$B_s$ Oscillation, $V_{TD}$ & $V_{TS}$, and Rare Decays

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B Mixing and Oscillations

\[ i \frac{d}{dt} \left( B^0 \right) = \left( M - \frac{i \Gamma}{2} \right) \left( M_{12} - \frac{i \Gamma_{12}}{2} \right) \left( \bar{B}^0 \right) \]

CP Eigenstates: \[ |B^{\text{even}}\rangle = |B^0\rangle + |\bar{B}^0\rangle \quad |B^{\text{odd}}\rangle = |B^0\rangle - |\bar{B}^0\rangle \]

Mass Eigenstates: \[ |B^H\rangle = p |B^0\rangle + q |\bar{B}^0\rangle \quad |B^L\rangle = p |B^0\rangle - q |\bar{B}^0\rangle \]

- Mass Difference: \( \Delta m = M_H - M_L \sim 2|M_{12}| \)
- Directly probes \( V_{td} \) and \( V_{ts} \) in oscillations of \( B_d \) & \( B_s \)

\[ \Delta m_d \propto |V_{tb}^* V_{td}|^2 \]
\[ \Delta m_s \propto |V_{tb}^* V_{ts}|^2 \]
Analysis Details

I. Measurement of production flavour
   - OS kaon flavour
   - SS kaon flavour
   - lepton flavour
     \[ b \rightarrow X l^- \text{, but } b \rightarrow c \rightarrow X l^+ \]
   - Jet Charge multivariate

II. Measurement of decay flavour
   - lepton or flavour specific final state

III. Measurement of Proper Time
   - depends on resolution of tracking system

See Talk by H. Evans for details of measurement
The measurements of $\Delta m_s$ are presented for both the DØ and CDF experiments. For DØ, the significance is 2.9 $\sigma$ with a value of $\Delta m_s = 18.53 \pm 0.93{\text{(stat)}} \pm 0.30{\text{(syst)}}$ ps$^{-1}$. For CDF, the significance is greater than 5 $\sigma$ with a value of $\Delta m_s = 17.77 \pm 0.10{\text{(stat)}} \pm 0.07{\text{(syst)}}$ ps$^{-1}$. See the talk by H. Evans for the details of the measurement.

The plots show the likelihood ratio and the CDF Run II Preliminary results with $L = 1.0$ fb$^{-1}$. The plot includes a sensitivity of 27.3 ps$^{-1}$ (tot).
Vts & Vtd

\[
\left| \frac{V_{td}}{V_{ts}} \right|^2 = \xi^2 \left( \frac{\Delta m_d}{\Delta m_s} \right) \left( \frac{M_{B_s}}{M_{B_d}} \right)
\]

D0: \(0.2018 \pm 0.0053\) (exp) \(\pm 0.0010(\Delta m_d) + 0.0078-0.0058(\xi)\)

CDF: \(0.2060 \pm 0.0007\) (exp) \(\pm 0.0010(\Delta m_d) + 0.0080-0.0060(\xi)\)

Ave: \(0.2059 \pm 0.0007\) (exp) \(\pm 0.0010(\Delta m_d) + 0.0080-0.0060(\xi)\)

- Uncertainty driven by theoretical calculation of \(\xi\).
- Full Uncertainties (added in naive quadrature)
  - D0 - 4.3%  CDF - 3.5%
  - Require theoretical improvements to progress here...
Future of Vts & Vtd

• Progress needs to be made on lattice calculations of $\xi$

\[
\frac{V_{td}}{V_{ts}} = \frac{f_{B_s} \sqrt{B_{Bs}}}{f_{B_d} \sqrt{B_{Bd}}} \sqrt{\frac{\Delta M_{d} M_{B_s}}{\Delta M_{s} M_{B_d}}}
\]

<table>
<thead>
<tr>
<th></th>
<th>$f_{B_q} \sqrt{B_{B_q}}$</th>
<th>$\xi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>statistics + fitting</td>
<td>1 – 3%</td>
<td>$\sim$ 1 – 2%</td>
</tr>
<tr>
<td>inputs ($a$, $m_b$ ...)</td>
<td>2.5%</td>
<td>&lt; 0.1%</td>
</tr>
<tr>
<td>Higher order matching</td>
<td>$\sim$ 3.5% cancel to a large extent</td>
<td></td>
</tr>
<tr>
<td>Heavy quark action</td>
<td>1.5 – 2%</td>
<td>&lt; 0.2%</td>
</tr>
<tr>
<td>Light quark discret.</td>
<td>2 – 4%*</td>
<td>&lt; 2%*</td>
</tr>
<tr>
<td>+ $\chi$PT fits</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total (estimate)</strong></td>
<td>5 – 7%</td>
<td>2 – 3%</td>
</tr>
</tbody>
</table>

• Possibility of reducing errors by factor of 1.5 - 2 over next two years
• Progress is difficult
Last Word on Oscillations

excluded area has CL > 0.95

$\sin 2\beta$

$|V_{ub}/V_{cb}|$

$\varepsilon_K$

$\alpha$

$\gamma$

$\rho$

$\Delta m_d$

$\Delta m_s & \Delta m_d$

$\varepsilon_K$

$\alpha$
Last Word on Oscillations

excluded area has CL > 0.95

sol. w/ cos2β < 0
(excl. at CL > 0.95)

excluded at CL > 0.95

CKM fit 2005

FPCP 2007
Rare Decays

- Processes
  - $B_s \rightarrow \mu \mu$, $B_s \rightarrow \mu \mu X$ (CDF & D0)
  - D Decays (D0 & CDF)

- All Depend on Integrated Luminosity
- Analysis presented here uses up to 2 fb$^{-1}$ of luminosity

- D0 (1 June 2008) Delivered 4.22 fb$^{-1}$
  Recorded 3.66 fb$^{-1}$

- Expect 7-10 fb$^{-1}$ by end of 2010

P5: Tevatron operation is expected to overlap for at least one year with physics operation of LHC. This overlap will be longer in favourable funding scenario. Most probable time for a decision about 2010 run is spring of 2009
\[ B^0_s \rightarrow \mu^+\mu^- \]

- \[ \text{Br}(B^0_s \rightarrow \mu^+\mu^-) = (3.42 \pm 0.54) \times 10^{-9} \]
- \[ \text{Br}(B^0_d \rightarrow \mu^+\mu^-) = (1.00 \pm 0.54) \times 10^{-9} \] suppressed by \( (V_{td}/V_{ts})^2 \)

- Expect 0 Events at Tevatron
- New Physics Contributions
  - MSSM \( \sim \tan^6(\beta) \), for large \( \tan(\beta) \),
    SUSY with R-parity violation, \( Z' \) with off diagonal couplings, ...
Analysis Steps - Example

\[ \text{BR} \left( B_S \rightarrow \mu^+ \mu^- \right) = \frac{N_{B_S}}{N_{B^+}} \cdot \frac{\alpha_{B^+} \cdot \epsilon_{B^+}}{\alpha_{B_S} \cdot \epsilon_{B_S}} \cdot \frac{f_{b \rightarrow B^+}}{f_{b \rightarrow B_S}} \]

\[ \text{BR} \left( B^+ \rightarrow J/\Psi K^+ \right) \cdot \text{BR} \left( J/\Psi \rightarrow \mu^+ \mu^- \right) \]

Reduce Background, keep efficiency high

1. Pre-selection cuts to reduce obvious backgrounds
2. Optimization (signal efficiency and expected background)
   Blind analysis
3. Reconstruct \( B^+ \rightarrow J/\Psi K^+ \) normalisation mode
4. Open the box \( \rightarrow \) Answer
Discriminating Variables

- $\mu^+\mu^-$ mass
  \[ \sim \pm 2.5\sigma \text{ mass window} \]
- B vertex displacement
- Isolation
  fraction of pT from $B\to\mu\mu$ within
  \[ \Delta R = (\Delta \eta^2 + \Delta \phi^2)^{1/2} \]
- Decay length significance
- $P_T(B) \& P_T(\mu)$
Discriminating Variables

Isolation

Flight length significance

$S_D$

$\Theta_D$

$\pi$ impact parameter significance

$I_D$

$\mu$

$\mu$

$\pi$

Isolation

Cut

Pointing angle [rad]

Arbitrary

Arbitrary

Cut

Signal MC

Signal MC

Sideband Data

Sideband Data

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$B_0^s \rightarrow \mu^+\mu^-$ Selection and Optimization

• **Signal:** MC
• **Background:** data mass sidebands
• **Final selection**
  • Likelihood ratio ($D0$)
  • Neural network (CDF)
• **Check selection with control samples**
  • Misidentified muon
  • Same sign muons
Results

- No excess observed (2 fb$^{-1}$)

90% Confidence limits on BR

$$B^0_s \rightarrow \mu^+\mu^- \quad B^0_d \rightarrow \mu^+\mu^-$$

CDF

$$< 4.7 \times 10^{-8} \quad < 1.5 \times 10^{-8}$$

D0

$$< 7.3 \times 10^{-8}$$

CDF II Preliminary (2 fb$^{-1}$)

HFAG Average:

$$< 4.7 \times 10^{-8}$$
History & Future

95% CL Limits on $\mathcal{B}(B_s \to \mu\mu)$

- 1998
- 2004
- 2005
- 2007

New Physics

CDF, D0

Standard Model Expectation

$10^7 \times$ Branching Fraction

$10^6 \times$ Branching Fraction

$10^5 \times$ Branching Fraction

$10^4 \times$ Branching Fraction

$10^3 \times$ Branching Fraction

$10^2 \times$ Branching Fraction

$10^1 \times$ Branching Fraction

$10^0 \times$ Branching Fraction

$10^{-1} \times$ Branching Fraction

$10^{-2} \times$ Branching Fraction

$10^{-3} \times$ Branching Fraction

$10^{-4} \times$ Branching Fraction

$10^{-5} \times$ Branching Fraction

$10^{-6} \times$ Branching Fraction

$10^{-7} \times$ Branching Fraction

$10^{-8} \times$ Branching Fraction

$10^{-9} \times$ Branching Fraction

analyzed luminosity (fb$^{-1}$)

Current sensitivity curve

< 3.0 x 10^{-9}

8.9 x SM

< 2.1 x 10^{-8}

6.1 x SM

~ 3.4 x 10^{-9}

Factor of 2 improvement in 2010 running

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mSUGRA Limits

95% CL Limits on $\mathcal{B}(B_s \rightarrow \mu\mu)$

mSUGRA at $\tan\beta = 50$
Arnowitt, Dutta, et al., PLB 538 (2002) 121

$A_0=0, \ \mu>0$
$\tan\beta=50$

$\alpha_\mu<11\times10^{-10}$

Standard Model Expectation

New Physics

Br($B_s \rightarrow \mu\mu$)
mSUGRA Limits

95% CL Limits on $\mathcal{B}(B_s \rightarrow \mu\mu)$

- 1998
- 2004
- 2005
- 2007

CDF ▲ D0

Standard Model Expectation

New Physics

x$10^{12}$ pp Collisions

m$_0$[GeV]

m$_{1/2}$[GeV]

mSUGRA at tan$\beta$ = 50
Arnowitt, Dutta, et al., PLB 538 (2002) 121

$A_0=0$, $\mu>0$
tan$\beta$=50

A$_\mu<11\times10^{-10}$

b$ightarrow s\gamma$

$\tau \rightarrow 3\pi$

$\tau \rightarrow 2\pi$

$\tau \rightarrow 4\pi$

17 GeV

120 GeV

10$^6$

10$^7$

10$^8$

dark matter allowed

m$_{\chi_0}>m_{\chi}$
\[ B^{(\pm,0)}(s) \rightarrow h^{(\pm,0)}\mu^+\mu^- \]

- Non resonant decays via box or penguin diagrams
- BaBar/Belle:
  \[ B^\pm \rightarrow K\mu^+\mu^- \quad \text{PRD73, 092001 (2006)} \]
  \[ B^0_d \rightarrow K^*\mu^+\mu^- \quad \text{PRL96, 251801 (2006)} \]
- Not yet observed:
  \[ B^{0_s} \rightarrow \phi\mu^+\mu^- \]
- Predicted branching ratio 1.6x10^{-6}
- NP:
  Larger BR, modified kinematic distributions
\(B^{(\pm,0)}(s) \rightarrow h^{(\pm,0)} \mu^+ \mu^-\)

CDF Run II Preliminary

\(B \rightarrow \mu \mu K^+\)

- \(B^+ \rightarrow \mu^+ \mu^+ K^+\) Data
- Signal region
- Sideband region
- Extrapolated fit

\(44.7 \pm 5.8\)

\(4.5 \sigma\)

CDF Run II Preliminary

\(B \rightarrow \mu \mu K^*\)

- \(B^0 \rightarrow \mu^+ \mu^- K^0\) Data
- Signal region
- Sideband region
- Extrapolated fit

\(18.5 \pm 3.6\)

\(2.9 \sigma\)

CDF Run II Preliminary

\(B \rightarrow \mu \mu \phi\)

- \(B_0 \rightarrow \mu^+ \mu^- \phi\) Data
- Signal region
- Sideband region
- Extrapolated fit

\(7.5 \pm 1.5\)

\(2.4 \sigma\)

\(\text{Events} / 5 \text{MeV}/c^2\)

- Sideband 1
- Signal region
- Sideband 2

\(\text{Invariant mass (}\mu^+ \mu^- K^+ K^-\) [GeV}/c^2]\)
$B^{(\pm,0)}_s \rightarrow h^{(\pm,0)} \mu^+ \mu^-$

- $\text{BR}(B^0_s \rightarrow \phi \mu^+ \mu^-) \@ 90\% \text{ CL}$

  - CDF(hep-ex/0804.3908) $< 5.0 \times 10^{-6}$
  - D0 (PRD 74, 031107 (2006)) $< 3.2 \times 10^{-6}$

Prediction $1.6 \times 10^{-6}$
• $B^0 \rightarrow \mu^+ \mu^-$ vs $D^0 \rightarrow \mu^+ \mu^-$
  • down quark sector vs up quark sector

• Short range contribution to BR is $\sim 10^{-18}$
  • suppressed by GIM

• Long range contribution to BR is $\sim 4 \times 10^{-13}$
  *Burdman et al. hep-ph/0112235*

• Significant enhancement possible in SUSY with R-parity violation

*SUSY with R-parity violation*
$D^0 \rightarrow \mu^+ \mu^-$

Detector

<table>
<thead>
<tr>
<th></th>
<th>CMU-CMU</th>
<th>CMU-CMX</th>
<th>CMX-CMX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected Background</td>
<td>4.9±1.3</td>
<td>2.7±1.0</td>
<td>1.0±0.5</td>
</tr>
<tr>
<td>Signal</td>
<td>3 (p=0.3)</td>
<td>0 (p=0.11)</td>
<td>1 (p=0.7)</td>
</tr>
</tbody>
</table>

$\text{BR}(D^0 \rightarrow \mu^+ \mu^-) < 4.3 \times 10^{-7}$ at 90% CL

$\lambda_{21k} \lambda_{22k} = 1.5 \sqrt{\text{BR}(D^0 \rightarrow \mu^+ \mu^-)} < 9.8 \times 10^{-4}$
$D(s)^+ \rightarrow \pi \mu^+ \mu^-$

- Orthogonal to $B^0_s \rightarrow \mu^+ \mu^-$
- Effects in up quark sector
- Long distance resonance production
- BR = $1.9 \times 10^{-6}$

Little Higgs models with new up sector vector quark

*Fajfer et al.*  *hep-ph/0511048*
RPV in the up sector and not the down sector

*Burdman et al.*  *hep-ph/0112235*
Resonant $D^+_s$ Decays

- Select events with $m(\mu\mu)$ in region of the $\phi$ mass
  - $N(D^+_s) = 254\pm 36$
  - $N(D^+) = 115\pm 31$

- Statistical Significance
  - $8\sigma$ for $D^+_s$ and $4.1\sigma$ for $D^+$
  - First observation of $D^+_s$
  - First evidence of $D^+$

$$\text{BR}(D^+ \rightarrow \phi \pi^+ \rightarrow \mu^+ \mu^- \pi^+) = (1.8 \pm 0.5 \pm 0.6) \times 10^{-6}$$
Resonant $D^{+}(s)$ Decays

- Exclude resonant $\phi \rightarrow \mu\mu$ mass region
- 19 candidates in $D^{+}$ region
- Expect $25.8 \pm 4.6$ background events (p-value=0.14)
- Normalise to $D^{+} \rightarrow \phi \pi^{+}$
- $\text{BR}(D^{+} \rightarrow \mu\mu\pi^{+}) < 3.9 \times 10^{-6}$ at 90% CL
The Last Word

- Measurement of $V_{ts}$ & $V_{td}$ now limited by theoretical inputs
  - Decade before significant improvement?

- B & D rare decays provide a sensitive probe into new physics
  - Sensitive to theoretical predictions in several extensions to the standard model.
  - Complementary to direct searches

- D0 & CDF will make major inroads before the LHC gets up and running

- Significant improvements expected with data set that should increase by a factor of 4