\(B_s\) mixing measurements at the Tevatron

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Representing the DØ and CDF collaborations
\[ i \frac{\partial}{\partial t} \left| \frac{M(t)}{\bar{M}(t)} \right\rangle = \begin{pmatrix} m_{11} - i \frac{\Gamma_{11}}{2} & m_{12} e^{-i\phi} - i \frac{\Gamma_{12}}{2} \\ m_{21} e^{i\phi} - i \frac{\Gamma_{21}}{2} & m_{11} - i \frac{\Gamma_{11}}{2} \end{pmatrix} \left| \frac{M(t)}{\bar{M}(t)} \right\rangle \]

- \( m_{12} \) stems from the real part of this box diagram, dominated by top
- \( \Gamma_{12} \) stems from the imaginary part, dominated by charm
- Heavy and light CP eigenstates are expected to have different widths
- New particles in the box can have large effects
  - Important test of CKM formalism
  - possible new sources of CP violation (needed to explain matter dominance)

\[ \Delta m = m_H - m_L = 2|m_{12}| \]
\[ \Delta \Gamma = \Gamma_L - \Gamma_H = 2|\Gamma_{12}| \cos \phi \]
\[ \phi = \arg \left( -\frac{m_{12}}{\Gamma_{12}} \right) \]
\[ \bar{\Gamma} = \frac{1}{\bar{t}} = \frac{1}{2} \left( \Gamma_L + \Gamma_H \right) \]
\[ \Delta \Gamma_{CP} = \Gamma_{even} - \Gamma_{odd} = 2|\Gamma_{12}| \]
The Fermilab Tevatron

\[ \sqrt{s} = 1.96 \text{ TeV} \]
\[ \Delta t = 396 \text{ ns} \]
Over 2 fb\(^{-1}\) of collisions have been delivered to the experiments in Run II

- Analysis presented today use 1 fb\(^{-1}\)
The CDF Run II Detector

- Strong central tracking
- Excellent silicon vertex detector
- Good lepton ID
- Particle ID (TOF and dE/dx)
- Excellent mass resolution
- Level 1 displaced track trigger
The DØ Run II Detector

- Silicon vertex detector
  - $|\eta| < 3.0$
- Central fiber tracker and pre-shower detectors
  - $|\eta| < 1.6$
- 2 T solenoid magnet
- New low pT central muon trigger scintillators
- New forward $\mu$ system
  - Excellent muon purity and coverage: $|\eta| < 2.0$
- Second level displaced track trigger, NN B tagging at 3rd level
- reconstruct $B_s$ decays, decay flavor from decay products
- measure proper time of the decay (very precisely)
- infer $B_s$ production flavor (flavor tagging)
- fit unmixed - mixed asymmetry as a function of proper time
asured asymmetry

- Asymmetry is degraded by:
  - flavor tagging dilution
  - decay length resolution
  - momentum resolution

\[
\frac{1}{\sigma_A} = \sqrt{\frac{n_S \varepsilon D^2}{2}} \sqrt{\frac{n_S}{n_S + n_B}} \exp\left(-\frac{(\Delta m \sigma_{ct})^2}{2}\right)
\]

\[
\sigma_{ct} = \sqrt{\left(\sigma_{ct}^0\right)^2 + \left(ct \frac{\sigma_p}{p}\right)^2}
\]
At Moriond 2006, D0 presents the first two sided limit on dms
- Consistent with SM/CKM

CDF soon confirms results

And now has made a precision measurement with the same data set
Impact on the Unitarity Triangle

\[ \sin 2\beta \]

\[ |V_{ub}/V_{cb}| \]

\[ \varepsilon_K \]

\[ \Delta m_d \]

\[ \Delta m_s & \Delta m_d \]

\[ \alpha \]

\[ \beta \]

\[ \gamma \]

sol. w/ \cos 2\beta < 0
(excl. at CL > 0.95)

\[ \rho \]

CKM
Filter
EPS 2005
Improvements to the CDF analysis

- **Flavor tagging**
  - added opposite side kaon tag
  - use Neural Net to combine all opposite side taggers
  - use NN for same side tag

- **Increased signal yield**
  - added partially reconstructed decays
  - use particle ID in the selection
  - use NN selection for hadronic modes
  - loosen kinematic selection

- **Increased the effective statistics by a factor of 2.5!**
Neural Network selection performance

CDF Run II Preliminary

L = 1.0 fb⁻¹

Neural Network

Cut Based

Neural Network, but not Cut Based

Cut Based, but not Neural Network

candidates per 20.0 MeV/c² candidates per 20.0 MeV/c²

candidate mass [GeV/c²] candidate mass [GeV/c²]
Bs hadronic decay signals

- Use decays with lost $\gamma$ or $\pi^0$ in golden mode $D_s(\phi\pi)\pi$ ($\Delta p/p \sim 2\%$)
- Improve selection with PID D and NN

<table>
<thead>
<tr>
<th>$B_s$ decay</th>
<th>Signal</th>
<th>April 06</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_s(\phi\pi)\pi$</td>
<td>2000</td>
<td>1600</td>
</tr>
<tr>
<td>Partially rec.</td>
<td>3100</td>
<td>—</td>
</tr>
<tr>
<td>$D_s(K^*K)\pi$</td>
<td>1400</td>
<td>800</td>
</tr>
<tr>
<td>$D_s(3\pi)\pi$</td>
<td>700</td>
<td>600</td>
</tr>
<tr>
<td>$D_s(\phi\pi)3\pi$</td>
<td>700</td>
<td>500</td>
</tr>
<tr>
<td>$D_s(K^*K)3\pi$</td>
<td>600</td>
<td>200</td>
</tr>
<tr>
<td>$D_s(3\pi)3\pi$</td>
<td>200</td>
<td>—</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>8700</strong></td>
<td><strong>3600</strong></td>
</tr>
</tbody>
</table>
Neural Network same side kaon tag

- particle ID
- $\Delta R$
- $p_T$
- $p_L^{\text{rel}}$
- $p_T^{\text{rel}}$

Also use NN to improve opposite side tags
Amplitude Scan

CDF Run II Preliminary

$A/\sigma_A = 6.1$

Sensitivity $31.3 \text{ ps}^{-1}$

$A(\Delta m_s = 17.75) = 1.21 \pm 0.20$

Hadronic & semileptonic decays combined
Measurement of $\Delta m_s$

Hypothesis of $A=1$ compared to $A=0$

\[ \Delta m_s = 17.77 \pm 0.10 \text{ (stat.)} \pm 0.07 \text{ (syst.)} \text{ ps}^{-1} \]
\[ \frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2} \]

- inputs:
  - \( m(B^0)/m(B_s) = 0.9830 \) (PDG 2006)
  - \( \xi = 1.21^{+0.047}_{-0.035} \) (M. Okamoto, hep-lat/0510113)
  - \( \Delta m_d = 0.507 \pm 0.005 \) (PDG 2006)

\[ |V_{td}| / |V_{ts}| = 0.208^{+0.008}_{-0.007} \text{ (stat + syst)} \]
Search for CPV with part per mil precision by looking for asymmetry in like-sign dimuons and exclusive (untagged) Bs-Dsm events

\[
\frac{N(\mu^+ \mu^+) - N(\mu^- \mu^-)}{N(\mu^+ \mu^+) + N(\mu^- \mu^-)} = A_{SL} (\text{tagged}) = 2A_{SL} (\text{untagged})
\]

\[
\frac{N(D_s \mu^+) - N(D_s \mu^-)}{N(D_s \mu^+) + N(D_s \mu^-)} = A_{SL} (\text{untagged}) \approx \frac{\Delta \Gamma}{\Delta m} \tan \phi
\]
Detector Asymmetries

- Detector asymmetries on the order of a few % are present due to geometry of the muon system.

Cancel to first order by alternating the muon and inner tracker magnet polarities.
Dimuon sample composition

signal

backgrounds which dilute the asymmetry

Reaction $K^- N \rightarrow Y \pi$ ($Y = \Lambda, \Sigma...$) has no $K^+N$ analog

Measured in data using kaons from semileptonic decays

Cross-check:

$\chi(D0) = 0.136 \pm 0.001 \pm 0.024$

$\chi(PDG) = 0.1281 \pm 0.0076$
Dimuon asymmetry

$A_{SL} = \frac{f_s Z_s}{f_d Z_d} A_{SL}(B_s)$

$\sim 60/40$ mix of $B_d$ and $B_s$

$A_{SL} = -0.0092 \pm 0.0044 \pm 0.0032$

PRD 74, 092001 (2006)

$Z \sim 2\chi$

$A_{SL}(B_d)$ from B-factories:

$A_{SL}(B_d) = -0.0047 \pm 0.0046$ (HFAG)

$A_{SL}(B_s, \mu\mu) = -0.0064 \pm 0.0101$
Exclusive $D_s \mu$

$A_{SL}(B_s, D_s \mu) = 0.0245 \pm 0.0193 \pm 0.0035$

hep-ex/0701007 submitted to PRL

Combined:

$A_{SL}(B_s, \mu\mu + D_s \mu) = 0.0001 \pm 0.0090$

Using $\Delta m_s$ from CDF:

$\Delta \Gamma_s \cdot \tan \phi_s = 0.02 \pm 0.16 \text{ ps}^{-1}$
Relation of matrix elements to decay and oscillation parameters:

\[
\begin{align*}
\Delta m &= M_H - M_L \approx 2|M_{12}| \\
\Delta \Gamma &= \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}| \cos \phi \\
\phi &= \arg \left(- \frac{M_{12}}{\Gamma_{12}} \right)
\end{align*}
\]

In the Standard Model:

- The CP violating phase, \( \phi \), is expected to be small.
- Mass eigenstates are \( \sim \) CP eigenstates with definite lifetimes.

The \( J/\psi \phi \) final state is a mixture of CP states:

- \( L=0, 2; \) CP even; \( (A_0, A_||) \)
- \( L=1; \) CP odd; \( (A_\perp) \)
- We allow, however, CP cons. And CPV interference terms.

measure two \( B_s \) lifetimes, \( \tau_L \) and \( \tau_H \), (or \( \Delta \Gamma/\Gamma \) and \( \tau \)), and \( \phi \) by simultaneously fitting time evolution and angular distribution in untagged \( B_s \to J/\psi \phi \) decays.
Reconstructed $B_s \rightarrow J/\psi \phi$
$$\theta = \text{transversity}$$

$$\frac{d^3 \Gamma \rightarrow J/\psi(\rightarrow 1^+)}{d \cos \theta \, d \phi \, d \cos \psi \, dt} \propto \frac{9}{16\pi} \left[ 2|A_0(0)|^2 \, e^{-t \Delta t} \cos^2 \psi (1 - \sin^2 \theta \cos^2 \phi) + \sin^2 \psi \left\{ |A_{\parallel}(0)|^2 \, e^{-t \Delta t} (1 - \sin^2 \theta \sin^2 \phi) + |A_{\perp}(0)|^2 \, e^{-t \Delta t} \sin^2 \theta \right\} + \frac{1}{\sqrt{2}} \sin 2 \psi \left\{ |A_0(0)||A_{\perp}(0)| \cos (\delta_2 - \delta_1) e^{-t \Delta t} \sin^2 \theta \sin^2 \phi \right\} + \frac{1}{\sqrt{2}} \left\{ |A_0(0)||A_{\perp}(0)| \cos \delta_2 \sin 2 \psi \sin 2 \theta \cos \phi \right\} \frac{1}{2} \left\{ e^{-t \Delta t} \cdot e^{-t \Delta t} \right\} \delta \phi - \frac{1}{\sqrt{2}} \left\{ |A_0(0)||A_{\perp}(0)| \cos \delta_1 \sin 2 \psi \sin 2 \theta \sin \phi \right\} \frac{1}{2} \left\{ e^{-t \Delta t} \cdot e^{-t \Delta t} \right\} \delta \phi \right] H(\cos \psi) F(\phi) G(\cos \theta)$$
\[ \Delta \Gamma_s = 0.17 \pm 0.09 \pm 0.02 \text{ ps}^{-1} \]

\[ \phi_s = -0.79 \pm 0.56^{+0.14}_{-0.01} \]
ΔΓₚ Results

Flavour Specific WA Lifetime

DØ, 1.1 fb⁻¹

Bₛ⁰ → J/ψ φ

★ Constrained

△Γₛ (1/ps)

τₛ (ps)
Combined results

\[ \Delta \Gamma_s = 0.13 \pm 0.09 \, \text{ps}^{-1} \]

\[ \phi_s = -0.70^{+0.47}_{-0.39} \]
Conclusions

- We now have measurements of all the $B_s$ mixing parameters from the Tevatron
  - $\Delta m_s$ consistent with SM/CKM
    - precision measurement of $V_{td}/V_{ts}$
  - $\Delta \Gamma_s$ also consistent with SM
  - CPV phase $\phi_S$ still has room for new physics

- Expect many more improvements to come
  - Lots more data (already a factor of two)
  - More decay modes and new techniques
    - e.g. flavor tagged $J/\psi+\phi$ analysis
Separate amplitude scans

$$D_s(\phi\pi)\pi + \text{part. rec.}$$

$$A(\Delta m_s=17.75) = 1.27 \pm 0.34$$

Other hadronic

$$A(\Delta m_s=17.75) = 1.29 \pm 0.29$$

Part. rec. only

$$A(\Delta m_s=17.75) = 1.02 \pm 0.56$$

Semileptonic

$$A(\Delta m_s=17.75) = 0.86 \pm 0.49$$
Systematics in measurement of $\Delta m_s$

- Systematics dominated by $ct$-scale uncertainty

<table>
<thead>
<tr>
<th></th>
<th>Syst. Unc</th>
</tr>
</thead>
<tbody>
<tr>
<td>SVX Alignment</td>
<td>0.04 ps$^{-1}$</td>
</tr>
<tr>
<td>Track Fit Bias</td>
<td>0.05 ps$^{-1}$</td>
</tr>
<tr>
<td>PV bias from tagging</td>
<td>0.02 ps$^{-1}$</td>
</tr>
<tr>
<td>All Other Sys</td>
<td>&lt; 0.01 ps$^{-1}$</td>
</tr>
<tr>
<td>Total</td>
<td>0.07 ps$^{-1}$</td>
</tr>
</tbody>
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