Run II Beauty Physics at CDF and DØ

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1. Introduction
2. Run II Detectors
3. CP Violation
4. $B_s$ Mixing
Introduction

- Why study B physics at the Tevatron?
  - Large rate:
    \[
    \sigma(p p \rightarrow b \bar{b}) \approx 150 \ \text{\mu}b \text{ at } 2 \text{ TeV}
    \]
    \[
    \sigma(e^+ e^- \rightarrow b \bar{b}) \approx 7 \ nb \text{ at } Z^0
    \]
    \[
    \sigma(e^+ e^- \rightarrow B \bar{B}) \approx 1 \ nb \text{ at } \Upsilon(4S)
    \]

- All species, including $B_s$, $B_c$, $\Lambda_b$, produced
Topics include

- CP violation and CKM angles
  - $\Delta \sin(2 \beta)$ ($B^0 \rightarrow J/\psi K_s$)
  - $\Delta \alpha$ ($B^0 \rightarrow \pi^+ \pi^-$)
  - $\Delta \gamma$ ($B_{s0} \rightarrow K^+ K^-$)
- $B_s$ mixing
- Cross sections
- Spectroscopy and lifetimes
- Rare and radiative decays
- Charmonium polarization
Highlights for Run II

- Trigger on tracks at Level 1
- Trigger on displaced tracks (impact parameter) at Level 2
- New tracking systems
- Increased muon coverage
- DØ has magnet, fiber tracker, silicon vertex detector, EM preshower
- CDF has Time-Of-Flight for kaon ID, layer 00 silicon, EM plug calorimeter
CKM Matrix

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} 
\approx 
\begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix}
\]

\[V_{tb}^* V_{td} + V_{cb}^* V_{cd} + V_{ub}^* V_{ud} = 0\]

- \(\lambda\) is the sine of the Cabibbo angle
- \(A\) and \(\lambda\) have been measured to a few percent
CP Violation in $B^0$ Decays

- Direct and mixed decays yield the same CP eigenstates at different rates

$$A(B_d \rightarrow \overline{B}_d) \propto m_t^2 V_{td}^2 \approx |A| e^{i2\beta}$$

$$A(\overline{B}_d \rightarrow B_d) \propto m_t^2 V_{td}^{*2} \approx |A| e^{-i2\beta}$$

- Reconstruct $B^0 \rightarrow J/\psi K_s$ decays to measure $\sin(2\beta)$

$$A_{CP}(t) = \frac{\Gamma(B^0 \rightarrow J/\psi K_S^0)}{\Gamma(B^0 \rightarrow J/\psi K_S^0)} - \frac{\Gamma(B^0 \rightarrow J/\psi K_S^0)}{\Gamma(B^0 \rightarrow J/\psi K_S^0) + \Gamma(B^0 \rightarrow J/\psi K_S^0)}$$

$$= \sin(2\beta) \sin(\Delta m_d t)$$
**B^0 \rightarrow J/\psi K_s** Reconstruction

- Measure decay length
- Tag flavour at production

**SST - pion charge**

**OST - lepton and jet charge**

Q > 0.2
Flavour Tagging

- Determine production flavour ($B^0$ vs $\bar{B}^0$)
- Opposite-side tags (other b)
  - charge of lepton from semileptonic decay
  - charge sum of particles in jet
- Same-side tags
  - charge of pion produced in fragmentation or $B^{**}$ decay
- Tagging efficiency $\epsilon = \frac{N_{\text{tag}}}{N_{\text{tot}}}$
- Dilution $D = (N_R - N_W) / (N_R + N_W)$
- Tag quality $= \epsilon D^2$
- CDF uses Run I $B^{\pm} \rightarrow J/\psi K^{\pm}$ events to calibrate flavour tagging algorithms.

- Charge of kaon tells you $B$ or $\bar{B}$

- Trigger and reconstruction similar to $B^{\circ} \rightarrow J/\psi K_s$
<table>
<thead>
<tr>
<th>Tag</th>
<th>$\varepsilon D^2$ (%) measured CDF Run I</th>
<th>$\varepsilon D^2$ (%) expected CDF Run II</th>
<th>Relevant DØ difference</th>
<th>DØ capabilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Same side</td>
<td>$1.8 \pm 0.4 \pm 0.3$</td>
<td>$2.0$</td>
<td>same</td>
<td>2.0</td>
</tr>
<tr>
<td>Soft lepton</td>
<td>$0.9 \pm 0.1 \pm 0.1$</td>
<td>$1.7$</td>
<td>$\mu, e$ ID coverage</td>
<td>3.1</td>
</tr>
<tr>
<td>Jet charge</td>
<td>$0.8 \pm 0.1 \pm 0.1$</td>
<td>$3.0$</td>
<td>forward tracking</td>
<td>4.7</td>
</tr>
<tr>
<td>Opp. side $K$</td>
<td>$2.4$</td>
<td></td>
<td>no K ID</td>
<td>none</td>
</tr>
<tr>
<td>Combined</td>
<td>$9.1$</td>
<td></td>
<td></td>
<td>9.8</td>
</tr>
</tbody>
</table>
- 4-track fit
- $m(\pi\pi) = m(K_s)$
- $m(\mu\mu) = m(J/\psi)$
- $K_s$ momentum points back to B vertex
- B momentum points back to primary vertex
CDF Run I $\sin(2\beta)$ Result

$\sin(2\beta) = 0.79^{+0.41}_{-0.44} \ (stat + syst)$
Run II $\sin(2\beta)$

- Reconstruct 30K-40K $B^0 \rightarrow J/\psi K_s$ events
- Expect $\sigma(\sin2\beta) \approx 0.04$ due to
  - improved muon acceptance
  - lower muon trigger thresholds
  - improved flavour tagging ($K$ ID (CDF), lepton ID)
  - Forward tracking (DØ)
  - trigger on $J/\psi \rightarrow e^+e^-$
- Result continues to be statistics limited due to size of tagging calibration samples
$\alpha$ and $\gamma$ in $B_{(s)}$ Decays

- $\sin(2\alpha)$ extracted from $A_{CP}(B^0 \rightarrow \pi^+ \pi^-)$
- Low branching fraction: $(0.5-1) \times 10^{-5}$
- Large backgrounds, mostly heavy flavour daughters
- DØ triggers on opposite-side lepton
- CDF uses all-hadronic trigger (L1 track + L2 impact parameter)
- Expect 5000 (500) events in 2 fb$^{-1}$
- Complicated by penguin contributions!
Reconstruct

- $B^0 \rightarrow \pi^+ \pi^-$
- $B^0 \rightarrow K^+ \pi^-$
- $B_s^0 \rightarrow \pi^+ K^-$
- $B_s^0 \rightarrow K^+ K^-$

In 1:4:0.5:2 ratios
Five observables in likelihood fit:

- $A_{cp}^{\text{dir}}(\pi^+ \pi^-)$
- $A_{cp}^{\text{dir}}(K^+ K^-)$
- $A_{cp}^{\text{mix}}(K^+ K^-)$
- $A_{cp}^{\text{mix}}(\pi^+ \pi^-)$
- $\sin(2\beta)$

Without penguins,

- $A_{cp}^{\text{mix}}(\pi^+ \pi^-) = \sin(2(\beta + \gamma)) = \sin(2\alpha)$
- $A_{cp}^{\text{mix}}(K^+ K^-) = \sin(2\gamma)$
- $A_{cp}^{\text{dir}}(\pi^+ \pi^-) = A_{cp}^{\text{dir}}(K^+ K^-) = 0$

- Predict $\sigma(A_{cp}(B^0 \rightarrow \pi^+ \pi^-)) \approx 0.15$
- Predict $\sigma(\gamma) = +5.4_{-6.8}^{+3} \text{ deg (CDF)}$
- Weak eigenstates ≠ mass eigenstates
- Mixing due to higher order corrections
- $\Delta m_q = m(B^0_{\text{heavy}}) - m(B^0_{\text{light}})$
- $p_{\text{mixed}}(t) = \frac{1}{2}(1 - \cos \Delta m_q t)$, $\Delta m_q \propto |V_{tb} \cdot V_{tq}|^2$
- Mixing parameters $x_q = \Delta m_q / \Gamma_q$ and $\Delta \Gamma_q$
Semileptonic Mode $B_s$

\[ B_s^0 \to D_s^- \ell^+ \nu X \]
\[ D_s^- \to \phi X \]
\[ \phi \to K^+ K^- \]

- trigger on dilepton events
- initial flavour tagged by opposite side lepton
- final flavour tagged by same side lepton
- require $D_s$ daughters kinematically consistent with $D_s$
- use amplitude fit method
- good for $x_s < 30$ (momentum uncertainty of missing $\nu$)
- 40 000 events in 2 fb$^{-1}$
Hadronic Mode $B_s$

*no missing neutrino

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

$$D_s^- \rightarrow \phi \pi^-$$

$$\phi \rightarrow K^+ K^-$$

- CDF uses 2-track hadronic trigger
- initial flavour tagged by opposite-side event (3 tags available)
- final flavour tagged by charge of $D_s$
- expect 5K-30K events in 2 fb$^{-1}$
- probe $x_s < 60$

- DØ triggers on opposite side lepton
- lepton charge tags initial flavour
- final flavour tagged by charge of $D_s$
- expect 1000 events in 2 fb$^{-1}$
- probe $x_s < 33$
Run II Tevatron Plan

- Run II starts March 2001
- No long shutdowns
- Gradual luminosity improvement over time
- Start at 396 ns bunch spacing
- Move to 132 ns bunch spacing in 2003
- Reach $2.0 \times 10^{32} \text{ cm}^{-1}\text{s}^{-1}$ by 2004
- Collect 15 fb$^{-1}$ by 2008
- CDF/DØ make way for BTeV in 2008
Conclusions

- After 2 years/2 fb\(^{-1}\) of data we will
  - measure \(\sin(2\beta)\) to an accuracy of 0.04
  - probe \(B_s\) mixing to \(x_s \approx 30\) with semileptonic decays
  - probe \(B_s\) mixing to \(x_s \approx 60\) in hadronic mode
  - measure \(A_{CP}(B^0 \rightarrow \pi^+ \pi^-)\) to an accuracy of 0.15 and \(\gamma\) to an accuracy of 8 degrees
  - Full reconstruction of \(B_c\) decay modes
  - Precision lifetime ratios (\(B_s/B^0\), \(\Lambda_b/B^0\), \(B_c/B^0\))
  - Rare decays: \(B^0_{(s)} \rightarrow \mu\mu K^{(*)}\), \(K^{*}\gamma\), \(\phi\gamma\)