B Physics at CDF

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Introduction: \textit{B} Physics at Tevatron/CDF

Production rates are high

\[
\sigma(e^+e^- \rightarrow b\bar{b}) \approx 1 \text{ nb at } \Upsilon(4S), \quad 6 \text{ nb at } Z^0
\]

\[
\bar{p}p \rightarrow b\bar{b}X
\]

via strong interaction

\[
\sigma \sim 10 \mu \text{b at } 1.8 \text{ TeV}
\]
Tevatron Accelerator

- New 120/150 GeV Main Injector replaced Main Ring
  - Increased intensity of protons and antiprotons.
- Tevatron operates with 36 x 36 bunches
- Increased CM energy from 1.8 TeV to 1.96 TeV

Run II started in March 2001.
Tevatron Run-II weekly and total integrated luminosity

Typical detector efficiency ~85-90%

Luminosity used for HF analyses 6–140 pb⁻¹

~220 pb⁻¹ on tape per experiment
Many detector components are brand-new
- Tracking system
  - Silicon detectors
  - Main drift chamber
- FE electronics
- Trigger/DAQ
- Plug calorimeter
- Extended muon coverage
- TOF system

Retained good momentum resolution & lepton ID.
Central Outer Tracker
30 k sense wires
$\sigma(p_T)/p_T = 0.0008 \, p_T\, (\text{GeV/c})$
Relativistic rise $dE/dx$

Silicon detector
700 k channels,
max 15 hits per track.

New plug calorimeter
To $|\eta| < 3.6$, electron ID
TOF particle ID
$K/\pi$ separation to 1.5 GeV

Muon coverage
To do $B$ physics at hadron colliders, you need to trigger on $B$ decays.

Traditionally CDF relied on leptons:

- **Single leptons** ($e$, $\mu$)

  $$\overline{B} \rightarrow \ell^- \bar{\nu} X$$

  - $b \rightarrow \ell^- X$, $\overline{b} \rightarrow \ell^+ X'$

  - $W^-$
  - $(\ell^- \bar{\nu})$
  - $(d \bar{u})$
  - $(s \bar{c})$
  - $c, u D, D^*, ...$

- **Di-leptons** ($\mu\mu$, $e\mu$)

  $$B \rightarrow J/\psi X, \ J/\psi \rightarrow \mu^+\mu^-, \ b \rightarrow \ell^- X, \overline{b} \rightarrow \ell^+ X'$$

  - $\psi J/ \rightarrow \ell^+\ell^-$
  - $c \overline{c}$
  - $\overline{s} \overline{q}$ $K, K^*, ...$

- $b \rightarrow \ell^- X$, $\overline{b} \rightarrow \ell^+ X'$
Run-I signal: \( J/\psi \rightarrow \mu^+\mu^- \)

- \( \sim 240 \text{ k} J/\psi \rightarrow \mu^+\mu^- \).
- Mass resolution \( \sim 16 \text{ MeV}/c^2 \).
- \( \sim 20\% \) from \( B \) decays, others direct / \( \chi_c \rightarrow J/\psi \gamma \).
CDF-II silicon detectors

**SVX II**
- Radii 2.5 cm to 11 cm
- 5 layers
- Double-sided, $90^\circ$ and $1.2^\circ$ stereo
- Main vertex detector

**Intermediate silicon layers (ISL)**
- 3 more layers at $R = 20 - 29$ cm
- Construction similar to SVX II
- Precision tracking to higher $\eta$.
- Aid linking from COT to SVX.

**Layer 00**
- At radius $\sim 1.6$ cm, on beam pipe.
- Minimize multiple scattering effects.
- Single-sided.
Run-II Silicon Vertex Trigger: SVT

Use silicon information at the 2nd level of trigger

- Find a track in the main tracker COT.
- Extrapolate toward the SVX.
- Find SVX hits along the road.
- Calculate impact parameter wrt the primary vertex (beam spot).
- Resolution $\sim 50\ \mu m$ for $>2$ GeV/c.

Typical trigger:
- two tracks above 2 GeV/c,
- $|d| > 120\ \mu m$,
- $L_{xy} > 500\ \mu m$. 
Huge charm signals observed

\[ D^0 \rightarrow K^- \pi^+ \]

CDF RunII Preliminary \[ L = 65 \pm 4 \text{ pb}^{-1} \]

450 k ev. / 65 pb\(^{-1}\)
More charm

\[ D^+ \to K^+ \pi^+ \pi^+ \]

CDF RunII Preliminary

\[ D^\pm \to K \pi \pi \quad N_D = 287600 \pm 700 \]

Uncorr. Mean = 1862.2 \pm 0.2 \text{ MeV/}c^2

Width = 8.4 \pm 0.1 \text{ MeV/}c^2

\[ L = 65 \pm 4 \text{ pb}^{-1} \]

\[ D_s^+ \to \phi \pi^+ \quad \phi \to K^+K^- \]

CDF Run II Preliminary, Jun '02

D, \ D_s \to \phi \pi, \ \phi \to KK

Luminosity: \ 11.6 \text{ pb}^{-1}

D meson production cross-sections measured.

Sub. to PRL (hep-ex/0307080)
Search for $D^0 \rightarrow \mu^+\mu^-$

FCNC decay. Proceed via loop and box diagrams in SM.

Also helicity suppressed:
B.F. $\sim 10^{-13}$.
Good place to look for new physics effects.

Use $D^0 \rightarrow \pi^+\pi^-$ as normalization.
Can also feed into signal region.
$D^0 \rightarrow \mu^+ \mu^-$ search result

CDF Run II Preliminary

0 events in the ±2σ search window

$D^0 \rightarrow \mu^+ \mu^-$ Search

0 candidate observed, 1.7 BG expected.

$\mathcal{B}(D^0 \rightarrow \mu^+ \mu^-) < 2.4 \times 10^{-6}$
(90% C.L.)

PDG 2002:
$\mathcal{B}(D^0 \rightarrow \mu^+ \mu^-) < 4.1 \times 10^{-6}$

Sub. to PRD, hep-ex/0308059
$B$ physics: does the unitarity triangle close?

- $|V_{cb}|$ from $b \to c \ell \nu$, $|V_{ub}|$ from $b \to u \ell \nu$.
- $|V_{td}|$ from $\Delta m_d$, but large QCD uncertainties.
- Use ratio to partially cancel the uncertainties

$$\frac{\Delta m_s}{\Delta m_d} = \left| \frac{V_{ts}}{V_{td}} \right|^2 \frac{M_{B_s}}{M_{B_d}} \xi^2 \quad (\xi = 1.14 \pm 0.03^{+0.13}_{-0.02})$$

- Present limit on $\Delta m_s$ (95% C.L.)

$$\frac{\Delta m_s}{\Delta m_d} > \frac{13.1}{0.489} \Rightarrow \left| \frac{V_{td}}{\lambda V_{ts}} \right| < 1.1$$

hep-ph/0307039
S. Aoki et al.
Run-II Di-muon data

CDF Run II Preliminary, L=70pb^{-1}

$J/\psi \rightarrow \mu^+\mu^-$
510K signal candidates

CDF Run 2 Preliminary
Signal Region Events

- Total Fit
- $J/\psi$ Contribution
- Background Contribution

$p_T$ threshold lowered:
from 2 GeV/c to 1.5 GeV/c

Yield $\sim 2 \times$ Run I

$B$ fraction $\sim 15\%$

$\tau(B) = 1.526 \pm 0.034 \pm 0.035$ ps
State $X(3780) \rightarrow J/\psi \pi^+\pi^-$

CDF confirms Belle discovery

**Run II --- CDF Preliminary**

$M(\pi\pi) > 500$ MeV/c$^2$

- 3678 ± 99 $\psi$(2S)
- Mass: 3685.67 ± 0.08 (stat) MeV/c$^2$
- $\sigma$: 3.41 ± 0.09 (stat) MeV/c$^2$
- 704 ± 67 Candidates
- Mass: 3871.4 ± 0.7 (stat) MeV/c$^2$
- $\sigma$ (Fixed): 4.3 MeV/c$^2$

Mass: $3871.4 \pm 0.7 \pm 0.4$ MeV/$c^2$

Width: narrow, consistent with resolution.
$B^+ \rightarrow J/\psi \ K^+$

CDF Run II Preliminary 80 pb$^{-1}$

$B^+ \rightarrow J/\psi \ K^+$

$N(B_u)=828.3 \pm 31.0$

$m(B^+)=5279.32 \pm 0.68 \pm 0.94 \text{ MeV}/c^2$

$\tau(B^+)=1.57 \pm 0.07 \pm 0.02 \text{ ps}$
\[ B^0 \rightarrow J/\psi K^{*0} \rightarrow \mu^+ \mu^- K^+ \pi^- \]

\[ B^0 \rightarrow J/\psi K^0_S \rightarrow \mu^+ \mu^- \pi^+ \pi^- \]

CDF Run II Preliminary 80 pb^{-1}

\[ B^0 \rightarrow J/\psi K^{0*} \]

N(Bd)=550.9 \pm 30.5

CDF Run II Preliminary 80 pb^{-1}

\[ B^0 \rightarrow J/\psi K_s \]

N(Bd)= 178 \pm 10

\[ m(B^0) = 5280.30 \pm 0.92 \pm 0.96 \text{ MeV/c}^2 \]

Mode for \( \sin 2\beta \).
\[ B_s^0 \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+ K^- \]

CDF Run II Preliminary, \( L=70 \text{pb}^{-1} \)

\[ B_s \rightarrow J/\psi \phi \]
\[ 74 \pm 11 \text{ signal candidates} \]
\[ L_{xy} > 100 \mu \text{m} \]

Predict \( \tau(B_s^0)/\tau(B^0) = 1.0 \pm \mathcal{O}(1\%) \)

But expect \( \Delta \Gamma_s / \Gamma_s \sim 0.1 \).

This mode is dominated by CP-even eigenstate. Can exhibit different \( \tau \) from flavor eigenstates, e.g. \( \ell^- \bar{\nu} D_s^+ \) and \( D_s^+ \pi^- \).

\[ m(B_s^0) = 5365.50 \pm 1.29 \pm 0.94 \text{ MeV}/c^2 \]
\[ \tau(B_s^0) = 1.33 \pm 0.14 \pm 0.02 \text{ ps} \]

Future: look for CP-violation ~ zero expected in SM, \( \arg(V_{ts}) \).
Rare decays $B^0/B^0_s \rightarrow \mu^+ \mu^-$

- $V_{td}$ for $B^0$, $V_{ts}$ for $B^0_s$
- Helicity suppressed.
- B.F. very small.

SM predictions for B.F.

- $B^0 \rightarrow \mu^+ \mu^- (1.5 \pm 1.4) \times 10^{-10}$
- $B^0_s \rightarrow \mu^+ \mu^- (3.5 \pm 1.0) \times 10^{-9}$
- $B^0 \rightarrow e^+ e^- (3.4 \pm 3.1) \times 10^{-15}$
- $B^0_s \rightarrow e^+ e^- (8.0 \pm 3.5) \times 10^{-14}$
Search for $B^0/B_s^0 \rightarrow \mu^+\mu^-$

One candidate in the overlap region of $B^0$ and $B_s^0$ mass windows.

- B.R. $< 3.1 \times 10^{-7}$ for $B^0$
- B.R. $< 1.2 \times 10^{-6}$ for $B_s^0$ at 95% C.L.

Previous CDF limits:
- B.R. $< 8.6 \times 10^{-7}$ for $B^0$
- B.R. $< 2.6 \times 10^{-6}$ for $B_s^0$

PRD 57, 3811 (1998)

Some new physics models constrained.
$B$ signals from SVT triggers: full reconstruction

$B^- \rightarrow D^0 \pi^- \rightarrow (K^- \pi^+) \pi^-$

$\bar{B}^0 \rightarrow D^+ \pi^- \rightarrow (K^- \pi^+ \pi^+) \pi^-$

CDF Run II Preliminary

Calibration modes for $B^0_s - \bar{B}^0_s$ oscillations.

Understand proper time resolution and flavor tagging.
What we wanted: \( \bar{B}_s^0 \rightarrow D_s^+ \pi^- \rightarrow (\phi \pi^+) \pi^- \)

Next step:
Accumulate stats, look for oscillations.

\( \Delta m_s \Rightarrow \)
Crucial for \(|V_{td}/V_{ts}|\)

Theory:
To what extent does the \( f_B \) uncertainty cancel in the ratio \( \xi \)?
Does not seem as simple as we once thought…
What we wanted II: $B^0 / B^0_s \rightarrow h^+ h^-$

Peak is mixture of

- $B^0 \rightarrow \pi^+ \pi^-, K^+ \pi^-$
- $B^0_s \rightarrow K^+ K^-, K^- \pi^+$

CDF Run 2 Preliminary

$B \rightarrow h^+ h^-$

280 ± 26 signal events
Mean $5.252 \pm 0.004$ GeV/c$^2$
Width $0.041 \pm 0.004$ GeV/c$^2$

Use $dE/dx$ and mass distributions to determine composition
\( B^0 / B_s^0 \rightarrow h^+h'^- \) composition

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield (65 pb(^{-1}))</th>
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<tbody>
<tr>
<td>( B^0 \rightarrow K^+\pi^- )</td>
<td>148 ± 17 ± 17</td>
</tr>
<tr>
<td>( B^0 \rightarrow \pi^+\pi^- )</td>
<td>39 ± 14 ± 17</td>
</tr>
<tr>
<td>( B_s^0 \rightarrow K+K^- )</td>
<td>90 ± 17 ± 17</td>
</tr>
<tr>
<td>( B_s^0 \rightarrow K^+\pi^- )</td>
<td>3 ± 11 ± 17</td>
</tr>
</tbody>
</table>

First observation of \( B_s^0 \rightarrow K+K^- \)

\[
\frac{f(b \rightarrow B_s^0) \cdot \mathcal{B}(B_s^0 \rightarrow K+K^-)}{f(b \rightarrow B_d^0) \cdot \mathcal{B}(B_d^0 \rightarrow K^+\pi^-)} = 0.74 \pm 0.20 \pm 0.22
\]

Also:

\[
\frac{\mathcal{B}(B_d^0 \rightarrow \pi^+\pi^-)}{\mathcal{B}(B_d^0 \rightarrow K^+\pi^-)} = 0.26 \pm 0.11 \pm 0.06
\]

\[
\mathcal{A}_{CP}(B^0 \rightarrow K^+\pi^-) = 0.02 \pm 0.15 \pm 0.02
\]

Hope to extract angle \( \gamma \) in a longer term (after \( \Delta m_s \))
Even $B^+ \rightarrow \phi K^+$ is seen

CDF Run II Preliminary, $66 \pm 4$ pb$^{-1}$

$B^\pm \rightarrow \phi K^\pm$

$13.4 \pm 5.7$ Events

$\mathcal{B}(B^+ \rightarrow \phi K^+) = (0.68 \pm 0.21 \pm 0.07) \times 10^{-2}$
Summary

CDF Run-II in progress since 2001:

- Finally we are back in business.
- So far recorded 250 pb\(^{-1}\), analyzed up to \(\sim 100\) pb\(^{-1}\)
  - surpassed Run-I total. More to come.
- Enhanced B physics capabilities:
  - has added silicon-based trigger, enabling to collect all-hadronic final states such as \(B \rightarrow D \pi\).
  - lepton triggers remain valuable.
- Hope to collect \(\sim 2\) fb\(^{-1}\) in the coming few years, and to make significant measurements of B decays. Some are quite complementary to Belle/BaBar.
Plans

- Open and onium charm/bottom production.
- $B^{-}$, $\bar{B}^{0}$, $\bar{B}_{s}^{0}$, $\Lambda_{b}^{0}$, $B_{c}^{-}$ masses/lifetimes.
  Also $\Delta\Gamma_{s}$.
- Re-establish $B^{0}$-$\bar{B}^{0}$ oscillations, calibrate flavor tagging.
- Measure $\sin 2\beta$.
- Rare decays, $B \to K^{(*)}\ell^{+}\ell^{-}$, $B_{s}^{0}/D^{0} \to \mu^{+}\mu^{-}$.
- Measure $\Delta m_{s}$ with $\bar{B}_{s}^{0} \to D_{s}^{+}\pi^{-}$.
- Measure CP violation in $B^{0} \to \pi^{+}\pi^{-}$ and $B_{s}^{0} \to K^{+}K^{-}$.
  Angle $\gamma$ to 10°?
- Look for CP violation in $B_{s}^{0} \to J/\psi \phi$,
  new phase in $B_{s}^{0}$ oscillations ??
- Angle $\gamma$ from $\bar{B}_{s}^{0} \to D_{s}^{\pm}K^{\mp}$ ???
Backup Slides follow
\( \bar{B} \rightarrow D \pi^- \) mass distribution from Monte Carlo

CDF Run II Monte Carlo

\[ B^- \rightarrow D^0 \pi^- \]

\[ \bar{B}^0_s \rightarrow D_s^+ \pi^- \]

Structure below B mass understood from missing neutrals.
Probing angle $\gamma$ (phase of $V_{ub}$)

- $B^0 \rightarrow \pi^+ \pi^-$ once thought to be the mode for $\sin 2(\pi - \gamma - \beta)$.
  (assuming $b \rightarrow u$ tree dominance over penguin)
- CLEO finds much larger $K^- \pi^+$ and tiny $\pi^+ \pi^-$.  
- Not just small rates, but also means penguin pollution.
  - Relation to $\sin(2\alpha)$ less clear.
- Strategies proposed, but are challenging experimentally...

Throw in $B^0_s \rightarrow K^+K^-$, measure asymmetries in both $B^0$ and $B^0_s$.

In general, for a decay $B^0 \rightarrow f$ ($f =$ CP eigenstate):

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

$A_{dir}$: “direct” CP violation, $A_{mix}$: CP violation thru mixing.

Experimentally, measure 4 $A$'s from $B^0 \rightarrow \pi^+ \pi^-$ and $B^0_s \rightarrow K^+K^-$.  
Then extract $\beta$, $\gamma$ and penguin and tree decay amplitudes.
Angle $\gamma$ (phase of $V_{ub}$) continued

Four CP asymmetries to measure. ($\lambda = \sin \theta_c$)

- $A_{\text{dir}}(B^0 \rightarrow \pi^+ \pi^-) = -2d \sin \theta \sin \gamma / (1 - 2d \cos \theta \cos \gamma + d^2)$
- $A_{\text{mix}}(B^0 \rightarrow \pi^+ \pi^-) = \left[ \sin 2(\beta+\gamma) - 2d \cos \theta \sin(2\beta+\gamma) + d^2 \sin 2\beta \right] / \left[ 1 - 2d \cos \theta \cos \gamma + d^2 \right]$
- $A_{\text{dir}}(B^0_s \rightarrow K^+ K^-) \sim 2(\lambda^2/d) \sin \theta \sin \gamma$
- $A_{\text{mix}}(B^0_s \rightarrow K^+ K^-) \sim 2(\lambda^2/d) \cos \theta \sin \gamma$

Four unknowns to extract:

- $\beta, \gamma =$ angles of the unitarity triangle.
- $d =$ ratio of penguin ($P$) to tree ($T$) decay amplitudes,
  $\theta =$ phase of "$P/T$"
  $d' e^{i\theta} \equiv \lambda |V_{cb}/V_{ub}| / (1-\lambda^2/2) [ \ P / (T+P) \ ]$

If no penguin,
$A_{\text{dir}} = 0 \quad (B^0, B^0_s)$
$A_{\text{mix}} = \sin 2(\beta+\gamma) (B^0)$
$A_{\text{mix}} = \sin(2\gamma) \quad (B^0_s)$

Expect $\sim 5 k \ B^0 \rightarrow \pi^+ \pi^-, \sim 10 k \ B^0_s \rightarrow K^+ K^-$
$\rightarrow$ angle $\gamma$ to $\sim 10^\circ$. 
TOF kaon identification

$\phi \rightarrow K^+ K^-$
$(p_T < 1.5 \text{ GeV}/c)$

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

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

$\int Ldt = 1.5 \text{ pb}^{-1}$
$|\Delta t_K/\sigma_t| < 3$

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

S/N improves by a factor of 20, while keeping 82% of signal.
CDF $B_s$ Sensitivity Estimate

- **Current performance:**
  - $S=1600$ events / fb$^{-1}$
  - $S/B = 2/1$
  - $\varepsilon D^2 = 4\%$
  - $\sigma_t = 67$ fs
  
  $2\sigma$ sensitivity for $\Delta m_s = 15$ ps$^{-1}$ with $\sim 0.5$ fb$^{-1}$ of data
  - surpass the current world average

- **With “modest” improvements**
  - $S=2000$ / fb (improve trigger, reconstruct more modes)
  - $S/B = 2/1$ (unchanged)
  - $\varepsilon D^2 = 5\%$ (kaon tagging)
  - $\sigma_t = 50$ fs (event-by-event vertex + L00)
  
  $5\sigma$ sensitivity for $\Delta m_s = 18$ ps$^{-1}$ with $\sim 1.7$ fb$^{-1}$ of data
  $5\sigma$ sensitivity for $\Delta m_s = 24$ ps$^{-1}$ with $\sim 3.2$ fb$^{-1}$ of data
  
  $\Delta m_s = 24$ ps$^{-1}$ “covers” the expected region based upon indirect fits.

- **This is a difficult measurement.**
- **There are ways to further improve this sensitivity…**
Semileptonic B decay signals

\[ \bar{B} \rightarrow \ell^- \bar{\nu} D^0 X \]

\[ \bar{B}_s^0 \rightarrow \ell^- \bar{\nu} D_s^+ X \]

CDF Run II Preliminary

Luminosity 60 pb\(^{-1}\)

Events/5 MeV/c\(^2\)

$N(D^0) = 10508 \pm 147$

$\sim 10 \text{k}$

CDF Run II Preliminary

60 pb\(^{-1}\)

Number of Candidates / 0.01 [GeV]

$B_s \rightarrow \ell \nu D_s X$

$D_s \rightarrow \phi \pi, \phi \rightarrow K^+ K^-$

$N_{D_s} : 385 \pm 22$

$N_{D^+} : 112 \pm 19$

$\sim 400$
Flavor tagging example: same-side pion tag

CDF Run II Preliminary

$B^+ \rightarrow \bar{D}^0 \pi^+$

- Right Sign, 563 ± 32 events
- Wrong Sign, 396 ± 26 events

Look at near $B^- \rightarrow D^0 \pi^-$

Blue: right-sign tags
Red: wrong-sign tags

$\varepsilon D^2 = (2.1 \pm 0.7)\%$ for $B^+$

Also, muon tagging

$\varepsilon D^2 = (0.7 \pm 0.1)\%$
D** mesons:

$L = 0 : J = S = 0, 1 \Rightarrow D, D^*$

$L = 1$ and $S = 0, 1 : J^P = 1^+, 0^+, 1^+, 2^+$

Spectroscopy of D mesons

CDF Run II Preliminary

$D_1^0, D_2^{*0} \rightarrow D^{*+}\pi^-$

Luminosity: 9 pb$^{-1}$