First Measurement of the $B_s$ Oscillation Frequency

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Theory and Motivation
Matter in the Standard Model

Matter build of families of fermion doublets

Leptons
\[ \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L, \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L \]

Quarks
\[ \begin{pmatrix} u \\ d' \end{pmatrix}_L, \begin{pmatrix} c \\ s' \end{pmatrix}_L, \begin{pmatrix} t \\ b' \end{pmatrix}_L \]

Weak interaction through $W^\pm$ bosons

In general: weak eigenstates $\neq$ strong eigenstates

- mixing between families possible
- lower quark doublet components absorb difference
- neutrinos also mix
Cabbibo–Kobayashi–Maskawa Matrix

Example: two families of quark pairs → one mixing angle

\[
\begin{pmatrix}
  d' \\
  s'
\end{pmatrix}
= \begin{pmatrix}
  \cos \theta & \sin \theta \\
  -\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
  d \\
  s
\end{pmatrix}
\]

rotation matrix

Matrix has to be unitary: \( V^\dagger V = 1 \)

Describe mixing between three quark-pair families

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

\( V \) is Cabbibo–Kobayashi–Maskawa matrix

Three families → 4 degrees of freedom

☞ 3 angles

☞ 1 complex phase → CP violation
CKM Matrix

Matrix structure
☞ mostly diagonal
☞ crossing of families suppressed
☞ the further the less probable
☞ values not predicted

Particles are conserved:
\[ V^\dagger V = 1 \]
→ unitarity condition

Wolfenstein parametrization (\( \lambda = 0.224 \pm 0.012 \)):

\[
V = \begin{pmatrix}
1 - \lambda^2 / 2 & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \lambda^2 / 2 & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + o(\lambda^4)
\]

Least known parameters: \( \rho \) and \( \eta \)
Unitarity Triangle

Unitarity condition: $V^\dagger V = 1$

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

\[
\rightarrow V_{ud}V^*_u + V_{cd}V^*_c + V_{td}V^*_t = 0 \\
\rightarrow 1 + V_{ud}V^*_u/V_{cd}V^*_c + V_{td}V^*_t/V_{cd}V^*_c = 0
\]

\[
\frac{V_{td}V^*_t}{V_{cd}V^*_c} \approx \frac{\lambda}{V^*_{ts}} \\
\lambda = \sin \theta_c
\]
Neutral B Meson Mixing

Quark mixing → non diagonal Hamiltonian for \( \langle \bar{B} | H | B \rangle \)

\[
H = \begin{pmatrix}
M & M_{12} \\
M_{12}^* & M
\end{pmatrix} - \frac{i}{2} \begin{pmatrix}
\Gamma & \Gamma_{12} \\
\Gamma_{12}^* & \Gamma
\end{pmatrix}
\]

Diagonalizing the Hamiltonian results in

- two masses: \( m_H \) and \( m_L \) and \( \Delta m = m_H - m_L \)
- two decay widths: \( \Gamma_H \) and \( \Gamma_L \) and \( \Delta \Gamma = \Gamma_H - \Gamma_L \)
- remember: \( \Gamma = 1/\tau \)

Mass and decay width (lifetime) are measurable!!
Observables: Neutral B Meson Mixing

For $B_s$ no imaginary matrix element involved

$$|B_{s,H}\rangle = \frac{1}{\sqrt{2}}(|B_s\rangle + |\overline{B}_s\rangle) \quad CP \text{ odd}$$
$$|B_{s,L}\rangle = \frac{1}{\sqrt{2}}(|B_s\rangle - |\overline{B}_s\rangle) \quad CP \text{ even}$$

Initial particles and anti-particles

$$|B_s\rangle = \frac{1}{\sqrt{2}}(|B_{s,H}\rangle + |B_{s,L}\rangle)$$
$$|\overline{B}_s\rangle = \frac{1}{\sqrt{2}}(|B_{s,H}\rangle - |B_{s,L}\rangle)$$

Behavior in proper time

$$P(t)_{B^0_\rightarrow B^0} = \frac{1}{2\tau}e^{-t/\tau}(1 + \cos \Delta m t)$$
$$P(t)_{\overline{B^0} \rightarrow \overline{B^0}} = \frac{1}{2\tau}e^{-t/\tau}(1 - \cos \Delta m t)$$

Determine asymmetry

$$A_0(t) = \frac{N(t)_{\text{unmixed}} - N(t)_{\text{mixed}}}{N(t)_{\text{unmixed}} + N(t)_{\text{mixed}}} = \cos(\Delta m t)$$
First Measurement of $B$ Mixing from UA1

Signature: like sign high $p_T$ leptons

Result

- time integrated
  $\bar{\chi} = 0.121 \pm 0.047$
- implied heavy top

For $B_s$

- too fast: $\chi_s = 0.5$

Argus excluded this value at the time at 90%
Later $B$ factories took over: Argus, CLEO etc.
Theoretical Predictions - $\Delta m$

Theory prediction for $B^0/B_s^0$ mix through box diagram

$$\Delta m_q \propto m_{B_q} \hat{B}_{B_q} f_{B_q}^2 |V_{tb} V^*_{tq}|^2 \quad q = s, d$$

Lattice QCD calculations

$$\hat{B}_{B_d} f_{B_d}^2 = (246 \pm 11 \pm 25) \text{ MeV}^2$$

Hadronic uncertainties limit $|V_{td}|$ determination to $\approx 11\%$

In ratio most theory uncertainties cancel

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \frac{\xi^2 |V_{ts}|^2}{|V_{td}|^2} \quad \text{with} \quad \xi = 1.21^{+0.047}_{-0.035}$$

Determine $\frac{|V_{ts}|^2}{|V_{td}|^2}$ to $\approx 3.4\%$
New Physics in Loops?

Supersymmetry model
- gluino in loop
- squarks in loop
- describes all data
- allows very high $\Delta m_s$
- $\Delta m_s$ excludes models

$\rightarrow \Delta m_s$ sensitive to New Physics
Apex \((\bar{\rho}, \bar{\eta})\)

Squeezing along side \(b\)
- \(\sin 2\beta\)
- \(V_{ub}/V_{cb}\)

Squeezing along side \(c\)
- \(\Delta m_d\)
- \(\Delta m_s\)
- \(\gamma\)

CKM fit result:
\[
\Delta m_s = 18.3^{+6.5}_{-1.5} \text{ ps}^{-1}
\]
The Method
Ingredients to measure mixing
- proper decay time \( ct \), \( B \) rest frame
- \( B \) flavor at decay, final state
- \( B \) flavor at production, flavor tagging
Behavior in proper time

\[ P(t)_{B^0 \rightarrow B^0} = \frac{1}{2\tau} e^{-t/\tau} (1 + \cos \Delta m t) \]
\[ P(t)_{\overline{B^0} \rightarrow \overline{B^0}} = \frac{1}{2\tau} e^{-t/\tau} (1 - \cos \Delta m t) \]

Determine asymmetry

\[ A_0(t) = \frac{N(t)_{\text{unmixed}} - N(t)_{\text{mixed}}}{N(t)_{\text{unmixed}} + N(t)_{\text{mixed}}} = \cos \Delta m t \]

In a perfect world
What Do We See in the End?

Flavor tagging

- Realistic tag D=0.2

Vertex

- Realistic resolution: vtx: 50 µm

Vertex and Momentum

- Realistic resolutions: vtx: 50 µm pt: σ(p)/p = 5%

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

\[
\sigma_{ct} = \sqrt{(\sigma_{ct}^0)^2 + \left(ct \frac{\sigma_p}{p}\right)^2}
\]
Unbinned likelihood fit: $p \sim \exp(-t/\tau)(1 \pm AD \cos \Delta mt)$

- scan $\Delta m$ for signal: determine amplitude, $A$
- measure $\Delta m_s$ with $A = 1$
Status: Scanning for $B_s$ Oscillation Signal

Before this analysis

PDG 2006

recent DØ result
Equipment Used for the Measurements
Accelerator Setup at Fermilab

Complex accelerator system

Tevatron Collider

- Tevatron 1 km ring radius, CM energy $\sqrt{s} = 1.96$ TeV
- 36x36 colliding $p$, $\bar{p}$ bunches, $10^{11}(10^{10})$ $p(\bar{p})$ per bunch
Tevatron Machine Performance – Luminosity

"Data Taking Period 1"  “2”  “3”

$B_s$ Mixing Analysis uses: $1 \, \text{fb}^{-1}$
CDF II Detector

- Muon Detectors
- Time of flight
- Silicon Vertex Detector
- Central Drift Chamber
- Miniplug
- Endplug Calorimeter
CDF II Detector - Key Features

'Deadtimeless' trigger system
☞ 3 level, pipelined, flexible system
☞ Silicon Vertex Trigger (SVT) at 2nd level (≈25 kHz)

Charged particle reconstruction
☞ redundancy for pattern reco in busy environment
☞ excellent momentum resolution: \( R = 1.4\text{m}, B = 1.4\text{T} \)
☞ excellent vertex resolution: L00 at 1.5cm

Particle identification
☞ energy loss in drift chamber \( (dE/dx) \)
☞ Time-of-Flight system at 1.4 m radius
☞ electron and muon identification
CDF Detector – Opened Up
Sample Selection
Disadvantages
- $n_{qq} = 1000 \times n_{bb}$
- hostile environment
- second $b$ often outside fiducial

Advantages
- larger cross section $\times 10^5$
- larger boost $\times 10$
- $b$ hadrons: $B^+, B^0, B_s, B_c, \Lambda_b, ..$

Conclusion
- Fast event selection necessary, we call this trigger
- Typical rejection factors are 1/50,000
Upgrades: Displaced Track Trigger

Sketch of a B Decay

B Production Point

B Decay Point

d0 – impact parameter

Challenge:

☞ fast readout (20 TB/sec)
☞ track at 20 kHz (50k CPU)

B Signatures

☞ electrons, muons
☞ high momentum tracks
☞ displaced tracks

\[ p \]

\[ B \text{ Decay Point} \]

\[ B \text{ Production Point} \]

\[ d_0 \text{ – impact parameter} \]

\[ P_t \geq 2 \text{ GeV/c}; \chi^2_{SVT} \leq 25 \]

\[ \sigma = 47 \mu m \]

Includes 33 \mu m beamspot

\[ \text{tracks per 10 \mu m} \]

\[ \text{tracks per 10 \mu m} \]

\[ \text{SVT } d_0 (\mu m) \]
**Samples - Semileptonic Versus Hadronic**

CDF Run II Preliminary  \( L \approx 355 \text{ pb}^{-1} \)

Hadronic \( D\pi(\pi\pi) \)

- I\(^\ddagger\) reconstruct: \( ct = L_{xy} \frac{m_{B}^{B}}{p_{T}^{B}} \)
- I\(^\ddagger\) great \( ct \), mass resolution
- I\(^\ddagger\) sample is clean
- I\(^\ddagger\) small branching ratio

Semileptonic \( \ell DX \)

- I\(^\ddagger\) reconstruct: \( ct^{*} = L_{xy} \frac{m_{B}^{B}}{p_{T}^{D}} \)
- I\(^\ddagger\) large branching ratio
- I\(^\ddagger\) bad \( ct \), mass resolution
- I\(^\ddagger\) small branching ratio
**Samples - Hadronic: \( B \rightarrow D \pi(\pi\pi) \)**

### \( B_s \) Modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D_s(\phi \pi)\pi )</td>
<td>1600</td>
</tr>
<tr>
<td>( D_s(K^*0K)\pi )</td>
<td>800</td>
</tr>
<tr>
<td>( D_s(3\pi)\pi )</td>
<td>600</td>
</tr>
<tr>
<td>( D_s(\phi \pi)3\pi )</td>
<td>500</td>
</tr>
<tr>
<td>( D_s(K^*0K)3\pi )</td>
<td>200</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3700</strong></td>
</tr>
</tbody>
</table>

### \( B \) Modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B^+ : D^0 \pi )</td>
<td>26k</td>
</tr>
<tr>
<td>( B^0 : D^- \pi )</td>
<td>22k</td>
</tr>
</tbody>
</table>

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CDF Run II Preliminary

\[ L \approx 1 \text{ fb}^{-1} \]
# Samples - Semileptonic: $B \rightarrow ID$

<table>
<thead>
<tr>
<th>$B_s$ Modes</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_s(\phi \pi)\ell$</td>
<td>32k</td>
</tr>
<tr>
<td>$D_s(K^{*0}K)\ell$</td>
<td>11k</td>
</tr>
<tr>
<td>$D_s(3\pi)\ell$</td>
<td>10k</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td><strong>53k</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$B$ Modes</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0\ell$</td>
<td>540k</td>
</tr>
<tr>
<td>$D^{*-}\ell$</td>
<td>75k</td>
</tr>
<tr>
<td>$D^-\ell$</td>
<td>300k</td>
</tr>
</tbody>
</table>

CDF Run II Preliminary  \[ L \approx 1 \text{ fb}^{-1} \]

---

**Graph:**

- **Data**
- **Fit**
- **$B_s$ Signal**
- **Combinatorial + False Lepton**

**X-axis:** $D$ mass \[ [\text{GeV/c}^2] \]

**Y-axis:** Candidates per 1 MeV/c\(^2\)

### $B_s \rightarrow l D_s X$

---

**Notes:**

- CDF Run II Preliminary
- $L \approx 1 \text{ fb}^{-1}$
- $B_s \rightarrow l D_s X$
Proper Time Resolution
Proper Time Resolution - Basics

Significance revisited

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

Reconstructed proper decay time

\[
ct = L_x^B \frac{m_B}{p_T^B}
\]

\[
ct = L_{xy}^{\ell D} \frac{m_B}{p_T^{\ell D}} \cdot \left\langle \frac{p_T^{\ell D} L_x^B}{p_T^B L_{xy}^{\ell D}} \right\rangle_{\text{MC}}
\]

Understanding of resolution

☞ irrelevant for lifetime measurements
☞ critical piece for $B_s$ oscillations
☞ the faster the more important
☞ calibration on data needed
Proper Decay Time Resolution - Calibration

Use prompt $D^+$ and track
- large sample of prompt $D^+$
- most tracks from PV
- same topology as signal
- measure of $ct$ resolution

![Graph showing proper decay time resolution](image)

Calibrated on our data
Proper Decay Time Resolution - Results

CDF Run II Preliminary

$B_s \rightarrow D_s^- (3)\pi^+$

$\langle\sigma_{ct}\rangle = 26.0 \mu\text{m}$

Optimal use of data:
- PV per candidate
- resolution per candidate

Superior resolution:
- access to high $\Delta m_s$
- CDF plays in a new league

One oscillation at $\Delta m_s = 18/\text{ps}$
Layer 00

- innermost silicon layer: mounted on beampipe
- at distance of about 1.5 cm from the beamline
- significant boost for vertexing resolution
Proper Decay Time Resolution - Results

CDF Run II Monte Carlo

B → l D_s

**Hadronic** $B_s \rightarrow D_s(3)\pi$

☞ $\sigma^0_{ct} \sim 26 \mu m$, 87 fs; $\sigma_p/p < 1\%$

**Semileptonic** $B_s \rightarrow \ell D_s X$

☞ $\sigma^0_{ct} \sim 30-70 \mu m$, 100-230 fs; $\sigma_p/p \sim 3-20\%$

$m(\ell D)$ dependent $k$-factor significant improvement!
$b$ Flavor Tagging
Production flavor tagging

- combine same side and opposite side tags
- opposite side: muon, electron and jet charge taggers
  jet selection algorithms: vertex, jet probability and highest $p_T$
- same side: particle ID based Kaon Tagger
Flavor Taggers - Maximize Performance

Parametrize tagger performance in dependent variables: here muon tagger and $p_T^{\text{rel}}$

Tune on large $B^+$, $B^0$ samples: transfers directly to $B_s$

→ each event has predicted dilution
**Flavor Taggers - Fit for Tagger Performance**

**Fit $B^+$ and $B^0$**

- $\ell D$ and $D\pi(\pi\pi)$ are fit separately
- parameters: $D$ and $\Delta m_d$
- depicted: combined $\ell D$ samples with combined lepton tags

**$B^0$ Mixing Result**

- $0.536 \pm 0.028 \text{(stat)} \pm 0.006 \text{(syst)} \text{ ps}^{-1}$ hadronic
- $0.509 \pm 0.010 \text{(stat)} \pm 0.016 \text{(syst)} \text{ ps}^{-1}$ semileptonic
- $0.507 \pm 0.005 \text{ ps}^{-1}$ PDG 2006
Same Side Kaon Tagging

Fragmentation

- $B_{d/u}$ likely accompanied by $\pi^+/\pi^-$
- $B_s$ likely accompanied by a $K^+$
- processes differ
- no direct transfer $B^+, B^0 \rightarrow B_s$
- need MC to measure tagger dilution

Strategy

- tune MC with $B^+$ and $B^0$
- apply PID to de-weight pions
- use MC to parametrize dilution

ParticleID very important

- significantly improves $\varepsilon D^2$
- reduces MC dependence

$\rightarrow$ TOF ($dE/dx$) very important!

$\downarrow$

$\downarrow$

$\downarrow$

$\downarrow$

$\downarrow$

$\downarrow$

$\downarrow$

$\downarrow$

$\downarrow$

$\downarrow$

$\downarrow$
Flavor Tagging - Key Detector

Time-of-Flight Detector

- distinguish pions/kaons to $p \approx 1.5 \text{ GeV/c}$, 100 ps resolution
- most important information for same side tagger
Flavor Tagging - SSKT Calibration

- agreement is excellent, but data sample sizes are limited
- $B^+, B^0$ data/MC comparison dominate systematic: $\rightarrow 14\%$

CDF Run II Preliminary

$L \approx 355 \text{ pb}^{-1}$

max PID dilution $D$ [%]
Flavor Taggers - Results

Usage of flavor taggers
- OST: selection of best available OS tag
- OST and SST use disjunct input information
- simple uncorrelated OST/SST combination algorithm

<table>
<thead>
<tr>
<th></th>
<th>Hadronic</th>
<th>Semileptonic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>$\epsilon D^2$[%]</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muon</td>
<td>0.48 ± 0.06</td>
<td>0.62 ± 0.03</td>
</tr>
<tr>
<td>Electron</td>
<td>0.09 ± 0.03</td>
<td>0.09 ± 0.01</td>
</tr>
<tr>
<td>JQ/Vertex</td>
<td>0.30 ± 0.04</td>
<td>0.28 ± 0.02</td>
</tr>
<tr>
<td>JQ/JetCharge</td>
<td>0.46 ± 0.05</td>
<td>0.34 ± 0.02</td>
</tr>
<tr>
<td>JQ/highPt</td>
<td>0.14 ± 0.03</td>
<td>0.11 ± 0.01</td>
</tr>
<tr>
<td><strong>OST</strong></td>
<td>1.47 ± 0.10</td>
<td>1.44 ± 0.04</td>
</tr>
<tr>
<td><strong>SSKT</strong></td>
<td>3.42 ± 0.96</td>
<td>4.00 ± 1.12</td>
</tr>
</tbody>
</table>

SSKT improves tagging by factor of 3
Updates for the Publication

Changes to the analysis

☞ tagging in small subsample was not optimal
  → particle ID was not used
☞ small changes to: amplitude scans, $\Delta m_s$, $p$-value
☞ analysis got more sensitive, as expected

Status of publication

☞ finished at CDF
☞ being submitted today to PRL
Unbinned Likelihood Fit Overview

For each sample component and event

\[ L = L_m \cdot L_t \cdot L_{\sigma_t} \cdot L_D \]

Most complex is proper decay time description

\[ L_t = \frac{1}{N} \frac{e^{-\frac{\kappa t'}{\tau}}}{\kappa} 1 \pm \frac{A S_D D \cos(\Delta m_s \kappa t')}{2} \]
\[ \otimes R(t - t'; S_{\sigma_t \sigma_t}) \cdot \varepsilon(t) \]
\[ \otimes F(\kappa) \]
Amplitude Scan Method - Using B^0

Unbinned likelihood fit
- $p \sim (1 \pm AD \cos(\Delta m t))$
- scan fixed values of $\Delta m$
- record $A$ and $\sigma(A)$

Signal $\equiv$ unit amplitude
- else $A$ consistent with 0
- exclude $\Delta m \leq 95\% CL$ for $(1 - A) > 1.645 \sigma(A)$
# Amplitude Scans

## Semileptonic

CDF Run II Preliminary

$L = 1.0 \text{ fb}^{-1}$

- **data $\pm 1 \sigma$**
- **95% CL limit** 15.9 ps$^{-1}$
- **1.645 $\sigma$**
- **sensitivity** 17.3 ps$^{-1}$
- **data $\pm 1.645 \sigma$**
- **data $\pm 1.645 \sigma$ (stat. only)**

**Note**

- 2nd best semileptonic sensitivity
- Best hadronic and overall sensitivity

A compatible with 1 for $\Delta m_s \sim 17.3$ ps$^{-1}$

## Hadronic

CDF Run II Preliminary

$L = 1.0 \text{ fb}^{-1}$

- **data $\pm 1 \sigma$**
- **95% CL limit** 16.7 ps$^{-1}$
- **1.645 $\sigma$**
- **sensitivity** 25.4 ps$^{-1}$
- **data $\pm 1.645 \sigma$**
- **data $\pm 1.645 \sigma$ (stat. only)**

**Note**

- $B_s^0 \rightarrow \pi^+ \pi^-$
- $B_s^0 \rightarrow D_s^- \pi^+$

47
Combined Amplitude Scan

CDF Run II Preliminary  
$L = 1.0 \text{ fb}^{-1}$

- **data ± 1σ**
- **95% CL limit** $16.7 \text{ ps}^{-1}$
- **1.645 σ**
- **sensitivity** $25.8 \text{ ps}^{-1}$

- **data ± 1.645 σ**
- **data ± 1.645 σ (stat. only)**

$B_s^0 \rightarrow \ell^+ D_s^- X$, $B_s^0 \rightarrow D_s^- \pi^+$, $B_s^0 \rightarrow D_s^- \pi^+ \pi^+ \pi^-$

$A$ compatible with 1 for $\Delta m_s \sim 17.3 \text{ ps}^{-1}$
Amplitude Scans per Period

Semileptonic Samples

CDF Run II Preliminary

L = 355 pb$^{-1}$

$B^0_s \to D_s \ell^+ \tau^-$

$\Delta m_\tau [\text{ps}]$

Amplitude

CDF Run II Preliminary

L = 410 pb$^{-1}$

$B^0_s \to D_s \ell^+ \tau^-$

$\Delta m_\tau [\text{ps}]$

Amplitude

CDF Run II Preliminary

L = 230 pb$^{-1}$

$B^0_s \to D_s \ell^+ \tau^-$

$\Delta m_\tau [\text{ps}]$

Amplitude

Hadronic Samples

CDF Run II Preliminary

L = 0.355 fb$^{-1}$

$B^0_s \to D_s \pi^+, B^0_s \to D_s \pi^+ \pi^+$

$\Delta m_\tau [\text{ps}]$

Amplitude

CDF Run II Preliminary

L = 0.410 fb$^{-1}$

$B^0_s \to D_s \pi^+, B^0_s \to D_s \pi^+ \pi^+$

$\Delta m_\tau [\text{ps}]$

Amplitude

CDF Run II Preliminary

L = 0.230 fb$^{-1}$

$B^0_s \to D_s \pi^+, B^0_s \to D_s \pi^+ \pi^+$

$\Delta m_\tau [\text{ps}]$

Amplitude
Systematic Uncertainties on Amplitude

Hadronic

Semileptonic

Systematic uncertainties $\sim 0.15$-$0.20$ at high $\Delta m_s$: → analysis is statistically limited
Combined Amplitude Scan

CDF Run II Preliminary  \( L = 1.0 \text{ fb}^{-1} \)

\[ \frac{A}{\sigma_A(\Delta m_s = 17.3 \text{ ps}^{-1})} \sim 3.7, \text{ but what is the p-value?} \]
Likelihood Profile

Difference, $-\Delta \log(L)$

$$\log(\mathcal{L}(A = 1)) - \log(\mathcal{L}(A = 0))$$

Minimum: $-6.75$

Key question:

How often can random tags produce a likelihood minimum at least as deep?
**Likelihood Significance**

![Graph showing likelihood significance](image)

- **CDF Run II Preliminary**
- **1 fb⁻¹**
- **Randomized tags**
- **Expected for Δm_s = 18 ps⁻¹**
- **Observed value**
- **p-value ~ 0.2%**
- **Very small probability of being background fluctuation**

→ **Measure Δm_s**
\[ \Delta m_s \text{ Measurement} \]

\[ \Delta m_s = 17.31^{+0.33}_{-0.18}(\text{stat.}) \pm 0.07(\text{syst.})\text{ps}^{-1} \]

\[ \Delta m_s [\text{ps}^{-1}] \text{ at 90\% CL in} \]

\[ [17.01, 17.84] \]

\[ \Delta m_s [\text{ps}^{-1}] \text{ at 95\% CL in} \]

\[ [16.96, 17.91] \]

Systematic
- \( ct \) scale uncertainty
- rest: small
**Systematic on $\Delta m_s$**

**Relevant systematic uncertainties**

- All related to $ct$ scale
- Common for hadronic and semileptonic samples

<table>
<thead>
<tr>
<th>Source</th>
<th>Value [ps$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SVX alignment</td>
<td>0.04</td>
</tr>
<tr>
<td>Track fit bias</td>
<td>0.05</td>
</tr>
<tr>
<td>P.V. bias from tagging</td>
<td>0.02</td>
</tr>
<tr>
<td>Others</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.07</strong></td>
</tr>
</tbody>
</table>
Knowledge about $\Delta m_s$: before and after

![Graph showing the CKM fit without $\Delta m_s$, CDF measurement, and the D0 90% CL interval.](image-url)
Direct Measure of $|V_{td}/V_{ts}|$

Relation between $\Delta m_q$ and $V_{tq}$

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \left| \frac{V_{ts}}{V_{td}} \right|^2$$

Inputs

- $\frac{m_{B_d}}{m_{B_s}} = 0.9830$ (PDG 2006)
- $\xi = 1.21 \pm 0.047$ (M.Okamoto hep-lat/0510113)
- $\Delta m_d = 0.507 \pm 0.005$ (PDG 2006)

$$\left| \frac{V_{td}}{V_{ts}} \right| = 0.208 \pm^{+0.001}_{-0.002} (\text{exp}) \pm^{+0.008}_{-0.006} (\text{theo})$$

Best so far

- Belle: hep-ex/0506079

$$\left| \frac{V_{td}}{V_{ts}} \right| = 0.199 \pm^{+0.026}_{-0.025} (\text{exp}) \pm^{+0.018}_{-0.016} (\text{theo})$$
Summary of $|V_{td}/V_{ts}|$

- CKM fit w/o $\Delta m_s$
- CDF measurement
- BR($B^0 \rightarrow \rho^0 \gamma$) / BR($B^0 \rightarrow K^{*0} \gamma$)

$\xi_{\nu,\text{SU(3)}} = 1.21^{+0.047}_{-0.035}$ (hep-lat/0510113)

BRs WA - $\xi_{\nu,\text{SU(3)}} = 1.2 \pm 0.1$ (CKM 2005)

$|V_{td}/V_{ts}|$
**Impact on CKM Triangle**

Ellipse shrinks significantly: limited by theory uncertainty
improved $\xi$ from lattice groups very important
Conclusions

Long journey coming to an end

- 20 years of search to see $B_s - \bar{B}_s$ oscillations
- Found signature consistent with $B_s - \bar{B}_s$ oscillations
- Probability of fluctuation from random tags: 0.2%

\[ \Delta m_s = 17.31 ^{+0.33}_{-0.18} \text{(stat)} \pm 0.07 \text{(syst)} \]
world best: \[ \frac{|V_{td}|}{|V_{ts}|} = 0.208^{+0.001}_{-0.002} (\text{exp})^{+0.008}_{-0.006} (\text{theo}) \]
The End
Additional: Lifetime Results
Lifetime Checks

\[ ct \cdot p_t/m \]

- p\bar{p} collision  
- B decays
- reconstruct B meson mass, p_T, L_{xy}
- calculate proper decay time (ct)
- extract c\tau from combined mass+lifetime fit
- signal probability:
  \[ p_{\text{signal}}(t) = e^{-t/\tau} \otimes R(t',t) \]
- background \( p_{\text{bkgd}}(t) \) modeled from sidebands
**Lifetime Checks**

- SVT trigger, event selection sculpts lifetime distribution
- correct for on average using efficiency function:
  \[ p = e^{-t'/\tau} \otimes R(t',t) \cdot \varepsilon(t) \]
- efficiency function shape contributions:
  - event selection, trigger
- details of efficiency curve
  - important for lifetime measurement
  - inconsequential for mixing measurement

\[ \text{pattern limit } \left| d_0 \right| < 1 \text{ mm} \]

\[ \text{proper time (cm)} \]
Lifetime Checks

CDF Run II Preliminary \( L \approx 1 \text{ fb}^{-1} \)

<table>
<thead>
<tr>
<th>Mode</th>
<th>Lifetime [ps] (stat. only)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B^0 \rightarrow D^- \pi^+ )</td>
<td>( 1.508 \pm 0.017 )</td>
</tr>
<tr>
<td>( B^- \rightarrow D^0 \pi^- )</td>
<td>( 1.638 \pm 0.017 )</td>
</tr>
<tr>
<td>( B_s \rightarrow D_s \pi(\pi\pi) )</td>
<td>( 1.538 \pm 0.040 )</td>
</tr>
</tbody>
</table>

- World Average:
  - \( B^0 \rightarrow 1.534 \pm 0.013 \text{ ps}^{-1} \)
  - \( B^+ \rightarrow 1.653 \pm 0.014 \text{ ps}^{-1} \)
  - \( B_s \rightarrow 1.469 \pm 0.059 \text{ ps}^{-1} \)

Excellent agreement!
Lifetime Checks

- neutrino momentum not reconstructed
  \[ K = \frac{p_T(lD)}{p_T(B)} \cdot \frac{L(B)}{L(lD)} \]

- correct for neutrino on average
Lifetime Checks

\[ \text{Lifetime Checks} \]

CDF Run II Preliminary \( L \approx 1 \text{ fb}^{-1} \)

\[ ct^* = \frac{L(lD) \cdot m(B)}{p_T(lD)} \]

Lepton

\( B_\text{s} \rightarrow l D_\text{s} X \)

Lepton SVT Track

\( B_\text{s} \) lifetime in 355 pb\(^{-1}\): 1.48 ± 0.03 (stat) ps

World Average value: 1.469 ± 0.059 ps