_{\parallel}(t) \sin \psi}{\sqrt{2}}, -\frac{A_{\perp}(t) \sin \psi}{\sqrt{2}})$ and $\hat{n} = (\sin \theta \cos \phi, \sin \theta \sin \phi, \cos \theta)$

- Time evolution of transversity amplitudes $A_0, A_{\parallel}, A_{\perp}$:

$$A_i = \frac{e^{-\Gamma t/2}}{\sqrt{\tau_H + \tau_L \pm \cos 2\beta_s (\tau_L - \tau_H)}} \left[ E_+(t) \pm e^{2i\beta_s} E_-(t) \right] a_i$$

where $\pm$ corresponds to CP-even and CP-odd final states, $\sum_i |a_i|^2 = 1$ and

$$E_\pm(t) = \frac{1}{2} \left[ e^{+ \left( -\frac{\Delta m}{4} + i \frac{\Delta m}{2} \right) t} \pm e^{- \left( \frac{\Delta m}{4} + i \frac{\Delta m}{2} \right) t} \right]$$

- Finally:

$$P_B(\theta, \psi, \phi, t) = \frac{9}{16\pi} \left\{ |A_+(t) \times \hat{n}|^2 + |A_-(t) \times \hat{n}|^2 + 2Re((A_+(t) \times \hat{n}) \cdot (A_-^*(t) \times \hat{n})) \right\}$$

$$= \frac{9}{16\pi} \left\{ |A_+ \times \hat{n}|^2 |f_+(t)|^2 + |A_- \times \hat{n}|^2 |f_-(t)|^2 + 2Re((A_+ \times \hat{n}) \cdot (A_-^* \times \hat{n}) \cdot f_+(t) \cdot f_-^*(t)) \right\}$$

$$|f_\pm(t)|^2 = \frac{1}{2} \frac{(1 \pm \cos 2\beta_s) e^{-\Gamma t} + (1 \mp \cos 2\beta_s) e^{-\Gamma t} \mp 2 \sin 2\beta_s e^{-\Gamma t} \sin \Delta mt}{\tau_L (1 \pm \cos 2\beta_s) + \tau_H (1 \mp \cos 2\beta_s)}$$

$$f_+(t) f_-^*(t) = \frac{e^{-\Gamma t} \cos \Delta mt + i \sin 2\beta_s e^{-\Gamma t} \sin \Delta mt + i \sin 2\beta_s (e^{-\Gamma t} - e^{-\Gamma t'})}{\sqrt{[\tau_L - \tau_H \sin 2\beta_s]^2 + 4\tau_L \tau_H}}$$


**Decay Rate with S-Wave Included**

- Including the s-wave contribution the probability density function becomes:

\[
\rho_B(\theta, \phi, \psi, t, \mu) = \frac{9}{16\pi} \left| \sqrt{1 - F_s g(\mu)} A(t) + e^{i\delta_s} \sqrt{F_s} \frac{h(\mu)}{\sqrt{3}} B(t) \right| \times \hat{n}^2
\]

where: \( B(t) = (B(t), 0, 0) \) and \( B(t) = \frac{e^{-\Gamma t/2}}{\sqrt{\tau_H + \tau_L - \cos 2\beta_s (\tau_L - \tau_H)}} \left[ E_+(t) - e^{2i\beta_s} E_-(t) \right] \)

- Integrating out the dependence on the KK mass:

\[
\rho_B(\theta, \psi, \phi, t) = (1 - F_s) \cdot P_B(\theta, \psi, \phi, t) + F_s Q_B(\theta, \psi, \phi, t)
+ 2 \frac{\sqrt{27}}{16\pi} \text{Re} \left[ I_\mu \left( (A_- \times \hat{n}) \cdot (B \times \hat{n}) \cdot |f_-(t)|^2 + (A_+ \times \hat{n}) \cdot (B \times \hat{n}) \cdot f_+(t) \cdot f_-(t) \right) \right]
\]

where: \( I(\mu) \) is a function of the s-wave phase and \( Q_B(\theta, \phi, \psi, t) = \frac{3}{16\pi} |B(t) \times \hat{n}|^2 \)
Analysis Improvements with Respect To 2008 Update

- Almost doubled data sample (from 2.8 fb\(^{-1}\) in 2008 to 5.2 fb\(^{-1}\) now)

- Improved signal selection:
  - use particle ID (dE/dx and TOF) for full dataset
  - use pseudo-experiments to optimize neural network selection to minimize \(\beta_s\) statistical uncertainty (previously used \(S/(S+B)^{1/2}\) as figure of merit)

- Same side kaon tagger (SSKT) used for the full dataset
  - re-calibrated by measuring \(B_s\) mixing frequency with 5.2 fb\(^{-1}\)

- Inclusion of S-wave contamination in the likelihood fit
Comparison between tagged and un-tagged fit with and without accounting for $S$-wave

\[
\begin{align*}
ct &= 458.64 \pm 7.54 \text{ (stat.) } \mu m \\
\Delta \Gamma &= 0.075 \pm 0.035 \text{ (stat.) } ps^{-1} \\
|A_\parallel|^2 &= 0.231 \pm 0.014 \text{ (stat.)} \\
|A_0|^2 &= 0.524 \pm 0.013 \text{ (stat.)} \\
\phi_\perp &= 2.95 \pm 0.64 \text{ (stat.)}
\end{align*}
\]

Tagged, with $S$-wave

\[
\begin{align*}
ct &= 459.1 \pm 7.7 \text{ (stat.) } \mu m \\
\Delta \Gamma &= 0.073 \pm 0.03 \text{ (stat.) } ps^{-1} \\
|A_\parallel|^2 &= 0.232 \pm 0.014 \text{ (stat.)} \\
|A_0|^2 &= 0.523 \pm 0.012 \text{ (stat.)} \\
\phi_\perp &= 2.80 \pm 0.56
\end{align*}
\]

Tagged, no $S$-wave

\[
\begin{align*}
ct &= 456.93 \pm 7.69 \text{ (stat.) } \mu m \\
\Delta \Gamma &= 0.071 \pm 0.036 \text{ (stat.) } ps^{-1} \\
|A_\parallel|^2 &= 0.233 \pm 0.015 \text{ (stat.)} \\
|A_0|^2 &= 0.521 \pm 0.013 \text{ (stat.)}
\end{align*}
\]

Untagged, with $S$-wave

\[
\begin{align*}
ct &= 457.2 \pm 7.9 \text{ (stat.) } \mu m \\
\Delta \Gamma &= 0.070 \pm 0.04 \text{ (stat.) } ps^{-1} \\
|A_\parallel|^2 &= 0.233 \pm 0.016 \text{ (stat.)} \\
|A_0|^2 &= 0.520 \pm 0.013 \text{ (stat.)}
\end{align*}
\]

Untagged, no $S$-wave
## Systematic Uncertainties

| Systematic                                      | $\Delta\Gamma$ | $c\tau_s$ | $|A_{\parallel}(0)|^2$ | $|A_0(0)|^2$ | $\phi_\perp$ |
|-------------------------------------------------|----------------|-----------|-------------------------|---------------|--------------|
| **Signal efficiency:**                           |                |           |                         |               |              |
| Parameterisation                                | 0.0024         | 0.96      | 0.0076                  | 0.008         | 0.016        |
| MC reweighting                                  | 0.0008         | 0.94      | 0.0129                  | 0.0129        | 0.022        |
| **Signal mass model**                           | 0.0013         | 0.26      | 0.0009                  | 0.0011        | 0.009        |
| **Background mass model**                       | 0.0009         | 1.4       | 0.0004                  | 0.0005        | 0.004        |
| Resolution model                                | 0.0004         | 0.69      | 0.0002                  | 0.0003        | 0.022        |
| Background lifetime model                       | 0.0036         | 2.0       | 0.0007                  | 0.0011        | 0.058        |
| **Background angular distribution:**            |                |           |                         |               |              |
| Parameterisation                                | 0.0002         | 0.02      | 0.0001                  | 0.0001        | 0.001        |
| $\sigma(c\tau)$ correlation                    | 0.0002         | 0.14      | 0.0007                  | 0.0007        | 0.006        |
| Non-factorisation                               | 0.0001         | 0.06      | 0.0004                  | 0.0004        | 0.003        |
| $B^0 \rightarrow J_{\psi}K^*$ crossfeed        | 0.0014         | 0.24      | 0.0007                  | 0.0010        | 0.006        |
| SVX alignment                                   | 0.0006         | 2.0       | 0.0001                  | 0.0002        | 0.002        |
| Mass error                                      | 0.0001         | 0.58      | 0.0004                  | 0.0004        | 0.002        |
| $c\tau$ error                                   | 0.0012         | 0.17      | 0.0005                  | 0.0007        | 0.013        |
| Pull bias                                       | 0.0028         |           | 0.0013                  |               | 0.0021       |
| **Totals**                                      | 0.01           | 3.6       | 0.015                   | 0.015         | 0.07         |
## Dilution Scale Factor Systematic Uncertainties

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<tr>
<th>Modification</th>
<th>Systematic Uncertainty</th>
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<td>$\Delta \Gamma / \Gamma$</td>
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<tr>
<td>Trigger Composition</td>
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<tr>
<td>Signal Mass Model</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>0.13</strong></td>
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S-Wave Cross Check Using KK Mass Spectrum

- Cross check the result from angular fit by fitting the KK invariant mass spectrum

- From a fit to the $B_s$ mass distribution with wide KK mass range selection (0.980, 1.080 GeV), determine contributions of combinatorial background, mis-reconstructed $B^0$, and $B_s$ events

- Good fit of the KK mass spectrum with 2% $f^0$ contributions
$\beta_s - \Delta \Gamma$ Contours Without Coverage Adjustment

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

- Red: 5.99
- Blue: 2.30
- Black: SM prediction
$\beta_s - \Delta \Gamma$ Contours With Coverage Adjustment

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

Adjusted for non-Gaussian errors

- 7.34
- 2.85
- SM prediction
Agreement with SM expectation is at ~0.8σ level

**β_s-ΔΓ Contours With Systematics on Coverage**

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

- 95% CL
- 68% CL
- SM prediction

Agreement with SM prediction at ~0.8σ level
strong phases could separate the two minima

\[ 2 \Delta \log(L) = 2.30 \]
\[ 2 \Delta \log(L) = 5.99 \]

\[ \cos(\delta_1) < 0 \]
\[ \cos(\delta_\perp - \delta_\parallel) > 0 \]
Sensitivity

![Graph showing sensitivity with CDF only and probability of 5σ observation for 8 fb⁻¹ and 6 fb⁻¹.]