Prospects for CP violation at the Tevatron (all angles)

Petar Maksimovic, for CDF and D0

CDF and D0 caught between

1) idealistic projections from long ago

2) realistic extrapolations from recent measurements

⇒ report on (2) only in several cases

show progress in other areas
Hadronic environment

Disadvantages:

• "messy"
• opp. side b-hadron not recostruc\nted 20-40% of time (coverage an \nissue -- points for D0)

Advantages:

• huge $b\bar{b}$ cross-section ($\sim 100 \, \mu b$ total)
• (still only 1 per $\sim 1000$ soft QCD collisions)

$\Rightarrow$ live and die by the trigger

(displaced track triggers: CDF from beginning, D0 commissioning now; faster DAQ -- points for CDF)
# Ingredient #1: Luminosity

<table>
<thead>
<tr>
<th>Luminosity in inverse fb</th>
<th>By 2008</th>
<th>By 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base projection</td>
<td>2.11</td>
<td>4.41</td>
</tr>
<tr>
<td>Design projection</td>
<td>3.78</td>
<td>8.57</td>
</tr>
</tbody>
</table>

(more optimistic, relies on electron cooling)

- Consider 2 inv.fb and 3.5 inv.fb
- Not clear if current B triggers are OK > 2007
Ingredient #2: flavor tagging

jet charge

decay kaon

fragmentation pion or kaon

soft lepton

b-hadron

P.V.

B

$\pi^+$

$\pi^-$

flavor tag side

vertexing side

ct
## Ingredient #2: flavor tagging

<table>
<thead>
<tr>
<th>$\epsilon D^2$ [%]</th>
<th>CDF</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft Muons</td>
<td>0.66±0.09</td>
<td>1.6±1.1</td>
</tr>
<tr>
<td>Soft Electrons</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Jet Charge</td>
<td>?</td>
<td>3.3±1.7</td>
</tr>
<tr>
<td>Same Side</td>
<td>1.9±0.9</td>
<td>5.5±2.0</td>
</tr>
<tr>
<td>Opp.Side Kaon</td>
<td>? [2.4]</td>
<td>N/A</td>
</tr>
<tr>
<td>Same Side Kaon</td>
<td>? [4.2]</td>
<td>N/A</td>
</tr>
</tbody>
</table>

- For projections, CDF is using $\epsilon D^2 = 5\%$
  
  (Down from > 10\% since Kaon tagging not ready)
## Ingredient #3: time resolution

<table>
<thead>
<tr>
<th></th>
<th>Proper time resol [fs]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF</td>
<td>67 (50 with L00)</td>
</tr>
<tr>
<td>D0</td>
<td>110</td>
</tr>
</tbody>
</table>

### Other expected improvements:

- **D0**: significant trigger upgrade just installed -- **adding track-based triggers**!
- **CDF**: upgrades to DAQ and trigger logic in 2004 and 2005
- **CDF's Layer 00** ready for physics
Overall game plan

\( B^0 \rightarrow \pi^+ \pi^- \) (BaBar/Belle, CDF + Theory)

\( b \rightarrow u \ell v \) (CLEO, B factories)

\( B_s - B_s \) mixing (CDF/D0 + Theory)

\( B^+ \rightarrow D^0 K^+ \) (BaBar/Belle/CDF)

\( B_s \rightarrow D_s^{-} K^+ \) (CDF eventually??)

\( B_s \rightarrow K^+ K^- \) (CDF?)

\( B^0 \rightarrow J/\psi K_s^0 \) (BaBar/Belle/CDF/D0) (still interesting??)

\( B^0 \rightarrow \phi K_s^0 \) (BaBar/Belle/CDF?/D0??) (very interesting!!!)
Composition of $B \rightarrow h^+ h^-$

- Mixture of:
  - $B_d \rightarrow K\pi$
  - $B_d \rightarrow \pi\pi$
  - $B_s \rightarrow KK$
  - $B_s \rightarrow K\pi$

- Can't use ToF

- Effective $K/\pi$ separation of $dE/dx$ only $\sim 1.16 \sigma$

$\Rightarrow$ Separate on statistical basis
Multi-dim unbinned likelihood fit

For each particle, use:

- \( \frac{dE}{dx} \) (calibrated on D*)
- Kinematic: \( m(\pi\pi) \) and \( \alpha \)

Pion momenta, \( p_1 < p_2 \)

\[
\alpha = \left(1 - \frac{p_1}{p_2}\right) \cdot q_1
\]

Charge of #1

\( m(\pi\pi) \) vs \( \alpha \)
$B \to h^+ h^-$ Results

- 65/pb of data
- First observation of
  - Includes error on $f_s/f_d$

\[
\frac{BR(B_s \to K^\pm K^{\mp})}{BR(B_d \to K^{\pm} \pi^{\mp})} = 2.71 \pm 1.15
\]

- Direct $A_{CP} \sim 0$, syst comparable to B factories

\[
A_{CP}(B^0 \to K^- \pi^+) = 0.02 \pm 0.15 \text{ (stat)} \pm 0.02 \text{ (syst)}
\]

<table>
<thead>
<tr>
<th>mode</th>
<th>Yield (65 pb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \to K\pi$</td>
<td>148±17(stat.)±17(syst)</td>
</tr>
<tr>
<td>$B^0 \to \pi\pi$</td>
<td>39±14(stat.)±17(syst)</td>
</tr>
<tr>
<td>$B_s \to KK$</td>
<td>90±17(stat.) ±17(syst)</td>
</tr>
<tr>
<td>$B_s \to K\pi$</td>
<td>3±11(stat.) ±17(syst)</td>
</tr>
</tbody>
</table>
Projected yields in $B \rightarrow h^+h^-$

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield 2 fb$^{-1}$</th>
<th>Yield 3.5 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_d \rightarrow K\pi$</td>
<td>6700</td>
<td>11,725</td>
</tr>
<tr>
<td>$B_d \rightarrow \pi\pi$</td>
<td>1770</td>
<td>3097</td>
</tr>
<tr>
<td>$B_s \rightarrow KK$</td>
<td>4040</td>
<td>7070</td>
</tr>
<tr>
<td>$B_s \rightarrow K\pi$</td>
<td>1070</td>
<td>1870</td>
</tr>
</tbody>
</table>

- $B_s \rightarrow K^+\pi^-$ -- from theory (no sensitivity yet)
- Simultaneous fit to kinematics + mass + dE/dx
  - errors not $\sim \sqrt{N}$ -- $N$ must be scaled by x0.6
- Systematics dominated by dE/dx
  - calibrated by $D^*$ → improve with more data
Angles $\alpha$ and $\gamma$: fitting for $A_{CP}$

- Use flavor tagging -- $\epsilon D^2 = 5\%$
- Separate Acp components into $B^0 \rightarrow \pi^+\pi^-$ (measures $\sin 2\alpha$) and $B_s \rightarrow K^+K^-$ ($\sin 2\gamma$)

$$A_{CP}(B^0) = A_{CP}^{dir} \cos(\Delta m_d t) + A_{CP}^{mix} \sin(\Delta m_d t)$$

$\Rightarrow$ Trigger favors mixing Acp (due to Lxy cut)

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

Large but unknown
Error on $A_{CP}$ vs luminosity

CDF RunII Preliminary

$B^0 \rightarrow \pi\pi$

$\epsilon = D^2 = 5\%$

A factor of 4 below Yellow Book
Error on $A_{CP}$ vs luminosity

CDF RunII Preliminary

$B_S \rightarrow KK$

$\epsilon \in D^2 = 5\%$

$\sigma_t = 50$ fs

$x_S = 50$

$x_S = 30$

$x_S = 20$
Decay modes

- Estimates of yields only
- Need to do a combined mass vs dE/dx fit for Cabibbo suppressed $B \to DK$ modes first
- $B_s \to D_sK$ tied to Bs mixing in $B_s \to D_s\pi$
- BaBar/Belle: $\frac{BR(B^+ \to D^0K)}{BR(B^+ \to D^0\pi)} = (8.31 \pm 0.35 \pm 0.20)\%$

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield in 2 fb$^{-1}$</th>
<th>Yield in 3.5 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^\pm \to \bar{D}^0\pi, \bar{D}^0 \to K\pi$</td>
<td>48,000</td>
<td>84,000</td>
</tr>
<tr>
<td>$B^\pm \to \bar{D}^0K, \bar{D}^0 \to K\pi$</td>
<td>3990</td>
<td>6980</td>
</tr>
<tr>
<td>$B^\pm \to \bar{D}^0K, (\bar{D}^0 \to KK + \bar{D}^0 \to \pi\pi)$</td>
<td>520</td>
<td>910</td>
</tr>
<tr>
<td>$B_s \to D_s\pi, D_s \to \phi\pi$</td>
<td>3200</td>
<td>5600</td>
</tr>
<tr>
<td>$B_s \to D_sK, D_s \to \phi\pi$</td>
<td>256</td>
<td>448</td>
</tr>
</tbody>
</table>
$B \rightarrow DK$ mass plots

CDF Run II Preliminary, $L = 119 \text{ pb}^{-1}$

$N(B^+) = 1259 \pm 41$

$N(B_s^0) = 84 \pm 11$

$8\%$ D0 K

$8\%$ Ds K
CP violation in $B_s \rightarrow J/\psi \phi$

- Both D0 and CDF
- Needs $x_s$ first
- Measures

$$ \beta_s \equiv \arg \left( -\frac{V_{ts} V_{*tb}}{V_{cs} V_{*cb}} \right) $$

(directly $\sim \eta$)

- CDF's yield:
  120 ± 13 events in 140 pb-1

$B_s \rightarrow J/\psi \phi$

$N(B_s) = 133 \pm 17$
Direct CP violation

- $B^+ \rightarrow \phi K^+$ etc. especially interesting
- $B^0 \rightarrow \phi K^0_s$: a dedicated phi trigger will help
- Measure $A_{CP}$ for all decay modes
- Baryons too! e.g. $\Lambda_b \rightarrow pK$, and $\Lambda_b \rightarrow p\pi$

Food for thought: what if $A_{CP} \neq 0$?
Direct CP violation in Charm

- $D^{*+} \rightarrow D_{CP}^0 \pi^+$ (comparison from a recent review):

Table 7: Comparison of measurements in $A_{CP}$ for $D^0$ modes, from E791 (89), FOCUS (90), CDF (88), and CLEO (78)

<table>
<thead>
<tr>
<th>Mode</th>
<th>$A_{CP}$</th>
<th>Mode</th>
<th>$A_{CP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO $D^0 \rightarrow K^+K^-$</td>
<td>$(0.0 \pm 2.2 \pm 0.8)$%</td>
<td>$D^0 \rightarrow \pi^+\pi^-$</td>
<td>$(1.9 \pm 3.2 \pm 0.8)$%</td>
</tr>
<tr>
<td>E791 $D^0 \rightarrow K^+K^-$</td>
<td>$(-1.0 \pm 4.9 \pm 1.2)$%</td>
<td>$D^0 \rightarrow \pi^+\pi^-$</td>
<td>$(-4.9 \pm 7.8 \pm 2.5)$%</td>
</tr>
<tr>
<td>FOCUS $D^0 \rightarrow K^+K^-$</td>
<td>$(-0.1 \pm 2.2 \pm 1.5)$%</td>
<td>$D^0 \rightarrow \pi^+\pi^-$</td>
<td>$(4.8 \pm 3.9 \pm 2.5)$%</td>
</tr>
<tr>
<td>CDF $D^0 \rightarrow K^+K^-$</td>
<td>$(2.0 \pm 1.7 \pm 0.6)$%</td>
<td>$D^0 \rightarrow \pi^+\pi^-$</td>
<td>$(3.0 \pm 1.9 \pm 0.6)$%</td>
</tr>
<tr>
<td>CLEO $D^0 \rightarrow K_S^0\pi^0$</td>
<td>$(0.1 \pm 1.3)$%</td>
<td>$D^0 \rightarrow \pi^0\pi^0$</td>
<td>$(0.1 \pm 4.8)$%</td>
</tr>
<tr>
<td>CLEO $D^0 \rightarrow K_SK_S^0$</td>
<td>$(-23 \pm 19)$%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Projections for 2 fb-1:

  $D^0 \rightarrow \pi^+\pi^- \quad 0.4\% \quad 1.9\%\sqrt{65/2000}$

  $D^0 \rightarrow K^+K^- \quad 0.3\% \quad 1.7\%\sqrt{65/2000}$

  $D^+ \rightarrow \pi^+\pi^-\pi^+ \quad 0.2\% \quad 1/\sqrt{5nb*2fb^{-1/30}}$
Summary

• CDF and D0 ready for CP violation studies:
  – excellent understanding of tracking and of
  – most low-level components (e.g. dE/dx)
  – New: use of L00 in CDF and D0 trigger hardware
• Bottom line: below Yellow Book estimates
  – Improvements possible, require work
• Focus on Bs, baryons and low rate modes
• Exploit searches for direct CP violation
• Hidden opportunities in charm sector!
Backup slides
- D0 yield will improve due to new trigger hardware (just coming online)
- No updates on $\sigma(\sin 2\beta)$ yet