CP violation at CDF

Mixing: $B_s, B_d, D^0$

Lifetimes: $\Delta \Gamma, \Lambda_b, B_s, B_{c^+}, B_d$

B and D BR and $A_{cp}$

Masses: $B_{c^+}, \Lambda_b, B_s$

New particles $\Sigma_b, \Xi_b$

Production $\sigma(b), \sigma(J/\psi), \sigma(D^0)$

Rare decays $B_s \rightarrow \mu^+\mu^-, D^0 \rightarrow \mu^+\mu^-$

Surprises!?!

Petar Maksimovic, Johns Hopkins

Exciting time at the Tevatron for heavy flavor physics!
Outline

- Standard Model, physics beyond SM (BSM or NP) and the role of indirect searches for BSM.
  - CP violation in b-hadron decays as a tool to search for BSM
- Tevatron and CDF II detector
  - doing $B$ physics in hadronic environment
- CP violation measurements at CDF:
  - $B_s \rightarrow J/\psi \phi$: lifetime, $\Delta \Gamma_s$ and CP violation in $B_s$ system
  - charge asymmetry in semileptonic $B_s$ decays
  - CPV in fully hadronic channels
    - $B_s \rightarrow K\pi$, $B^0 \rightarrow K\pi$, and $\Lambda_b \rightarrow p\pi$, $pK$ decays
    - $B^+ \rightarrow D^0_{CP}K^+$
- Conclusions
Role of precision measurements

- Standard Model works well: excellent agreement with data for 30+ years.

- Perhaps too well: we don't understand many things (dark matter, dark energy, neutrino masses, baryon asymmetry, no Higgs yet, etc.)

- We all believe there's deeper physics that underlies SM
  - Beyond SM (“BSM”), or New Physics (“NP”)

- Road to New Physics:
  - direct searches at Tevatron (now) and LHC (soon)
  - indirect searches: check internal consistency of SM
CP violation as `precision' tests

- If there were New Physics:

\[ A_{\text{meas}} = A^{SM} + A^{NP} = |A^{SM}|e^{i\phi^{SM}} + |A^{NP}|e^{i\phi^{NP}} \]

- New Physics can affect the magnitude, i.e.

\[ |A_{\text{meas}}|^2 \neq |A^{SM}|^2 \]

- Or if there's phase difference, i.e., \( \phi^{SM} \neq \phi^{NP} \), there will be interference which would be a new source of CP violation

- CP violation is any difference between properties of a decay and its "mirror image" resulting from C and P transformations. It could include:
  - decay rate (this requires \( A^{SM} \) to also contain a strong phase)
  - triple products (works even when strong phase is 0)
  - coefficients describing angular decomposition of the amplitude, etc.
Most consistency checks (especially in electroweak data) have achieved amazing precision (think of W mass)

`Null' measurements (in cases where SM predicts ~ 0) are especially powerful

- e.g., $\text{BR}(B_s \rightarrow \mu \mu)$ in SUSY may be significantly larger than in SM

CP violation measurements often have lower precision

So, null CP violation measurements are particularly useful – any *significant* deviation from 0 is a potential signal of BSM

Null CP violation is the main topic of this talk
Example of possible NP contribution

New physics, if any, in suppressed processes, as flavor-mixing (or FCNC).

Effective field theory factorizes New Physics into a complex amplitude

$$\langle M | H_{\text{eff}}^{\text{full}} | \bar{M} \rangle = C_M e^{2i\phi_M}$$

$$C_{B_s} e^{2i\phi_{B_s}} = \frac{A_s^{\text{SM}} e^{-2i\beta_s} + A_s^{\text{NP}} e^{2i(\phi_{NP} - \beta_s)}}{A_s^{\text{SM}} e^{-2i\beta_s}} = \frac{\langle B_s | H_{\text{eff}}^{\text{full}} | \bar{B}_s \rangle}{\langle B_s | H_{\text{eff}}^{\text{SM}} | B_s \rangle},$$

Bottom line: to constrain NP need to measure magnitude and phase
CP violation in Standard Model

• Standard Model CP violation occurs through complex phases in the unitary CKM quark mixing matrix (3 real params + one phase)

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

• Expanded in \( \lambda = \sin(\theta_{\text{Cabibbo}}) \approx 0.23 \):

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

Highly suppressed CP violation \( \sim \lambda^5 \)

Large CP violation \( \sim \lambda^3 \)

Suppressed CP violation \( \sim \lambda^4 \)
CP violation in Standard Model (2)

$B_d$ unitarity triangle

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

\[ (0,0) \quad \alpha = \phi_2 \]

\[ (0,0) \quad \gamma = \phi_3 \]

\[ (1,0) \quad \beta = \phi_1 \]

All three angles large

$\Rightarrow \beta \equiv \text{arg} \left( -\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right) \sim 22^0$

$\Rightarrow \text{Acp} \text{ large}$

$B_s$ unitarity triangle

$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$

\[ (0,0) \quad \beta_s = \text{arg} \left( -\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*} \right) = \mathcal{O}(\lambda^2) \sim 1.1^0 \]

$\Rightarrow \text{Acp} \sim 0$
Current status – all measurements

Kaon physics and $B$ factories: satisfactory SM picture of CP violation - at least at tree level in $B^0$ and $B^+$ decays.

Using ‘tree’-only observables

Using ‘loop’-only observables
Current status – phases in mixing

$B^0$ mixing

$K^0$ mixing

$B^0_s$ mixing

Lattice-QCD dominated uncertainty

$$\frac{\langle M | H_{\text{eff}}^{\text{full}} | \bar{M} \rangle}{\langle M | H_{\text{eff}}^{\text{SM}} | \bar{M} \rangle} = C_M e^{2i\phi_M}$$

Experimentally-dominated uncertainty. This measurement is today’s topic
Tevatron + CDF = $b$-hadron factory

- Tevatron: $p\bar{p}$ collisions at 1.96 GeV/c²
- All species of $b$-hadrons produced! ($B^+, B^0, B_s, B_c, \Lambda_b, \Xi_b, \Sigma_b...$)
- performs really well: $\sim 3 \text{ fb}^{-1}$ data on tape
Relevant subsystems of CDF

- **muons (for B reconstruction) up to |\( \eta \)|<1 (high-\( \eta \) muons used for flavor tagging)**

- **central electrons used for B reco, soft electrons also used for flavor tagging**

- CDF has excellent tracking:
  - **\( d_0 \) resolution** (needed for B physics)
  - **\( p_T \) resolution** (needed to measure masses)
Reconstructing heavy hadrons

- b-quarks CDF can reconstruct are boosted sideways
- \( ct = L_{xy} \left( \frac{m}{p_T} \right) \)
- Decays of hadrons with b and c quarks can be observed with a **Silicon Detector**
Mining $b$'s from mountains of junk!

- Production rate of $b$-quarks is very large... but rate of (uninteresting) soft QCD is 1000x larger!

- $b$-physics program lives and dies by the “trigger system”
  - very fast electronics
  - examines events in real time
  - decides to keep some events e.g. those with
    - 2 muons
    - $e$ or $\mu + 1$ displaced track
    - 2 displaced tracks (fully hadronic!)

- *Silicon Vertex Trigger* (SVT) – part of trigger system that finds displaced tracks and triggers on heavy hadrons
CDF data used in these analyses

- 1.7 fb\(^{-1}\), untagged \(B_s \rightarrow J/\psi \phi\)
- 1.6 fb\(^{-1}\), CP asymmetry in semileptonic decays
- \(\sim 1.0\) fb\(^{-1}\), CP violation studies in displaced trigger data
- 1.3 fb\(^{-1}\), tagged \(B_s \rightarrow J/\psi \phi\)
Neutral $B_s$ System

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

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

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

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

where

$$q/p = \frac{V_{tb} V_{ts}^*}{V_{tb}^* V_{ts}}$$

mass eigenvalues are 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 $\Delta m_s = 17.77 \pm 0.12$ ps$^{-1}$
  DØ $\Delta m_s = 18.56 \pm 0.87$ ps$^{-1}$

- Mass eigenstates have different decay widths
  $\Delta \Gamma = \Gamma_L \quad \Gamma_H \approx 2|\Gamma_{12}| \cos(\Phi_s)$ \quad 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 occurs through interference of decay with and without mixing:

$$B^0 \rightarrow J/\Psi K^0_s$$
$$B^0 \rightarrow J/\Psi \phi$$

$$B_s^0 \rightarrow J/\Psi K^0_s$$
$$B_s^0 \rightarrow J/\Psi \phi$$

$\Rightarrow \sin(2\beta)$

$\Rightarrow \sin(2\beta_s)$

- $\beta_s$ in SM is predicted to be very small:

$$\beta_s^{SM} = \text{arg}(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) \approx 0.02$$

- New Physics affects the CP violation phase

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

- If NP phase $\phi_s^{NP}$ dominates

$$2\beta_s = -\phi_s^{NP}$$
**$B_s \rightarrow J/\psi\phi$ phenomenology**

- Extremely rich physics

- Can measure lifetime, decay width, and, using known $\Delta m_s$, CP violating phase $\beta_s$

- $B_s$ (spin 0) $\rightarrow J/\psi$(spin 1) $\phi$(spin 1) $\Rightarrow$
  
  3 different angular momentum final states:
  
  $L = 0$ (s-wave),  $L = 2$ (d-wave) $\rightarrow$ CP even
  
  $L = 1$ (p-wave) $\rightarrow$ CP odd

• Three angular momentum states form a basis for the final $J/\psi\phi$ state

• Use alternative “transversity basis” in which the vector meson polarizations w.r.t. direction of motion are either:
  
  - **longitudinal (0)** $\rightarrow$ CP even
  
  - **transverse** (|| parallel to each other) $\rightarrow$ CP even

  - **transverse** (⊥ perpendicular to each other) $\rightarrow$ CP odd
“Transversity” Basis

Two different reference frames

J/ψ at rest

Φ at rest

Decay amplitude decomposed (in terms of linear polarization) when J/ψ and Φ are

\( A_0 \): longitudinally polarized \hspace{1cm} \text{(CP-even)}

\( A_∥ \): transversely polarized and \( || \) to each other \hspace{1cm} \text{(CP-even)}

\( A_⊥ \): transversely polarized and \( \perp \) to each other \hspace{1cm} \text{(CP-odd)}

\[ \Rightarrow \text{3 angles describe directions of final decay products: } \rho = \rho(\cos \theta, \phi, \cos \psi) \]

“Strong” phases: \( \delta_⊥ = \arg[A⊥A_0] \), \( \delta_∥ = \arg[A∥A_0] \),
$B_s \rightarrow J/\psi \phi$ phenomenology

- Good approximation: $\phi_s \approx 0$
  
  $\Rightarrow$ mass eigenstates $|B_s^L\rangle$ and $|B_s^H\rangle$ are CP eigenstates

  $\Rightarrow$ use angular information to separate heavy and light states

  $\Rightarrow$ determine decay width difference
  
  $\Delta \Gamma = \Gamma_L - \Gamma_H$

  $\Rightarrow$ some sensitivity to CP violating phase $\beta_s$

- Determine $B_s$ flavor at production (flavor tagging)
  
  $\Rightarrow$ improve sensitivity to $\beta_s$

- Cross-check procedure for angular decomposition on $B^0 \rightarrow J/\psi K^{*0}$
  (~7800 events from 1.3 fb$^{-1}$)
Check amplitude decomposition on $B^0 \rightarrow J/\psi K^*$

- In agreement *(and competitive with)* the latest BaBar and Belle result: e.g., BaBar: PRD 76,031102 (2007)

\[
c \tau = 456 \pm 6 \text{ (stat)} \pm 6 \text{ (syst)} \text{ \mu m}
\]
\[
|A_0(0)|^2 = 0.569 \pm 0.009 \text{ (stat)} \pm 0.009 \text{ (syst)}
\]
\[
|A_\parallel(0)|^2 = 0.211 \pm 0.012 \text{ (stat)} \pm 0.006 \text{ (syst)}
\]
\[
\delta_\parallel = -2.96 \pm 0.08 \text{ (stat)} \pm 0.03 \text{ (syst)}
\]
\[
\delta_\perp = 2.97 \pm 0.06 \text{ (stat)} \pm 0.01 \text{ (syst)}
\]
\[
|A_0(0)|^2 = 0.556 \pm 0.009 \text{ (stat)} \pm 0.010 \text{ (syst)}
\]
\[
|A_\parallel(0)|^2 = 0.211 \pm 0.010 \text{ (stat)} \pm 0.006 \text{ (syst)}
\]
\[
\delta_\parallel = -2.93 \pm 0.08 \text{ (stat)} \pm 0.04 \text{ (syst)}
\]
\[
\delta_\perp = 2.91 \pm 0.05 \text{ (stat)} \pm 0.03 \text{ (syst)}
\]
Decay PDF for $B^0_s$ and $\bar{B}^0_s$

$B^0_s$ term

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

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

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

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

Anti-$B^0_s$

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

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

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

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

$A_0, A_\parallel, A_\perp$: transition amplitudes in a given polarization state at time 0

$f(\rho)$: angular distribution for a given polarization state
\[ I_\pm = e^{-\Gamma t} \times [\cosh(\Delta \Gamma t/2) \mp \cos(2\beta_s)\sinh(\Delta \Gamma t/2)] \]

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

\[ V_\pm = \pm e^{-\Gamma t} \times [\sin(\delta_\perp) \cos(\Delta m_s t) - \cos(\delta_\perp) \cos(2\beta_s) \sin(\Delta m_s t) \pm \cos(\delta_\perp) \sin(2\beta_s) \sinh(\Delta \Gamma t/2)] \]
Step #1: “untagged” $B_s \to J/\psi \phi$ analysis

- “Untagged” = No flavor tagging information

- Sum up $B_s^0$ and anti-$B_s^0$ PDF equally

- Many terms cancel

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

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

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

- Suited for precise measurement of $\Delta \Gamma$ and $\tau$

- Still sensitive to $\beta_s$
$B_s \rightarrow J/\psi\phi$ sample for untagged analysis

- ~ 2500 signal events in 1.7 fb-1
- Assume no CP violation ($i.e. \beta_s = 0$)
- Most precise measurement of the $B_s$ lifetime to date
- Confirms $\tau_s \sim \tau_d$

$\tau_s = 1.52 \pm 0.04 \text{ (stat)} \pm 0.02 \text{ (syst) ps}$
$B_s \rightarrow J/\psi \phi$ untagged: angle projections

- Comb. bkg is high = this is whole mass region
- Completely pinned down by data from sidebands
- (Sideband-subtracted data agree well with signal PDF)
$\Delta \Gamma_s$ ($B_s$ decay width)

- CP-even ($\approx B_s^{\text{light}}$) and CP-odd ($\approx B_s^{\text{heavy}}$) components have different lifetimes $\rightarrow \Delta \Gamma \neq 0$

- In agreement and 30-50% better than previous best measurements (DØ, 2007) and 2x better than PDG

| $|A_0(0)|^2$ | $0.531 \pm 0.020 \text{ (stat)} \pm 0.007 \text{ (syst)}$ |
| $|A_\parallel(0)|^2$ | $0.230 \pm 0.026 \text{ (stat)} \pm 0.009 \text{ (syst)}$ |
| $|A_\perp(0)|^2$ | $0.239 \pm 0.029 \text{ (stat)} \pm 0.011 \text{ (syst)}$ |

$\Delta \Gamma = 0.08 +/- 0.06 \text{ (stat)} +/- 0.01 \text{ (syst)} \text{ ps}^{-1}$
\( B_s \rightarrow J/\psi \phi \) untagged: floating \( \beta_s \)

Even without tagging, have some sensitivity to \( \beta_s \)

But, there are biases seen in pseudo experiments

Reasons:

- Loss of degrees of freedom: e.g. when \( \Delta \Gamma \rightarrow 0 \), \( \delta_{\perp} \) is undetermined, no sensitivity to \( \beta_s \) at all: \( \cos(\delta_{\perp}) \sin(2/\beta_s) \sinh(\Delta \Gamma t/2) \]

- 4-fold ambiguity existed in likelihood function (=> there are 4 equivalent minima!)

\[
\begin{align*}
2\beta_s &\rightarrow -2\beta_s, \quad \delta_{\perp} \rightarrow \delta_{\perp} + \pi \\
\Delta \Gamma &\rightarrow -\Delta \Gamma, \quad 2\beta_s \rightarrow 2\beta_s + \pi
\end{align*}
\]
Use Likelihood-Ratio ordering (Feldman-Cousins) to determine Confidence Region in $\beta_s - \Delta \Gamma$ space.

Under assumption of SM, the probability of data fluctuating to our observation or better is 22% or 1.2$\sigma$. 
Step #2: add flavor tagging

- Flavor tagging produces
  - tag decision
  - this tag's *predicted* dilution (*i.e.* = 1-2w)

- Opposite Side Tagging (OST) calibrated on $B^+$

- Same Side (Kaon) Tagging calibrated on MC (but checked on mixing measurement)

**OST efficiency** 96 +/- 1%
**OST dilution**: 11 +/- 2%

**SST efficiency** 50 +/- 1%
**SST dilution** 27 +/- 4%

**Total $\varepsilon D^2 \sim 4.5\%$**
Study effect of tagging in Toy MC

- PDF predicts better sensitivity to $\beta_s$ but still with 2 minima due to symmetry:

\[
\begin{align*}
2\beta_s &\rightarrow \pi - 2\beta_s \\
\Delta \Gamma &\rightarrow -\Delta \Gamma \\
\delta_\parallel &\rightarrow 2\pi - \delta_\parallel \\
\delta_\perp &\rightarrow \pi - \delta_\perp
\end{align*}
\]

- Improvement of parameter resolution is small due to limited tagging power ($\varepsilon D^2 \sim 4.5\%$ vs $\sim 30\%$ at BaBar/Belle)

- 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!

2$\Delta \log(L) = 2.3 \approx 68\%$ CL

2$\Delta \log(L) = 6.0 \approx 95\%$ CL
Tagged $B_s \rightarrow J/\psi\phi$ analysis

- First tagged analysis of $B_s \rightarrow J/\psi\phi$ (1.4 fb$^{-1}$)
- Signal $B_s$ yield $\sim$2000 events with S/B $\sim$ 1

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

strong phases can separate the two minima

\[
\cos(\delta_\perp) > 0 \quad \cos(\delta_\perp - \delta_\parallel) < 0
\]
Tagged $B_s \rightarrow J/\psi\phi$ analysis

• As in untagged: irregular likelihood doesn't allow quoting point estimate
• Quote Feldman-Cousins confidence regions (including systematics!)

- Confidence regions are under estimated when using $2\Delta \log L = 2.3$ (6.0) to approximate 68% (95%) C.L. regions
\[ \beta_s \text{ with external constraints} \]

- Spectator model: \( B_s \) and \( B^0 \) have similar lifetimes and strong phases
- Likelihood profiles with external constraints from \( B \) factories:

constrain strong phases to \( B^0 \):

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

constrain lifetime and strong phases:

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

- External constraints on strong phases remove residual 2-fold ambiguity
$\beta_s$: 1-Dimensional Feldman-Cousins results

- 1D Feldman-Cousins procedure without external constraints:
  $2\beta_s$ in $[0.32, 2.82]$ at the 68% C.L.

- 1D Feldman-Cousins with external constraints on strong phases, lifetime and $|\Gamma_{12}| = 0.048 \pm 0.018$ ps$^{-1}$:
  $2\beta_s$ in $[0.40, 1.20]$ at 68% C.L.
Impact of the tagged $\beta_s$ analysis

2D result from Feldman-Cousins

1D result from Feldman Cousins
CP asymmetry in semileptonic Bs decays

- Alternative approach to $\phi_s$ ($\beta_s$): an *inclusive* measurement

- Semileptonic CP asymmetry related to

$$\phi_s^{SM} = \arg(-\frac{M_{12}}{\Gamma_{12}})$$

$$A_{SL}^{s,unt} = \frac{1}{2} \frac{\Delta \Gamma_s}{\Delta m_s} \tan \phi_s$$

- It could be combined with $2\beta_s - \Delta \Gamma$ measurement from $B_s \to J/\psi \phi$ but CDF hasn't done so yet.

- We measure it by counting the number of $++$ and $--$ muon pairs:

$$A_{corr} = \frac{N_{++}^{obs} \left( \frac{1}{\epsilon_+^2} \right) - N_{--}^{obs} \left( \frac{1}{\epsilon_-^2} \right)}{N_{++}^{obs} \left( \frac{1}{\epsilon_+^2} \right) + N_{--}^{obs} \left( \frac{1}{\epsilon_-^2} \right)} = \frac{N_{++}^{obs} - N_{--}^{obs} \left( \frac{\epsilon_+}{\epsilon_-} \right)^2}{N_{++}^{obs} + N_{--}^{obs} \left( \frac{\epsilon_+}{\epsilon_-} \right)^2}$$
CP asymmetry in semileptonic $B_s$ decays

- dedicated di-$\mu$ trigger (high mass)
  - 660k opposite sign
  - 440k same sign dimuon pairs
- use $d_0$ of two muons to separate
  - di-$\mu$ from BB pair
  - charm (CC)
  - prompt (PP)
  - $B^+$prompt (BP)
- correct for
  - hadrons faking muons
  - detector and trigger asymmetries
  - Neglect $A_{CP}$ from $B^+$ and $\Lambda_b$
  - Correct for $A_{SL}^d$ from B factories:

$$A_{SL}^s = 0.020 \pm 0.021(stat) \pm 0.016(syst) \pm 0.009(inputs)$$
D0 result and new UTfit preprint

\[ \phi_s = -0.57^{+0.24}_{-0.30} \text{(stat)} +^{0.07}_{-0.02} \text{(syst)} \]

\[ \Delta \Gamma = +0.19 \pm 0.07 \text{(stat)} +^{0.02}_{-0.01} \text{(syst)} \text{ ps}^{-1} \]

With constraint from HFAG:
\[ \delta_1 = -0.46, \delta_2 = 2.92 \]
Constraint within \( \pi/5 \)

From UTfit 3\( \sigma \) ???:


**FIRST EVIDENCE OF NEW PHYSICS IN \( b \to s \) TRANSITIONS**

(UTfit Collaboration)

We combine all the available experimental information on \( B_s \) mixing, including the very recent tagged analyses of \( B_s \to J/\psi \phi \) by the CDF and D\( \phi \) collaborations. We find that the phase of the \( B_s \) mixing amplitude deviates more than 3\( \sigma \) from the Standard Model prediction. While no single measurement has a 3\( \sigma \) significance yet, all the constraints show a remarkable agreement with the combined result. This is a first evidence of physics beyond the Standard Model. This result disfavours New Physics models with Minimal Flavour Violation with the same significance.

3/18/2008, RPM at LBL
Composition of $B \rightarrow h^+ h'^-$

- Bump a mixture of:
  - $B_d \rightarrow K\pi$
  - $B_d \rightarrow \pi\pi$
  - $B_s \rightarrow KK$
  - $B_s \rightarrow K\pi$

- Need to optimize & disentangle

- Using $dE/dx$
  - Effective $K/\pi$ separation of $dE/dx \sim 1.4 \sigma$

⇒ Separate contributions on a statistical basis

CDF Run II Preliminary $L_{int} = 1 \text{ fb}^{-1}$

$(\pi^+\pi^- \text{ hypothesis})$

(trigger only selection)
Tools to decompose $B \rightarrow h^+ h'^-$

- Multi-dimensional unbinned likelihood fit
- $m(\pi\pi) +$ a quantity related to $dE/dx$
- Kinematics for two other dimensions:
  - $p_{tot} = p_1 + p_2$
  - Momentum imbalance $\alpha$ (assuming $p_1 < p_2$)
    
    
    $\alpha = \left(1 - \frac{p_1}{p_2}\right) \cdot q_1$

Mixes charge and kinematics

$\Rightarrow$ Can separate matter from antimatter!
$B \rightarrow h^+ h'^-$: old projections (as example)

- Can clearly separate these decay modes
  (But, these are *old* plots, story gets more complicated)

- A stubborn bump that doesn't go away when we blind the signal region and optimize using sidebands... ???
\[ B \rightarrow h^+ h'^- : \text{modern approach} \]

- Solution: also include \( \Lambda_b \rightarrow p\pi \) and \( \Lambda_b \rightarrow pK \) in the fit!

- Optimize twice:
  - once for \( B_s \rightarrow K\pi \)
  - separately for \( \Lambda_b \rightarrow p\pi \) and \( \Lambda_b \rightarrow pK \)

- Fit result: first observation of all three channels!

- Moral: no safe place to hide from the signal! (Just like SUSY @ LHC.)
BR's and Acp in $B_{s(d)} \rightarrow K^\pm \pi^\mp$ (in 1 fb$^{-1}$)

- $B_s \rightarrow K^\pm \pi^\mp$ mode can be used for measuring $\gamma$
- $A_{CP}$ in $B_s \rightarrow K^\pm \pi^\mp$ could provide a powerful model-independent test of the source of direct CP asymmetry observed in $B^0 \rightarrow K^\pm \pi^\mp$
- We see a $> 2\sigma$ effect:

$$A_{CP} = \frac{N(B_s^0 \rightarrow K^+\pi^-) - N(B_s^0 \rightarrow K^-\pi^+)}{N(B_s^0 \rightarrow K^+\pi^-) + N(B_s^0 \rightarrow K^-\pi^+)} = 0.39 \pm 0.15 \, (stat.) \pm 0.08 \, (syst.)$$

- CP asymmetry in $B^0 \rightarrow K^\pm \pi^\mp$ (improves world average from 6$\sigma$ to 7$\sigma$; and this is only 1/3 of the data...)

$$A_{CP} = \frac{N(B^0 \rightarrow K^-\pi^+) - N(B^0 \rightarrow K^+\pi^-)}{N(B^0 \rightarrow K^-\pi^+) + N(B^0 \rightarrow K^+\pi^-)} = -0.086 \pm 0.023 \, (stat.) \pm 0.009 \, (syst.)$$
BR's and Acp in $\Lambda_b \rightarrow p\pi(K)$ (in 1 fb$^{-1}$)

- Results:

  $$A_{CP}(\Lambda_b^0 \rightarrow p\pi^-) = \frac{B(\Lambda_b^0 \rightarrow p\pi^-) - B(\Lambda_b^0 \rightarrow \bar{p}\pi^+)}{B(\Lambda_b^0 \rightarrow p\pi^-) + B(\Lambda_b^0 \rightarrow \bar{p}\pi^+)} = 0.03 \pm 0.17 \text{ (stat.)} \pm 0.05 \text{ (syst.)}$$

  $$A_{CP}(\Lambda_b^0 \rightarrow pK^-) = \frac{B(\Lambda_b^0 \rightarrow pK^-) - B(\Lambda_b^0 \rightarrow \bar{p}K^+)}{B(\Lambda_b^0 \rightarrow pK^-) + B(\Lambda_b^0 \rightarrow \bar{p}K^+)} = 0.37 \pm 0.17 \text{ (stat.)} \pm 0.03 \text{ (syst.)}$$

- First CP asymmetry meas. in b-baryon decays (expect SM ~ 10%)

- Additionally, first measurement of branching fraction relative to $B^0 \rightarrow K\pi$ decays:

  $$\frac{\sigma(p\bar{p} \rightarrow \Lambda_b^0 X, p_T > 6 \text{ GeV}/c)}{\sigma(p\bar{p} \rightarrow B^0 X, p_T > 6 \text{ GeV}/c)} \cdot \frac{B(\Lambda_b^0 \rightarrow p\pi^-)}{B(B^0 \rightarrow K^+\pi^-)} = 0.0415 \pm 0.0074 \text{ (stat.)} \pm 0.0058 \text{ (syst.)}$$

  $$\frac{\sigma(p\bar{p} \rightarrow \Lambda_b^0 X, p_T > 6 \text{ GeV}/c)}{\sigma(p\bar{p} \rightarrow B^0 X, p_T > 6 \text{ GeV}/c)} \cdot \frac{B(\Lambda_b^0 \rightarrow pK^-)}{B(B^0 \rightarrow K^+\pi^-)} = 0.0663 \pm 0.0089 \text{ (stat.)} \pm 0.0084 \text{ (syst.)}$$
**BR's and Acp in $B^+ \rightarrow D^0 K^+$**

- Measures quantities relevant for determination of the CKM angle $\gamma$

$$ar g(-V_{ud} V_{ub}^*/V_{cd} V_{cb}^*)$$ by measuring $A^+_{CP}$, $A^-_{CP}$, $R^+_{CP}$ and $R^-_{CP}$

$$A_{CP+} = \frac{BR(B^- \rightarrow D_{CP+}^0 K^-) - BR(B^+ \rightarrow D_{CP+}^0 K^+)}{BR(B^- \rightarrow D_{CP+}^0 K^-) + BR(B^+ \rightarrow D_{CP+}^0 K^+)}$$

$$R_{CP+} = \frac{R_+}{R}$$

where:

$$R = \frac{BR(B^- \rightarrow D^0 K^-) + BR(B^+ \rightarrow \overline{D}^0 K^+)}{BR(B^- \rightarrow D_{CP+}^0 K^-) + BR(B^+ \rightarrow D_{CP+}^0 K^+)}$$

**CP even eigenstate:**

- $D_{CP+}^0 \rightarrow K^+ K^-$
- $D_{CP+}^0 \rightarrow \pi^+ \pi^-$

**Flavor eigenstate:**

- $D^0 \rightarrow K^- \pi^+$

**Signal yield:**

- $B^- \rightarrow D^0 \pi^-$: $\sim 8000$
- $D^0 \rightarrow K^- \pi^+$: $\sim 1100$
- $D_{CP+}^0 \rightarrow K^+ K^-$: $\sim 250$
BR's and Acp in $B^+ \rightarrow D^0 K^+$

- Apply the same trick to $B^+ \rightarrow D^0 \pi^+$ and $B^+ \rightarrow D^0 K^+$ decays

- $\alpha$ distribution stops being symmetric ($D$ is much heavier)

- But, the same approach works here as well!
BR's and Acp in $B^+ \rightarrow D^0 K^+$

- Results:
  - ratio of branching fractions:
    \[
    R = \frac{BR(B^- \rightarrow D^0 K^-) + BR(B^+ \rightarrow D^0 K^+)}{BR(B^- \rightarrow D^0 \pi^-) + BR(B^+ \rightarrow D^0 \pi^+)} = 0.0745 \pm 0.0043 \text{(stat.)} \pm 0.0045 \text{(syst.)}
    \]
    \[
    R_{CP^+} = \frac{BR(B^- \rightarrow D_{CP^+}^0 K^-) + BR(B^+ \rightarrow D_{CP^+}^0 K^+)}{[BR(B^- \rightarrow D^0 K^-) + BR(B^+ \rightarrow D^0 K^+)]/2} = 1.57 \pm 0.24 \text{(stat.)} \pm 0.12 \text{(syst.)}
    \]

- direct CP asymmetry:
  \[
  A_{CP^+} = \frac{BR(B^- \rightarrow D_{CP^+}^0 K^-) - BR(B^+ \rightarrow D_{CP^+}^0 K^+)}{BR(B^- \rightarrow D_{CP^+}^0 K^-) + BR(B^+ \rightarrow D_{CP^+}^0 K^+)} = 0.37 \pm 0.14 \text{(stat.)} \pm 0.04 \text{(syst.)}
  \]

Quantities measured for the first time at hadron colliders

Results in agreement and competitive with B factories

3/18/2008, RPM at LBL
Conclusions

- Very rich B physics program at Tevatron and CDF
  - Competitive with but also *complementary* to BaBar and Belle
  - Excluded a large domain of $\beta_s < 0$

- Great Tevatron performance
  - keep accumulating data
  - keep updating analyses
    - work hard to update of $B_s \rightarrow J/\psi\phi$ for the summer
    - properly combine likelihoods with D0
  - expect 6 fb-1 by the end of Run2

- This is an exciting time to work on CP violation and search for new phenomena in $B$ decays!

3/18/2008, RPM at LBL

Petar Maksimovic, JHU
Backup Slides
Rare decays

- With 2.0 fb^{-1}, best limit in:

\[
\mathcal{B}(B^+_s \rightarrow \mu^+\mu^-) < 5.8 \times 10^{-8} \quad (4.7 \times 10^{-8}) \\
\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 1.8 \times 10^{-8} \quad (1.5 \times 10^{-8})
\]

at 95(90)%CL

arXiv:0712.1708

- 0.9 fb-1

\[
\begin{align*}
\mathcal{B}(B^+ \rightarrow \mu^+\mu^-K^+) &= (0.60 \pm 0.15 \pm 0.04) \times 10^{-6}, \\
\mathcal{B}(B^0 \rightarrow \mu^+\mu^-K^0) &= (0.82 \pm 0.31 \pm 0.10) \times 10^{-6}
\end{align*}
\]

consistent with world average and competitive with best measurements

\[
\mathcal{B}(B_s \rightarrow \mu^+\mu^-\phi)/\mathcal{B}(B_s \rightarrow J/\psi\phi) < 2.61(2.30) \times 10^{-3} \text{ at 95(90)%CL}
\]

best limit

http://www-cdf.fnal.gov/physics/new/bottom/061130.blessed_bmumuh/

- First observation of \( \overline{B}_s^0 \rightarrow D_s^{\pm} K^{\mp} \) in 1.2 fb^{-1}

109 +/- 9 signal events with ~8 sigma significance

Measure branching fraction relative to Cabibbo allowed mode:

\[
\mathcal{B}(\overline{B}_s^0 \rightarrow D_s^{\pm} K^{\mp})/\mathcal{B}(\overline{B}_s^0 \rightarrow D_s^{\pm} \pi^-) = 0.107 \pm 0.019\text{(stat)} \pm 0.008\text{(sys)}
\]

http://www-cdf.fnal.gov/physics/new/bottom/070524.blessed-Bs-DsK/
- Triggers designed to select events with topologies consistent with B decays:

  - single lepton ( + displaced track) (semileptonic decays) ← DØ (CDF)

    ![Diagram of single lepton trigger]

  - di-lepton (B → J/Ψ, B → μμ, B → μμ + hadrom) ← both CDF and DØ

    ![Diagram of di-lepton trigger]

  - displaced tracks (hadronic decays) ← CDF

    ![Diagram of displaced track trigger]
Flavor tagging refresher

- Flavor asymmetry (from B mixing)

\[ A(t) \equiv \frac{N_{\text{unmix}} - N_{\text{mix}}}{N_{\text{unmix}} + N_{\text{mix}}} = D \cos \Delta m_s t \]

- To measure mixing:
  - Flavor at production (via “flavor tagging”)
  - Flavor at decay

- Flavor tagging characterized by:
  - efficiency \( \varepsilon \) and dilution \( D \) (\( = 1 - 2w \))
  - Statistical power \( \sim \varepsilon D^2 \)
Effect of Dilution asymmetry on $\beta_s$

- Effect of 20\% b-bbar dilution asymmetry is very small
**$B_s \rightarrow J/\Psi\Phi$ phenomenology**

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

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

where:

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

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

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

**Time dependence terms**

**Angular dependence terms**

**Terms with $\beta_s$ dependence**

**Terms with $\Delta m_s$ dependence due to initial state flavor tagging**

- ‘Strong’ phases:
  - $\delta_\parallel \equiv \arg(A_\parallel^* A_0)$
  - $\delta_\perp \equiv \arg(A_\perp^* A_0)$

- Tagging → better sensitivity to $\beta_s$
Systematics

Red curve:
regular likelihood profile: $\chi^2(2)$

Black histogram:
average LR distribution from FC

Dashed histograms:
16 Variations of 27 nuisance parameter within $5\sigma$ with FC

Perfect likelihood
FC profile
FC profile with systematics

3/18/2008, RPM at LBL
D⁰ Mixing

- After recent observation of fastest neutral meson oscillations in B_s system by CDF and DØ → time to look at the slowest oscillation of D⁰ mesons 😊

- D⁰ mixing in SM occurs through either:

  ‚short range’ processes (negligible in SM)

  ‘long range’ processes

<table>
<thead>
<tr>
<th></th>
<th>ΔM/Γ</th>
<th>ΔΓ/Γ</th>
</tr>
</thead>
<tbody>
<tr>
<td>K⁰</td>
<td>0.474</td>
<td>0.997</td>
</tr>
<tr>
<td>B⁰</td>
<td>0.77</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>B_s</td>
<td>27</td>
<td>0.15</td>
</tr>
<tr>
<td>D⁰</td>
<td>&lt; few%</td>
<td>&lt; few%</td>
</tr>
</tbody>
</table>

- Recent D⁰ mixing evidence ← different D⁰ decay time distributions in

  **Belle**
  \[D^0 \rightarrow \pi\pi, \, KK \text{ (CP eigenstates)}\]
  compared to \[D^0 \rightarrow K\pi\]

  **BaBar**
  doubly Cabibbo suppressed (DCS) \[D^0 \rightarrow K^+\pi^-\]
  compared to Cabibbo favored (CF) \[D^0 \rightarrow K^-\pi^+\]

(Belle does not see evidence in this mode)
Evidence for D⁰ Mixing

- CDF sees evidence for D⁰ mixing at 3.8σ significance by comparing DCS D⁰ → K⁺π⁻ decay time distribution to CF D⁰ → K⁻π⁺ (confirms BaBar).

- Ratio of decay time distributions:

\[ R(t/\tau) = R_D + \sqrt{R_{DY}} y'(t/\tau) + \frac{x'^2 + y'^2}{4} (t/\tau)^2 \]

where \( x' = x \cos \delta + y \sin \delta \) and \( y' = -x \sin \delta + y \cos \delta \)

\( \delta \) is strong phase between DCS and CF amplitudes. Mixing parameters \( x = \Delta M/\Gamma \) and \( y = \Delta \Gamma/2\Gamma \) are 0 in absence of mixing.