Bs Mixing and Lifetime Difference at CDF

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On behalf of the CDF Collaboration

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Outline

- Tevatron and CDF II
  - $B_s \rightarrow D_s D_s$
  - $B_s \rightarrow K K$
  - $B_s \rightarrow J/\psi\phi$

- $\Delta \Gamma$

- $B_s$ Mixing
  - For Flavor Tagging calibration to be used in $B_s \rightarrow J/\psi\phi$

- $\beta_s$
Tevatron at Fermilab

- $p\bar{p}$ collisions at 1.96 TeV
- All $b$ hadron species produced:
  \begin{itemize}
  \item $B$, $B_s$, $B_c$, $\Lambda_b$, $\Sigma_b$, $\Xi_b$, $\Omega_b$...
  \end{itemize}

- more than 5 fb$^{-1}$ data on tape for each experiment
- Show analyses $\leq 2.8$ fb$^{-1}$ of data

\begin{itemize}
\item Booster
\item $p$ source
\item CDF
\item Tevatron
\item DØ
\item Main Injector & Recycler
\end{itemize}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{trevatron.png}
\caption{Tevatron at Fermilab}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{luminosity.png}
\caption{Total Luminosity (pb$^{-1}$)}
\end{figure}
CDF II Detector

TRACKING system:

• Drift Chamber 96 layers ($|\eta|<1$)
  particle ID with $dE/dx$
• Silicon Tracker (L00+SVX+ISL, up to $|\eta|\approx2$)
  I.P. resolution 35 $\mu$m at 2 GeV

In Addition:

• Particle identification: $dE/dX$ and TOF
• Electron and muon ID by calorimeters and muon chambers
Neutral $B_s$ System

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

$$i\frac{d}{dt} \left( \frac{B^0_s(t)}{\bar{B}^0_s(t)} \right) = H \left( \frac{B^0_s(t)}{\bar{B}^0_s(t)} \right) = \left[ \begin{pmatrix} M_0 & M_{12} \\ M_{12}^* & M_0 \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma_0 & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_0 \end{pmatrix} \right] \left( \frac{B^0_s(t)}{\bar{B}^0_s(t)} \right)$$

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

$$|B^H_s\rangle = p |B^0_s\rangle - q |\bar{B}^0_s\rangle \quad |B^L_s\rangle = p |B^0_s\rangle + q |\bar{B}^0_s\rangle$$

- Flavor eigenstates differ from mass eigenstates and mass eigenvalues are different ($\Delta m_s = m_H - m_L \approx 2|M_{12}|$)

- Mass eigenstates have different decay widths
$$\Delta \Gamma = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}| \cos(\Phi_s) \quad \text{where} \quad \phi_s = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right) \approx 4 \times 10^{-3}$$
ΔΓ : Lifetime Difference

\[ \Delta \Gamma = \Gamma_L - \Gamma_H \]
CP Specific: $B_s \rightarrow D_s D_s$

- Assume no CP violation: $B_s^L = CP$ even, $B_s^H = CP$ odd
- $b \rightarrow ccs$ decay (e.g. $B_s \rightarrow D_s D_s$) is pure $CP$ even
- Thus a lifetime measurement of $B_s \rightarrow D_s D_s$ would measure $\Gamma_L$

**HOWEVER**

- Branching ratio is related to $\Delta \Gamma/\Gamma$ and if neglect small $CP$ odd component:

$$\frac{\Delta \Gamma}{\Gamma} = 2 Br \left( B_s^0 \rightarrow D_s^{(*)-} D_s^{(*)+} \right)$$

- BR ($B_s \rightarrow D_s D_s$) measured relative to $B^0 \rightarrow D_s D^-$
- Three $D_s$ decay modes reconstructed in each case

$$\ln \left( \frac{BR(B_s^0 \rightarrow D_s D_s)}{BR(B_d^0 \rightarrow D_s D^-)} \right) = 1.44^{+0.38}_{-0.31} (stat) ^{+0.08}_{-0.12} (sys) \pm 0.21 \left( \frac{f_s}{f_d} \right) \pm 0.20 (BR)$$

*Observation* 7.5$\sigma$
CP Specific: $B_s \to D_s DsDs$

With 355 pb$^{-1}$ → 95% C.L.: $\frac{\Delta \Gamma}{\Gamma} \geq 2 \text{Br} \left( B_s^0 \to D_s^{-} D_s^{(*)+} \right) \geq 0.012$


- New Analysis on going.
- New Neural Network Selection to increase acceptance (in 1.6 fb$^{-1}$): 
  - ~ 105 $B_s \to DsDs$
  - ~ 1930 $B_d \to DDs$
CP Specific: Bs → KK

- First Measurement of Bs → KK lifetime performed in 360 pb⁻¹. Bs → KK extracted using a Maximum Likelihood fit that combines kinematics and particle identification information.
- Lifetime measurement interesting since ~ 95% CP even.
- B→hh decays can be resolved at CDF
  - Displaced track trigger
  - Good mass resolution

$$\tau(B_s \rightarrow K^+K^-) = 1.53 \pm 0.18(\text{stat}) \pm 0.02(\text{sys}) \text{ ps}$$

Use HFAG flavour specific $$\tau = 1.454\pm0.040 \text{ ps}$$

360 pb⁻¹ $$\frac{\Delta \Gamma}{\Gamma} = -0.08 \pm 0.23(\text{stat}) \pm 0.03(\text{sys})$$

In 2fb⁻¹ we expect:
$$\tau \text{ stat error } 0.06-0.09 \text{ ps}$$

http://www-cdf.fnal.gov/physics/new/bottom/060126.blessed-BsKK_lifetime/
Bs → J/ψφ

- Extremely physics rich decay mode

- Can measure lifetime, decay width difference $\Delta \Gamma$ and CP violating phase $\beta_s$

- Decay of Bs (spin 0) to $J/\Psi$ (spin 1) $\Phi$ (spin 1) leads to three different angular momentum final states:
  
  $L = 0$ (s-wave), 2 (d-wave) → CP even ($\approx$ short lived or light $B_s$ if $\Phi_s \approx 0$)
  
  $L = 1$ (p-wave) → CP odd ($\approx$ long lived or heavy $B_s$ if $\Phi_s \approx 0$)

- three decay angles $\vec{\rho} = (\theta, \phi, \psi)$ describe directions of final decay products
Tagged Bs $\rightarrow J/\psi\phi$: $\Delta\Gamma$

- Performed simultaneous mass, lifetime and angular fit
- CDF reconstructed around 3200 events in 2.8 fb$^{-1}$ using selections based on Neural Network.
Tagged Bs $\rightarrow J/\psi\phi$: $\Delta\Gamma$

Assume No CP violation

In 2.8 fb$^{-1}$:

$c\tau_s = 459 \pm 12$ (stat) $\pm 3$ (sys) $\mu$m

$\Delta\Gamma = 0.02 \pm 0.05$ (stat) $\pm 0.01$ (sys) ps$^{-1}$

$|A_0|^2 = 0.508 \pm 0.024$ (stat) $\pm 0.008$ (sys)

$|A_\parallel|^2 = 0.241 \pm 0.019$ (stat) $\pm 0.007$ (sys)

Predicted $\Delta\Gamma$

0.096$\pm$ 0.039ps$^{-1}$
(arxiv: 0802.0977)

This result with 2.8 fb$^{-1}$:


Published analysis with 1.7fb$^{-1}$: Phys. Rev. Lett. 100, 121803 (2008)
Add Flavor Tagging

CP Violation Phase $\beta_s$ in $B_s \rightarrow J/\psi\phi$

- CP violation phase $\beta_s$ in SM is predicted to be very small, $O(\lambda^2)$
- New Physics CPV can compete or even dominate over small Standard Model CPV

- Ideal place to search for New Physics
**CP Violation Phase $\beta_s$ in Tagged $B_s \rightarrow J/\psi\phi$**

- Likelihood expression predicts better sensitivity to $\beta_s$ but still double minima due to symmetry:
  \[
  \begin{align*}
  2\beta_s &\rightarrow \pi - 2\beta_s \\
  \Delta \Gamma &\rightarrow -\Delta \Gamma \\
  \delta_\parallel &\rightarrow 2\pi - \delta_\parallel \\
  \delta_\perp &\rightarrow \pi - \delta_\perp
  \end{align*}
  \]

- 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 $\sim30\%$)

- However, $\beta_s \rightarrow -\beta_s$ no longer a symmetry
  \rightarrow 4$-fold$ ambiguity reduced to 2$-fold$ ambiguity
  \rightarrow allowed region for $\beta_s$ is reduced to half

\[
\begin{align*}
2\Delta \log(L) &= 2.3 \approx 68\% \text{ CL} \\
2\Delta \log(L) &= 6.0 \approx 95\% \text{ CL}
\end{align*}
\]

strong phases can separate the two minima
CP Violation Phase $\beta_s$ in Tagged $B_s \rightarrow J/\psi\phi$

- CDF: Standard Model probability 7%, $\sim 1.8\sigma$

- HFAG combines old CDF (1.4 fb$^{-1}$, 1.5 $\sigma$ from SM, PRL 100, 161802 (2008))

- DØ (2.8 fb$^{-1}$, 1.7 $\sigma$ from SM) results yield a 2.2 $\sigma$ deviation from SM (similar results from UTFit and CKM)

- Ongoing CDF and DØ work to produce Tevatron $\Delta \Gamma - \beta_s$ average using 2.8 fb$^{-1}$

- Investigating two combination methods:
  - combine 2D profile likelihoods
  - perform simultaneous fit of CDF and DØ data
  - expect to be more powerful, longer timescale
Future

- Tevatron can search for anomalously large values of $\beta_s$.
- Shown results with 2.8 fb\(^{-1}\), but more than 5 fb\(^{-1}\) already on tape to be analyzed soon with NEW flavor tagger.
- Currently considering other improvements.
- Expect 8 fb\(^{-1}\) by the end of Run 2 in 2010 (maybe 10 fb\(^{-1}\) by end of 2011?).

If $\beta_s$ is indeed large combined Tevatron results have good chance to prove it.
Bs Mixing is now a very important benchmark for flavor tagging calibration

- Tevatron: $b$-quarks mainly produced in $b$ anti-$b$-pairs → flavor of the $B$ meson at production inferred with
- OST: exploits decay products of other $b$-hadron in the event
- SST: exploits the correlations with particles produced in fragmentation

Old Tagger
- OST calibrated on data ($B^+, B^0$)
- SSKT calibrated on MC, but checked on $B_s$ mixing measurement
- Combined tagging power at CDF ~4.5%
  (compared to ~30% at B factories)
New Tagger Principle

Combine the information from all tracks in the event

- **Same Side:** tracks in the same side in which the same side B was found.
- **Leptons:** tracks that are electron or muon candidate.
- **Others:** all remaining tracks (very low B flavor information).

- **Split** all charged tracks into the three subsamples: same side, leptons and others.
- **Train** an independent “Track Flavor Correlation Neural Network” for each subsample.
- **Combine** tracks of each subsample in a separate Likelihood Ratio.

The new Tagger will be calibrated/checked on MC and on NEW B, mixing measurement with higher statistics data samples and used in NEW tagged Bs → J/ψφ.
Conclusions

• Several ways of measuring $\Delta \Gamma$ have been deployed; to be updated soon:

$$\Delta \Gamma(B_s \rightarrow J/\psi \phi) = 0.02 \pm 0.05 \text{(stat)} \pm 0.01 \text{(sys)} \text{ps}^{-1}$$

$$\frac{\Delta \Gamma}{\Gamma}(B_s \rightarrow K^+K^-) = -0.08 \pm 0.23 \text{(stat)} \pm 0.03 \text{(sys)}$$

$$\frac{\Delta \Gamma}{\Gamma} \geq 2 Br \left(B_s^0 \rightarrow D_s^{(*)-}D_s^{(*)+} \right) \geq 0.012 \quad (95\% \text{ C.L.})$$

• Significant regions in $\beta_s$ space are ruled out

• CDF observes 1.8 sigma $\beta_s$ deviations from SM predictions

• Combined HFAG result 2.2 sigma w.r.t SM expectation

• Soon: updated analyses from CDF with new tagger and more data
$B_s \to J/\Psi \Phi$ Decay Rate

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

$$\frac{d^4 P(t, \vec{\rho})}{dt d\vec{\rho}} \propto |A_0|^2 T_+ f_1(\vec{\rho}) + |A_\parallel|^2 T_+ f_2(\vec{\rho})$$

$$+ |A_\perp|^2 T_- f_3(\vec{\rho}) + |A_\parallel||A_\perp| \mathcal{U}_+ f_4(\vec{\rho})$$

$$+ |A_0||A_\parallel| \cos(\delta_\parallel) T_+ f_5(\vec{\rho})$$

$$+ |A_0||A_\perp| \mathcal{V}_+ f_6(\vec{\rho}),$$

$T_\pm = e^{-\Gamma t} \times [\cosh(\Delta \Gamma t/2) \mp \cos(2\beta_s) \sinh(\Delta \Gamma t/2)$

$$\pm i \sin(2\beta_s) \sin(\Delta m_s t)],$$

$\mathcal{U}_\pm = \pm e^{-\Gamma t} \times [\sin(\delta_\perp - \delta_\parallel) \cos(\Delta m_s t)$

$$- \cos(\delta_\perp - \delta_\parallel) \cos(2\beta_s) \sin(\Delta m_s t)$

$$\pm \cos(\delta_\perp - \delta_\parallel) \sin(2\beta_s) \sinh(\Delta \Gamma t/2)]$.$

$\mathcal{V}_\pm = \pm e^{-\Gamma t} \times [\sin(\delta_\perp) \cos(\Delta m_s t)$

$$- \cos(\delta_\perp) \cos(2\beta_s) \sin(\Delta m_s t)$

$$\pm \cos(\delta_\perp) \sin(2\beta_s) \sinh(\Delta \Gamma t/2)].$

Terms with $\Delta m_s$ dependence present if initial state of $B$ meson ($B$ vs anti-$B$) is determined (flavor tagged)

'Strong' phases:

$$\delta_\parallel \equiv \text{Arg}(A_\parallel(0)A_0^*(0))$$

$$\delta_\perp \equiv \text{Arg}(A_\perp(0)A_0^*(0))$$
Analysis without Flavor Tagging

- Drop information on production flavor
- Simpler but less powerful analysis

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

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

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

- Still sensitive to CP-violation phase $\beta_s$
- Suited for precise measurement of width-difference and average lifetime
Effect of Dilution Asymmetry on $\beta_s$

- Effect of 20% b-bbar dilution asymmetry is very small

![Graphs showing dilution asymmetry in $B^+ \to J/\Psi K^+$ and $B^- \to J/\Psi K^-$ transitions.](image)
S-wave Effect on Measurement of CP Violating Phases?

S. Stone, L. Zhang, arXiv:0812.2832

- What is effect of interference between S-wave $B_s \to J/\Psi f^0$ or $B_s \to J/\Psi K^+K^-$ (non-resonant) and $B_s \to J/\Psi \Phi$?

- Within statistics, no evidence for $f^0$ or non-resonant KK S-wave in $\Phi(KK)$ mass distribution

- $\cos(\Psi)$ distribution sensitive to S-wave interference:

Evidence for S-wave in $B^0 \to J/\Psi K^{*0}$

No evidence for S-wave in $B_s \to J/\Psi \Phi$
CDF Selection of $B_s$ Signal Using ANN

- NN maximizes $S/\sqrt{(S+B)}$, trained on MC for signal and mass sidebands for background

- Variables used by NN
  - $B^0_s$: use $p_T$ and vertex quality
  - $J/\psi$: use $p_T$ and vertex prob.
  - $\Phi$: use mass and vertex quality
  - PID (dE/dx + TOF) for Kaons from $\Phi$
  - ...

CDF Run 2 Preliminary $L \sim 2.8$ fb$^{-1}$

Candidates per 0.02

Neural network output
CDF Cross-check on $B^0 \rightarrow J/\Psi K^{*0}$

$B^0 \rightarrow J/\psi K^{*0}$: high-statistics test of angular efficiencies and fitter

$\sqrt{s} = 456 \pm 6 \ \text{(stat)} \pm 6 \ \text{(syst)} \ \mu$m

$|A_0(0)|^2 = 0.569 \pm 0.009 \ \text{(stat)} \pm 0.009 \ \text{(syst)}$

$|A_1(0)|^2 = 0.211 \pm 0.012 \ \text{(stat)} \pm 0.006 \ \text{(syst)}$

$\delta_1 = -2.96 \pm 0.08 \ \text{(stat)} \pm 0.03 \ \text{(syst)}$

$\delta_\perp = 2.97 \pm 0.06 \ \text{(stat)} \pm 0.01 \ \text{(syst)}$

- Not only agree with latest BaBar results, (PRD 76,031102 (2007)) but also competitive

$|A_0(0)|^2 = 0.556 \pm 0.009 \ \text{(stat)} \pm 0.010 \ \text{(syst)}$

$|A_1(0)|^2 = 0.211 \pm 0.010 \ \text{(stat)} \pm 0.006 \ \text{(syst)}$

$\delta_1 = -2.93 \pm 0.08 \ \text{(stat)} \pm 0.04 \ \text{(syst)}$

$\delta_\perp = 2.91 \pm 0.05 \ \text{(stat)} \pm 0.03 \ \text{(syst)}$
\[ \beta_s \text{ vs } \phi_s \]

- 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 can affect both phases by same quantity \( \phi_s^{NP} \) (A. Lenz, arxiv:0705.3802v2):

\begin{align*}
2\beta_s &= 2\beta_s^{SM} - \phi_s^{NP} \\
\phi_s &= \phi_s^{SM} + \phi_s^{NP}
\end{align*}

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

\[ 2\beta_s = -\phi_s^{NP} = -\phi_s \]
$\beta_s$ Phase and the CKM Matrix

- CKM matrix connects mass and weak quark eigenstates
- Expand CKM matrix in $\lambda = \sin(\theta_{\text{Cabibbo}}) \approx 0.23$

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

- To conserve probability CKM matrix must be unitary
  → 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:

$$\lambda^2 \sim \frac{V_{us}V_{ub}^*}{V_{cs}V_{cb}^*} \approx 1$$

very small CPV phase $\beta_s$ of order $\lambda^2$ accessible in $B_s$ decays