B Tagging and Mixing at Tevatron
(Focusing on Bs mixing prospect)
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• Key issues for B mixing analyses
• Current flavor tagging and Bs yield results
• Prospect in the next few years
B mixing and CKM matrices

- $\Delta m_s/\Delta m_d = (M_{B_s}/M_{B_0}) \xi |V_{ts}/V_{td}|^2$
- Exploring one side of CKM triangle
**B₀ mixing**

Δm₃ is well measured and serves CDF/D₀ as nice calibration tool.

Δm₃ = 0.502 ± 0.006 ps⁻¹ (HFAG 2003)

CDF Run-I: lep+D* with SLT

![Graph showing distribution of Δm₃ values with error bars and average values.](image)

Δm₃ = 0.512 ± 0.09 ± 0.04 ps⁻¹

**CDF Run-I: lep+D* with SLT**

- **ALEPH**: (3 analyses)
- **DELPHI**: (5 analyses)
- **L3**: (3 analyses)
- **OPAL**: (5 analyses)
- **CDF**: (4 analyses)
- **BABAR**: (3 analyses)
- **BELLE**: (4 analyses)

Average of above after adjustments

- **ARGUS + CLEO** (χ₀ measurements)

World average

Δm₃ (ps⁻¹)

- 0.446 ± 0.026 ± 0.019 ps⁻¹
- 0.519 ± 0.018 ± 0.011 ps⁻¹
- 0.444 ± 0.028 ± 0.028 ps⁻¹
- 0.479 ± 0.018 ± 0.015 ps⁻¹
- 0.495 ± 0.033 ± 0.027 ps⁻¹
- 0.500 ± 0.008 ± 0.006 ps⁻¹
- 0.506 ± 0.006 ± 0.008 ps⁻¹

Δm₃ = 0.502 ± 0.007 ps⁻¹

Δm₃ = 0.493 ± 0.032 ps⁻¹

Δm₃ = 0.502 ± 0.006 ps⁻¹

* working group average without adjustments
**Bs mixing**

- $B_s$ mixing is the top priority for $B$ physics at Tevatron
- A challenging measurement due to the rapid oscillation
  \[ \Delta m_s > 14.4 \text{ ps}^{-1} @ 90\% \text{ CL} \quad \text{(HFAG 03)} \]
  4 oscillations per lifetime cycle
- Unique Tevatron opportunity

*Combined limits of indirect measurements using amplitude methods from LEP, SLD & CDF Run I*
Key issues for Bs mixing

• High statistics with good signal-to-background ratio
  – Efficient triggering and fine mass resolution
  – Trigger on high pT leptons and displaced tracks (SVT/STT)

• Efficient Initial B flavor identification
  – Only 20-40% chance for both B in the detector acceptance
  – e/µ coverage (SLT), tracking (JetQ/SST) and PID (Kaon)

• Excellent proper decay length
  – Momentum and vertex resolution
  – Utilize the fully reconstructed decays
**CDF Silicon Detector**

- 8 layers with improved 3D ability
- L00 improves impact parameter resolution by 30-50%
- ISL extends tracking coverage for e/µ systems to |η|=2
CDF Silicon Vertex Trigger at Level-2

• Trigger on displaced tracks from b
  L1 track + Si hits = L2 SVT

• Excellent L2 impact parameter resolution
  \[ \sigma = 35\mu m \oplus 33 \mu m (\text{resol} \oplus \text{beam}) = 48 \mu m \]

• 2-track trigger for Bs\rightarrow Ds \pi etc.
  Tracks: \( p_T > 2 \text{ GeV}, d_0 > 120 \mu m \)

• e/\mu + displaced track trigger
  \( p_T (\text{e/\mu }) > 4 \text{ GeV} \) with \( p_T (\text{track}) > 2 \text{ GeV}, d_0 > 120 \mu m \)

First Run II paper!
**Bs→Ds π reconstruction**

- **700 event per fb⁻¹ of Bs→Dsπ with Ds→φπ, φ→K⁺K⁻**
- \(\text{Br}(\text{Bs} \rightarrow \text{Ds}^- \pi^+)/\text{Br}(\text{B}^0 \rightarrow \text{D}^- \pi^+) = 1.4\pm 0.2 \text{ (stat)} \pm 0.2 \text{ (syst)} \pm 0.4 \text{ (Br)} \pm 0.2 \text{(PR)}\)
Bs→Ds π yield (CDF)

• Results so far are using early CDF data

• Detector coverage and SVT efficiency improved since
  – SVX-II coverage (now ~90%)
  – SVT hits requirement optimization (4/4 → 4/5)
  – Better use of L2 trigger bandwidth (dynamic pre-scales)

• We are seeing a factor of 2 increase on Bs yield

• Current condition produces Bs at a rate 1600/fb⁻¹

• Not count additional Bs/Ds channels yet
  – Bs→Ds-π + π -π + / Ds →K*K, KsK
Proper time resolution (CDF)

- $\sigma_t = (\sigma_{Lxy}/\beta\gamma) \oplus (\sigma_{pT}/pT) \cdot t$
  - Proper time $t = L_{xy}/\beta\gamma$, $\beta\gamma = m/pT$

- $\sigma_{Lxy}$ dominates for fully reconstructed events

- $\sigma_{pT}/pT = 15\%$ for semileptonic decay

- From $B_s \rightarrow D_s\pi$ sample, $\sigma_{Lxy} \approx 50\mu m$ with run-averaged beam line and without using L00 hits
  - $\sigma_{lxy} \approx 40 \oplus 30\mu m$ (SVX $\oplus$ beam)

- $\sigma_t = 0.067ps$ now for $B_s \rightarrow D_s\pi$

- $\sigma_t = 0.050ps$ achievable (L00+event-by-event beam line)
Initial B flavor tagging at CDF/D0

• **Soft lepton tagging (SLT)**
  – Semileptonic decay from the 2nd B
  – High purity and lepton can be part of a trigger

• **Jet Charge Tagging (JetQ)**
  – Correlation of b-flavor and charge of a b-jet
  – High efficiency but Low purity

• **Opposite-side Kaon Tagging (OKT)**
  – \( \frac{N(B^0/B^+\rightarrow K^+)}{N(B^0/B^+\rightarrow K^-)} \approx 5 \) due to the \( b \rightarrow c \rightarrow s \)
  – Need PID for tagging purity
Flavor tagging at CDF/D0

• **Same Side Tagging (SST)**
  - \((\pi^- B^+, \pi^+ B^0, K^+ B_s)\) correlations from b fragmentation or from B** decays
  - No need for 2\(^{nd}\) B in the acceptance
  - High efficiency and reasonable purity
  - PID will enhance purity

• \(\varepsilon D^2 = \text{effective tagging efficiency}\)
  - \(\varepsilon = \frac{N_{\text{tag}}}{N_{\text{total}}}\) (efficiency of finding a tagger)
  - \(D = \frac{(N_R - N_w)}{N_{\text{tag}}}\) (ability for a right decision)
Flavor tagging results from D0

- **Tested on** $B^+ \rightarrow J/\Psi K^+$ events

  **SST:** $\varepsilon D^2 = (5.5 \pm 2.0)\%$
  
  ($\varepsilon = 79.2 \pm 2.1\%$ and $D = 26.4 \pm 4.8\%$)

  **Muon:** $\varepsilon D^2 = (1.6 \pm 1.1)\%$
  
  ($\varepsilon = 5.0 \pm 0.5\%$ and $D = 57.0 \pm 19.3\%$)

  **Jet-Q:** $\varepsilon D^2 = (3.3 \pm 1.7)\%$
  
  ($\varepsilon = 46.7 \pm 2.7\%$ and $D = 26.7 \pm 6.8\%$)
SLT result from CDF

- Test on high statistics $l$+SVT events

- Need to correct the Dilution (64%) from triggered lep+SVT pair due to mixing and charm/prompt background

Tagging efficiency:

$\varepsilon_{D^2}(\mu) = (0.7\pm0.1)\% \quad (\varepsilon=1\%)$
SST result from CDF

SST on $B^+ \rightarrow J/\Psi K^+$ and $B^+ \rightarrow D^0 K^+$

CDF Run II Preliminary

$B^+ \rightarrow D^0 \pi^+$

- Right Sign, $563 \pm 32$ events
- Wrong Sign, $396 \pm 26$ events

$\varepsilon D^2 = (2.1 \pm 0.7)\%$  ($\varepsilon = \sim 62\%$)
**TOF and flavor tagging**

- **TOF has big effect on tagging purity**
  - $2\sigma$ K-π separation for $p<1.6$ GeV/c which covers ~57% of the B tracks
  - Important for both OKT and SST-K ($\varepsilon D^2 2 \rightarrow 4.2\%$ for SST)
# Tagger Summary (CDF)

<table>
<thead>
<tr>
<th>$\varepsilon D^2 (%)$</th>
<th>Run-I</th>
<th>Run-II</th>
<th>Projection w/o TOF</th>
<th>Projection with TOF</th>
<th>Key improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>SST-$\pi/K$</td>
<td>1.5±0.4</td>
<td>2.1±0.7</td>
<td>2.0</td>
<td>2.0 - 4.2</td>
<td>SVX/TOF</td>
</tr>
<tr>
<td>SLT-$\mu$</td>
<td>0.6±0.1</td>
<td>0.7±0.1</td>
<td>1.0</td>
<td>1.0</td>
<td>CMX/IMU/ISL</td>
</tr>
<tr>
<td>SLT-e</td>
<td>0.3±0.1</td>
<td>0.7</td>
<td>0.7</td>
<td></td>
<td>Plug Cal/ISL</td>
</tr>
<tr>
<td>JetQ</td>
<td>1.0±0.3</td>
<td>3.0</td>
<td>3.0</td>
<td></td>
<td>COT/SVX</td>
</tr>
<tr>
<td>OKT</td>
<td></td>
<td></td>
<td>2.4</td>
<td></td>
<td>TOF</td>
</tr>
</tbody>
</table>

- Measurements with early data are consistent with projections.
- Update soon with improved detector coverage and performance.
- Projection for CDF Bs mixing sensitivity will use:

$$\varepsilon D^2 = 4\% \text{ (w/o TOF)} \rightarrow 5\% \text{ (with TOF)}$$
Bs mixing sensitivity formula

\[
\text{Significance} = \sqrt{\frac{S \varepsilon D^2 e^{-\frac{(\Delta m_s \sigma_t)^2}{2}}}{2}} \sqrt{\frac{S}{S + B}}
\]

- \( S \) = number of signal events
- \( S/B \) = signal/background ratio
- \( \sigma_t \) = proper time resolution
- \( \varepsilon D^2 \) = effective tagging efficiency

• It is the “averaged” significance of analyses using likelihood fittings

\[
\text{significance} = \sqrt{2 \Delta \log L} \quad \Rightarrow
\]
CDF Bs mixing prospect with 500pb$^{-1}$

**With current performance**
- $S=1600$ event/fb$^{-1}$
- $S/B = 2/1$
- $\varepsilon D^2 = 4\%$ (SLT+SST+JetQ)
- $\sigma_t = 0.067$ps

**2\sigma measurement if $\Delta m_s = 15$ps$^{-1}$ from 500pb$^{-1}$ data**
- Expect 590pb$^{-1}$ - 680pb$^{-1}$ from Tevatron by 2004
- Beat current limit from indirect measurements
- Reach Standard Model favored region
CDF Bs mixing prospect with 2fb⁻¹

• Expect Tevatron to deliver luminosity of
  – 2.11fb⁻¹ (based line) and 3.78fb⁻¹ (design) by 2007

• With modest improvement for CDF
  – Add Ds \rightarrow K^*K, KsK and Bs \rightarrow Ds-\pi + \pi -\pi +
    
    S=1600 \rightarrow 2000 \text{ event/fb}⁻¹
  – With improved TOF to enhance both SST and OKT
    \varepsilon D^2 = 4\% \rightarrow 5\%
  – With L00 silicon and event by event beamline
    \sigma_{ct} = 0.067 \rightarrow 0.05\text{ps}
CDF Bs mixing prospect by 2007

- Go beyond standard model preferred range
  - $5\sigma$ measurement if $\Delta m_s=18\text{ps}^{-1}$ with $1.7\text{fb}^{-1}$ data
  - $5\sigma$ measurement if $\Delta m_s=24\text{ps}^{-1}$ with $3.2\text{fb}^{-1}$ data
D0 Bs mixing sensitivity

- Detail in Vivek Jain’s talk on Tuesday
- Projections with 500 pb\(^{-1}\) data of inclusive muon trigger
  - Triggered muon used to reconstruct 15K Bs\(\rightarrow\)Ds \(\mu\) \(\nu\)
  - Triggered muon used as flavor tagger for 700 Bs \(\rightarrow\)Ds \(\pi\)
\[ \frac{\Delta \Gamma_s}{\Gamma_s} - \text{Bs lifetime difference} \]

- The mass difference \( \Delta m_s \) and lifetime difference \( \Delta \Gamma_s \) of the two CP eigenstates are linked by

\[
\frac{\Delta \Gamma_s}{\Delta m_s} = -\frac{3\pi}{2} \cdot \frac{m_b^2}{m_t^2} \cdot \frac{\eta(\Delta \Gamma_s)}{\eta(\Delta m_s)}
\]

- The QCD factor doesn’t depend on CKM

- \( \Delta m_s \) and \( \Delta \Gamma_s \) measurements are complementary

- \( \Delta \Gamma_s \) could be large enough to be detectable \((\Delta \Gamma_s/\Gamma_s \sim 15\%)\)
**$\Delta \Gamma_s/\Gamma_s$ Measurements**

- **Three methods suggested for extracting $\Delta \Gamma_s/\Gamma_s$**
- **Fitting well-defined decay with two lifetimes**
  - Fit $e^{-\Gamma_L t} + e^{-\Gamma_H t}$ for $B_s \rightarrow D_s \ell \nu$ or $B_s \rightarrow D_s^+ \pi^-$
- **Separate CP-even/odd states by transversity analysis**
  - $B_s \rightarrow J/\Psi \phi$ is the familiar channel to CDF/D0
- **Branching ratio from a pure CP state decay**
  - $B_s \rightarrow D_s^+ D_s^-$ a pure CP-even and triggered by CDF SVT trigger
  - $Br(B_s \rightarrow D_s^+ D_s^-) = \Delta \Gamma_s / [\Gamma_s (1 + \Delta \Gamma_s / 2 \Gamma_s)]$
  - Need to separate $B_s \rightarrow D_s^{+(*)} D_s^{-(*)}$ with fine mass resolution
**ΔΓ_s/Γ_s** from Bs semileptonic decays

- Plenty statistics from semileptonic decays
- Suffer from poor lifetime resolution due to partial reconstruction
- Useful for limits  $ΔΓ_s/Γ_s<0.83$ @95% CL from 600 Run-I signals
  $Δm_s>5.8$ ps$^{-1}$@ 95%CL from 700 SLT-tagged Run-I signals
\[ \Delta \Gamma_s/\Gamma_s \text{ from } B_s \rightarrow J/\Psi\phi \]

- \( \Delta \Gamma_s/\Gamma_s \) from \( B_s \rightarrow J/\Psi\phi \)

- \( \text{Run-I with 58 events gives } \Gamma^{\text{CP-even}}/\Gamma = 0.778\pm0.090\pm0.012 \)

- \( \text{With 4K event } \Rightarrow \text{ an error of 0.05 if } \Delta \Gamma_s/\Gamma_s = 15\% \) (Run II B workshop)

- \( \text{CDF result with 300 events from } 220\text{pb}^{-1} \text{ is coming} \)

- \( \text{CP states follow distributions:} \)
  - \( 3/8 \cdot (1+\cos^2 \Theta_T) \rightarrow \text{CP-even} \)
  - \( 3/4 \cdot (1-\cos^2 \Theta_T) \rightarrow \text{CP-odd} \)

\( \Theta_T = \text{Transversity angle} \)
Summary

• A lot of progress on flavor tagging from CDF/D0

• We are collecting Bs→Ds⁻π⁺ at 1600 event/fb⁻¹

• With 500 pb⁻¹ data, Bs mixing measurement reaches the Standard Model preferred region (Δms=15ps⁻¹)

• With 2fb⁻¹ data, Bs mixing measurement will go beyond the preferred region (Δms>18ps⁻¹)

• Precise ΔΓs /Γs measurements are also underway
Backup slides
CDF/D0 Detectors

Both detectors have very nice silicon device (lifetime), central tracking (mass), calorimeter & muon system (e/µ ID) and high bandwidth trigger/DAQ system

CDF

Silicon vertex trigger (SVT) 
trigger displaced track and e/µ
TOF for particle ID
2σ K-π separation at 1.5 GeV
Excellent mass resolution

DØ

Excellent muon coverage
trigger µ for pT>1.5 and |η|<2.0
Excellent tracking acceptance
SMT+SFT covers |η|<1.6
Silicon track trigger is coming
Separating $B_s \rightarrow D_s \pi$ from other $B$ reflections

- Mass resolution is crucial in achieving decent $S/B$
New $B^{**}$ result from D0

- **D0** uses fully reconstructed $B^+$
  - $65 \pm 17$ out of 1193 $B$ could be due from $B^{**0} \rightarrow B^+\pi^-$

- **CDF** Run-I used $B$ semileptonic decays
  - Fraction of $B$ from $B^{**} = 0.28 \pm 0.06 \pm 0.03$
TOF performance

- TOF is working and we are working on to improve its reconstruction efficiency

\[
\int \text{Ldt} = 1.5 \text{ pb}^{-1}
\]

w/o TOF

\[
N(\phi) = 2354 \pm 325 \\
N(\text{bkg}) = 93113
\]

With TOF

\[
N(\phi) = 1942 \pm 93 \\
N(\text{bkg}) = 4517
\]

\[\phi \rightarrow K K \text{ K decays}\]
\( \Delta \Gamma_s / \Gamma_s \) from Bs \( \rightarrow \) Ds+Ds-

- \( \text{Br}(\text{Bs} \rightarrow \text{Ds+Ds-}) = \Delta \Gamma_s / [\Gamma_s(1 + \Delta \Gamma_s / 2\Gamma_s)] \)

  Theory uncertainty could be large

- **Separates background of Ds* \( \rightarrow \) Ds \( \gamma \) using fine mass resolution

  Also introduce 3\% error on proper time

- \( 32 \pm 17 \text{ Bs} \rightarrow \text{Ds}^{(*)} \text{Ds}^{-(*)} \rightarrow \phi \phi \)

  \( \Delta \Gamma_s / \Gamma_s = 0.25 +0.21 -0.14 \) (ALEPH)

- **Channel is trigged with SVT of CDF**

  \( \text{Br}(\text{Bs} \rightarrow \text{Ds+Ds-}) / \text{Br}(\text{Bs} \rightarrow \text{Ds+}\pi-) \approx 2 \)

  Reconstruction efficiency will be lower

**GEANT for CDF**

(Run II B workshop)