Discovering anything virtual

Overview of Lecture 3

- New Physics vs Old Physics
  \[ \Rightarrow B \text{ decays as a probe for the Unknown} \]
- \( B_s \) mixing @ CDF
- Measuring \( \gamma \) @ CDF
- Measuring CP viol. phase of a penguin
New Physics via Observation of New Particle

$\rightarrow$ Highest energies, low precision

New Physics via Virtual Intermediate States

$\rightarrow$ Highest precision, low energy
Impact of New Physics in $B$ Decays

(Largely) independent of NP:

\[ |V_{cb}| \quad \text{and} \quad |V_{ub}| \ e^{i\gamma} \]

Strikingly sensitive to NP:

Excellent Review of NP effects: Y. Nir hep-ph/9911321
e.g. SUSY, LR-symmetry, Multi-Higgs, new fermions, etc.
Rehash of CKM Matrix

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} =
\begin{pmatrix}
c_x c_z & s_x c_z & s_z e^{-i\phi} \\
-s_x c_y - c_x s_y s_z e^{i\phi} & c_x c_y - s_x s_y s_z e^{i\phi} & s_y c_z \\
-s_x s_y - c_x c_y s_z e^{i\phi} & -c_x s_y - s_x c_y s_z e^{i\phi} & c_y c_z
\end{pmatrix}
\]

Subscript $x,y,z$ are the three Euler angles.
$s, c$ stands for sin, cos.

\[s_x = \lambda, \quad s_y = A\lambda^2, \quad s_z = O(\lambda^3) \quad \lambda = 0.22, \quad A = 0.8\]

Phase shows up at $O(\lambda^3), O(\lambda^4), O(\lambda^5), O(\lambda^6)$

Guiding principle for phase convention:
Dominant processes are chosen to have zero phase!

Note: KM originally chose convention that gives zero phase to first row and column.
**B Decays within the SM**

\[
\begin{pmatrix}
1 - \frac{1}{2} \lambda^2 & \lambda & |V_{ub}| e^{-i\gamma} \\
-\lambda & 1 - \frac{1}{2} \lambda^2 & |V_{cb}|
\end{pmatrix} + O(\lambda^4)
\]

Measurements free of New Physics in loops:
Roadmap towards anything Virtual

- Measure $\lambda, |V_{cb}|, |V_{ub}|, \gamma$ in tree level processes.
- Use theory to predict loop processes.
- Measure loop processes and compare with theory predictions.
Example: Meson Mixing

\[ i \frac{d}{dt} \begin{pmatrix} a \\ b \end{pmatrix} = (M - \frac{i}{2} \Gamma) \begin{pmatrix} a \\ b \end{pmatrix} \]

\[ |B(t)\rangle = a |B^0\rangle + b |\bar{B}^0\rangle \]

\[ |M_{12}| \gg |\Gamma_{12}| \]
Physical Observables in $B_d$ Mixing

\[
\Delta m = 2|M_{12}|
\]
\[
\Delta \Gamma = 2Re(M_{12}\Gamma_{12}^*)/|M_{12}| \propto \cos 2\beta
\]
\[
A_{cp}^{mix}(t) = \pm Im\left(\frac{M_{12}^* A}{|M_{12}| A}\right) \times \sin \Delta m t \propto \sin 2(\beta + \theta)
\]

\[
2\beta := \text{Arg}(M_{12})
\]
\[
2\theta := \text{Arg}(\frac{A}{\bar{A}})
\]

\[
b \to c \quad \rightarrow \quad \theta = 0 \quad \text{by definition}
\]
\[
b \to u \quad \rightarrow \quad \theta = \gamma
\]

We measure $\beta$ via $A_{cp}^{mix}(t)$ in $b \to c$ and $\gamma$ via comparison with $A_{cp}^{mix}(t)$ in $b \to u$. 
Observing New Physics in $M_{12}$

CP violating New Physics in mixing

|Vub/Vcb|

CP conserving New Physics in mixing

$\eta$

$\beta$

$\rho$

1

$\Delta m_d / \Delta m_s$

$\gamma$

$\delta$

$\Delta m_s$

$\rho$

1

$\frac{\Delta m_d}{\Delta m_s}$
$B_s$ Mixing
Measuring $B_s$ mixing

- Trigger on & reconstruct the signal
- Suppress bkg
- Measure the flavor @ production
- Measure flight distance
- Measure $B_s$ momentum
Meson Mixing

\[ A_{mix} = \frac{N_{unmixed} - N_{mixed}}{N_{unmixed} + N_{mixed}} \]

\[ = D \cos \Delta m t \]

\[ D = 2P_{tag} - 1 \]

\[ Sig(\Delta m) = \sqrt{\frac{NeD^2}{2}}e^{-\frac{(\Delta m \sigma_t)^2}{2}}\sqrt{\frac{S}{S+bkg}} \]

Note: \( \Delta m \sigma_t < 1 \) for \( \Delta m / \Gamma < 33(25) \) with(without) L00
### Trigger & reconstruct the Signal

<table>
<thead>
<tr>
<th>$B_s \rightarrow D_s^{\pm} \pi^\mp$</th>
<th>$D_s \rightarrow \phi\pi$</th>
<th>$16k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_s \rightarrow K^*{}^0 K^-$</td>
<td></td>
<td>$15k$</td>
</tr>
<tr>
<td>$D_s \rightarrow \pi^+\pi^-\pi^+$</td>
<td></td>
<td>$5.5k$</td>
</tr>
</tbody>
</table>

| $B_s \rightarrow D_s^{\pm} \pi^\mp$ | $all$ | $37k$ |

<table>
<thead>
<tr>
<th>$B_s \rightarrow D_s^{\pm} \pi^+\pi^-\pi^\mp$</th>
<th>$D_s \rightarrow \phi\pi$</th>
<th>$15k$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$D_s \rightarrow K^*{}^0 K^-$</td>
<td>$17k$</td>
</tr>
<tr>
<td></td>
<td>$D_s \rightarrow \pi^+\pi^-\pi^+$</td>
<td>$6k$</td>
</tr>
</tbody>
</table>

| $B_s \rightarrow D_s^{\pm} \pi^+\pi^-\pi^\mp$ | $all$ | $38k$ |

Note: This is official CDF PR. It includes only trigger & tracking acceptance.
Flavor Tagging at CDF

![Diagram showing opposite side and same side (vertexing) of kaon production](image)

\[ ct = L_{xy} \frac{m_B}{p_T} \]

<table>
<thead>
<tr>
<th></th>
<th>Run1</th>
<th>Run2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Same-Side</td>
<td>1.0</td>
<td>4.2</td>
</tr>
<tr>
<td>Soft Lepton</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>Jet Charge</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Opposite Kaon</td>
<td>0.0</td>
<td>2.4</td>
</tr>
<tr>
<td>Total</td>
<td>5.7</td>
<td>11.3</td>
</tr>
</tbody>
</table>

Table 1: \( \epsilon D^2 \) in \( \% \), Fermilab Proposal 909, 1998.
\( \Upsilon(4s) \) vs Hadron Collider

**\( \Upsilon(4s) \)**

- coherent \( B^0 - \overline{B^0} \) production.

  \[ \Rightarrow \text{the other } b-\text{quark ALWAYS tags the flavor.} \]

- Geometric Acceptance 95 – 98\% of 4\pi.

  \[ \Rightarrow \epsilon D^2 \text{ is large} \sim \text{(} 30\% \text{)} \]

**Hadron Colliders**

- the other \( b-\text{quark hadronizes as } B^0, B^+, B_s, \Lambda_b, \text{ etc.} \)

  \[ \Rightarrow D \text{ is decreased by mixing:} \]

  \[
  D_{max} = 2P_{max} - 1 \\
  = 2(1 - f_d \cdot \chi_d - f_s \chi_s) - 1 \\
  \sim 0.7
  \]

- Geometric Acceptance is far from complete because of production characteristics.

- inferior Kaon particle ID
PR: Mixing Reach in Hadronic Decays

![Graph showing the mixing reach in Hadronic Decays with different signal-to-background ratios.](image)

- **Sig:Bg = 2:1**
- **Sig:Bg = 1:1 (default)**
- **Sig:Bg = 1:2**

**CDF**

**Excluded**

**Int. luminosity for 5 sigma observation**

**B_s mixing parameter, x_s**
“Conservative” Perspective

Analysis cuts \times 2

\[ B_s \rightarrow D_s \pi \text{ only} \times 2 \]

no L00 \times 1.5 @ x_s = 25

svx & svt ineff. \times 2.4

Run1 \epsilon D^2 \times 2.0

Take your pick on these factors and multiply y-axis on previous page by it to arrive at your own best guess as to how mu8ch lumi is required to measure x_s.
Aside: Mixing via semi-leptonic decays

Proper time resolution

\[ ct = \frac{L_{xy} \gamma B_s}{p_T(lD_s)} \times \kappa \]

\[ \sigma_t = \sqrt{\sigma_{t0}^2 + \left( \frac{t \sigma_{\kappa}}{\kappa} \right)^2} \approx \sqrt{(60 fs)^2 + (0.14 t)^2} \]
Measuring $\gamma$
Measuring $\gamma$ — the principle

\[
\gamma = \text{Arg} (V_{ub}^* V_{ud} V_{cb} V_{cd}^*) = \text{Arg}(V_{ub}^*) + O(\lambda^5) \text{ (standard phase conv.)}
\]

BTeV expectations: $B_s \to D_s K, B_d \to DK$ results in $\sigma_\gamma \sim 5 - 10^\circ$ after two years of running, i.e. $\sim 2008 - 2010$.

Measuring $\gamma$ is very difficult !!!

Fertile ground for new ideas !!!
Measuring $\gamma$ — an alternative approach

If Penguins didn’t exist:

$$Im\left(\frac{\bar{A}M_{12}^*}{A|M_{12}|}\right)$$

$$B_d \to \pi^+\pi^- \quad \sin 2(\gamma + \beta)$$

$$B_d \to J/\psi K_s \quad \sin 2\beta$$

but nature’s not this simple ...
Dominant Subdominant

\[ B_d \rightarrow \pi^+\pi^- \quad b \quad \overline{u} \]

\[ B_s \rightarrow K^+K^- \quad b \quad \frac{w^-}{u,c,t} \quad s \]

\[ \frac{\text{Subdominant}}{\text{Dominant}} \sim 0.2 - 0.4 \]

Penguin cleanup by relating CP asymmetries in \( B_d \rightarrow \pi^+\pi^- \) to \( B_s \rightarrow K^+K^- \) via SU(3) flavor.
Measuring $\gamma$ @ CDF

CP Violation in $B_d \rightarrow \pi^+\pi^-, B_s \rightarrow K^+K^-$

$$A_{CP}(t) = A_{dir} \cos \Delta m t + A_{mix} \sin \Delta m t$$

Combined fit to $B_d \rightarrow \pi^+\pi^-, B_s \rightarrow K^+K^-$

- Measure $A_{dir}^{\pi\pi}, A_{mix}^{\pi\pi}, A_{dir}^{KK}, A_{mix}^{KK}$.
- UT triangle fixes $\beta$
- extract weak phase $\gamma$
- extract strong phase and modulus of penguin/tree ratio

Aside: Details in Tevatron Run II B-workshop write-up.
Measuring $\gamma$ — the details


$\chi^2$ fit to 5 experimental results

Four unknowns:

- $d =$ ratio of hadronic matrix elements "$P/T$" $\sim 0.3$
- $\theta =$ strong phase of ratio of hadronic matrix elements $\sim 0$???
- $\gamma, \beta =$ weak phases

Five observables:

\[
A_{cp}(t) = A_{cp}^{dir} \times \cos \Delta m t + A_{cp}^{mix} \times \sin \Delta m t
\]
\[
A_{cp}^{dir}(\pi^+ \pi^-) = -2d \sin \theta \sin \gamma + O(d^2)
\]
\[
A_{cp}^{dir}(K^+ K^-) = \frac{2\lambda^2}{d(1-\lambda^2)} \sin \theta \sin \gamma + O((\frac{\lambda^2}{d})^2)
\]
\[
A_{cp}^{mix}(K^+ K^-) = \frac{2\lambda^2}{d(1-\lambda^2)} \cos \theta \sin \gamma + O((\frac{\lambda^2}{d})^2)
\]
\[
A_{cp}^{mix}(\pi^+ \pi^-) = \sin 2(\beta + \gamma) + 2d \cos \theta \times \\
(\cos \gamma \sin 2(\beta + \gamma) - \sin(2\beta + \gamma)) + O(d^2)
\]
\[
A_{cp}^{mix}(J/\psi K_s) = \sin 2\beta
\]
Blue: \( A_{dir} = \Delta \Gamma = 0 \)

Black: \( \Delta \Gamma = 0 \)

Red: \( A_{dir}, A_{mix}, \Delta \Gamma \) non-zero

\[
\frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} = 2e^{-\langle \Gamma \rangle t} \frac{2e^{-\langle \Gamma \rangle t}}{e^{-\Gamma H^t + e^{-\Gamma L^t} + A_{\Delta \Gamma}(e^{-\Gamma H^t} - e^{-\Gamma L^t})}} \times \\
(A_{mix} \sin(\Delta mt) + A_{dir} \cos(\Delta mt))
\]
Yields and Expected errors

Assume SU(3) and $B_d/B_s$ production $\sim 2.5$

\[
\begin{array}{cccc}
B_d \rightarrow \pi^+\pi^- & B_d \rightarrow K^+\pi^- & B_s \rightarrow \pi^+K^- & B_s \rightarrow K^+K^-\\
1 & 4 & 0.5 & 2 \\
5-10k & 20-40k & 2.5-5k & 10-20k
\end{array}
\]

Experimental Errors for “nominal assumptions”:

\[
\sigma_{Acp} \sim 0.08 \text{ for } B_s \rightarrow K^+K^- \\
\sigma_{Acp} \sim 0.14 \text{ for } B_d \rightarrow \pi^+\pi^-
\]
Distinguishing $\pi\pi$, $K\pi$, $KK$

<table>
<thead>
<tr>
<th></th>
<th>$K\pi$</th>
<th>$\pi\pi$</th>
<th>$KK$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_d$</td>
<td>20k</td>
<td>5k</td>
<td>0</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>0.95%</td>
<td>2.8%</td>
<td>-</td>
</tr>
<tr>
<td>$B_s$</td>
<td>2.5k</td>
<td>0</td>
<td>10k</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>4.8%</td>
<td>-</td>
<td>1.6%</td>
</tr>
<tr>
<td>bkg</td>
<td>14k</td>
<td>28k</td>
<td>14k</td>
</tr>
<tr>
<td></td>
<td>“Effective” S/bkg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_s$:</td>
<td>0.21</td>
<td>-</td>
<td>0.64</td>
</tr>
<tr>
<td>$B_d$:</td>
<td>1.24</td>
<td>0.34</td>
<td>-</td>
</tr>
</tbody>
</table>
Sensitivity for $A_{cp}$ — analytical expressions

$$A_{cp} = A^\text{dir}_{cp} \times \cos xt + A^\text{mix}_{cp} \times \sin xt$$

$G = \text{inverse of cov. matrix for } A^\text{dir}_{cp}, A^\text{mix}_{cp}$
\[ \chi^2 \text{ fit for } \gamma: \]

\[ \sigma_\gamma = \frac{+5.4}{-6.8} \pm 3 \text{ degrees} \]

Systematic Error due to SU(3) breaking of 20%: 
\[ \sim 1/2 \text{ the expected experimental error} \]

Aside: Comparable to BTeV reach in \( B_s \rightarrow D_s K \) by 2008-2010.
A word about theory systematics ...

- $B_d \to \pi^+\pi^-$ measures $\sin 2(\beta + \gamma)$ up to $\sim 30\%$ “penguin pollution”.
- “penguin pollution” cleaned up by $B_s \to K^+K^-$ up to $\sim 20\%$ SU(3) breaking.

SU(3) symmetry breaking is a “2nd order” effect on the measurement of $\gamma$.

Aside: SU(3) breaking tends to cancel in rate ratios like CP asymmetries. To be conservative, we ignored this fact.
Dependence on “Nature’s choice”

Large Penguin Correction to untangle ⇔ Large error on $\gamma$
Chasing SUSY with Penguins

\[ A_{SM} \propto \lambda^2 \frac{\alpha_s}{4\pi} \quad A_{NP} \propto \frac{M_W^2}{M_{NP}^2} \]

\[ \frac{A_{NP}}{A_{SM}} \sim O(1) \quad \Leftrightarrow \quad M_{NP} \sim 3 \text{ TeV} \]

SUSY may lead to \( A_{CP}(B^\pm \rightarrow \phi K^\pm) \sim 30\% \) (PRD63 (2001) 015003)

Expect 1.4 – 1.9k events @ BR=5.5e-6
(\( \sim 1000 fb^{-1} @ \Upsilon(4S) \))

> 4σ “observation” up to S/bkg ~ 1/4
• $\Delta \Gamma \& \text{Arg}(M_{12})$ using $B_s \to J/\psi \phi$; CDF(BTeV) expects 4000(20,000) events/2fb$^{-1}$

• Measure $\beta + \gamma$ using $B_d \to \pi^+ \pi^- \pi^0$; BTeV expect $\epsilon D^2 \times \text{yield} = 500$ events.
- D0 & CDF Run2 physics program are finally starting.
- Likely to start being competitive with BaBelle by Summer 2003 on a number of charm- and B-physics topics.
- Unique opportunities: $\Delta m_s, \gamma$