B Physics at CDF

- Decays with 2 muons
- Hadronic B decays
- Something completely different: Pentaquarks

Moriond/EWK 2004. Jonas Rademacker, CDF
New Si microstrip detector → excellent time resolution

B triggers include
- $\mu\mu$ Trigger: finds $B \to J/\psi X$
- Displaced Track Trigger: finds $B$'s (and charm)!

$B_d \to J/\psi K^*$ event at CDF
Measured \( b \) X-sections at CDF:

Extract \( b \)-fraction in \( J/\psi(\mu\mu) \) data from fit to \( L_{xy} \)

\[ L_{xy} = \text{projection of decay distance onto } \vec{p}. \]

\( J/\psi \) from B’s have long, positive \( L_{xy} \), prompt \( J/\psi \) symmetric, centered on 0.

\[ \sigma(p\bar{p} \rightarrow \bar{b}X | y < 1.0) = 29.4 \pm 0.6 \pm 6.2 \mu b \]
Lifetime (ratios) and Heavy Quark Expansion

- HQE frequently used to relate measurements to CKM parameters e.g. \( B.R. \ of \ B \to \ell \nu X \) to \( |V_{cb}|, |V_{ub}| \) (see talks this morning).
- Need to be sure this tool works!
- HQE gives precise predictions for B-hadron lifetime ratios - good testing ground.

**HQE predictions for B lifetimes**

\[
\begin{align*}
\tau(B_c) & \ll \tau(\Xi_b^0) \\
& \sim \tau(\Lambda_b) < \tau(B_d^0) \sim \tau(B_s^0) < \tau(B^-) \\
& < \tau(\Xi_b^-) < \tau(\Omega_b)
\end{align*}
\]

- \( \tau(B^-)/\tau(B_d^0) = 1.067 \pm 0.027 \)
- \( \tau(B_s)/\tau(B_d^0) = 0.998 \pm 0.015 \)
- \( \tau(\Lambda_b)/\tau(B_d^0) = 0.9 \pm 0.05 \)
Lifetimes in $\mu\mu$ Trigger $B \rightarrow J/\psi(\mu\mu)X$ fully reco’ed

- Signal: exp $\otimes$ Gauss.
- Bckg model: (prompt + 1 negative and 2 positive exp) $\otimes$ Gauss.
- Use mass fit for evt-by-evt S/B.
- Unbinned fit with $\mathcal{L} = \mathcal{L}(\tau, \text{mass})$

$\sim 2.4 \text{ k } B^+ \rightarrow J/\psi K^{(*)+}$
$\sim 1.6 \text{ k } B^0 \rightarrow J/\psi K^{(*)0}$, 195 pb$^{-1}$

- $\tau_{B^+} = 1.66 \pm 0.04 \pm 0.02 \text{ ps}$
- $\tau_{B^0} = 1.49 \pm 0.05 \pm 0.03 \text{ ps}$
- $\tau_{B^+}/\tau_{B^0} = 1.12 \pm 0.046 \pm 0.014$
Lifetime $B_s \rightarrow J/\psi \phi$ $B \rightarrow J/\psi(\mu \mu)X$ fully reco’ed

Result for $138 \text{ pb}^{-1}$

- $\tau_{B_s} = 1.33 \pm 0.14 \pm 0.02 \text{ ps}$
- $\tau_{B_s}/\tau_{B^0} = 0.88 \pm 0.11(\text{stat})$

- Note: Measurement dominated by CP-even component

- Comes in 3 angular momentum states, 2 CP-even, 1 CP-odd.
- Can be disentangled by angular analysis. ⇒ measure $\Delta \Gamma_s$.
- ...with more statistics.
CDF Run II Results: Lifetime Ratios (prelim)

$B^+_u \to J/\psi(\mu^+\mu^-)K^{(*)+}$, $B^0_d \to J/\psi(\mu^+\mu^-)K^{(*)0}$, $B^0_s \to J/\psi(\mu^+\mu^-)\phi$, $\Lambda_b \to J/\psi(\mu^+\mu^-)\Lambda$

<table>
<thead>
<tr>
<th>Channel</th>
<th>Run II</th>
<th>WAv</th>
<th>HQE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+_u/B^0_d$</td>
<td>$1.12\pm0.05$</td>
<td>$1.091\pm0.050$</td>
<td>$1.086\pm0.017$</td>
</tr>
<tr>
<td>$B^0_s/B^0_d$</td>
<td>$0.88\pm0.11$</td>
<td>$0.899\pm0.072$</td>
<td>$0.951\pm0.038$</td>
</tr>
<tr>
<td>$\Lambda_b/B^0_d$</td>
<td>$0.91\pm0.20$</td>
<td>$0.835\pm0.11$</td>
<td>$0.797\pm0.053$</td>
</tr>
</tbody>
</table>

Run II $B^+/B_d$ from 195 pb$^{-1}$
Run II $B_s/B_d$ from 138 pb$^{-1}$
Run II $\Lambda_b/B_d$ from 65 pb$^{-1}$

Run I results: all channels combined. Run II (here): fully reconstructed $J/\psi(\mu\mu)X$ only.

Approaching Run I precision. Tevatron-specific: $B_s$ and $\Lambda_b$ lifetimes.
Run IIa will provide real test of HQE.
Search For \( B_s \rightarrow \mu^+ \mu^- \), \( B_d \rightarrow \mu^+ \mu^- \)

*High Sensitivity to New Physics*

\( \text{SM BR} \sim 10^{-9} \)

Many extension of SM (mSUGRA, SO(10)) predict enhancements by several orders of magnitude.

- Observation \( \Rightarrow \) New Physics.
- Else: Exclude some theories.

\( \text{BR}(B_s \rightarrow \mu^+ \mu^-) \approx 10^{-6} \tan^6 \beta \frac{M_{1/2}^2 \text{GeV}^4}{(M_{1/2}^2 + M_0^2)^3} \)

- Connection to \( a_\mu = \frac{(g-2)_\mu}{2} \):
  \[ \delta a_\mu \text{SUSY} = a_\mu \text{SUSY} - a_\mu \text{SM} \propto \tan \beta f(M_0) \frac{M_{1/2}^2}{M_{1/2}^2} \]

Search For $B_s \rightarrow \mu^+\mu^-$, $B_d \rightarrow \mu^+\mu^-$

Predicted Bg in search windows:

- $B_d$: $1.05 \pm 0.30$
- $B_s$: $1.07 \pm 0.31$

$\text{Bkg} = N(c\tau, \Delta \Phi) \cdot R(\text{Iso}) \cdot R(\text{mass})$

X-check Bg-predictions in $\mu^+\mu^+$, $\mu^-\mu^-$ and $(\mu^+\mu^- \text{ with } c\tau < 0)$. Then unblind.
Search For $B_S \rightarrow \mu^+\mu^-$, $B_d \rightarrow \mu^+\mu^-$ in 171 pb$^{-1}$

**Result:** 1evt in overlap region

**Limit vs Lumi up to 0.5 fb$^{-1}$**

$$\text{BR}(B_d \rightarrow \mu^+\mu^-) < 1.5 \times 10^{-7} \ (90\%\text{CL})$$

$$\text{BR}(B_S \rightarrow \mu^+\mu^-) < 5.8 \times 10^{-7} \ (90\%\text{CL})$$

Prev. best limits: $B_d$: $1.6 \times 10^{-7}$ (BELLE 2003) $B_s$: $2 \times 10^{-6}$ (CDF Run I)
$B_s \rightarrow \mu\mu$, $(g - 2)_\mu$, and mSUGRA.

Black $BR(B_s \rightarrow \mu\mu)$.  
Green $\delta a_\mu/10^{-10}$  
Red Mass of (lightest) Higgs (GeV)

For $\tan \beta = 50$ $A_0 = 0$, $\mu > 0$, $m_t = 175$ GeV

Inching into the allowed parameter space of mSUGRA.
Displaced Track Trigger

- 3 Level Trigger: $2.5 \text{ MHz} \rightarrow L1 \rightarrow 15 \text{ kHz} \rightarrow L2 \rightarrow 300 \text{ Hz} \rightarrow L3 \rightarrow 50 \text{ Hz} \Rightarrow \text{throw away 99.998\% of all events.}$

- Need to make sure that those $0.002\%$ we keep are carefully selected.

B Trigger

- Traditionally: Trigger on $\ell(e, \mu)$. Works well - see results on previous slides.

- Excludes important B decays, like $B^0_d \rightarrow \pi^+\pi^-$.  

- Run 2: First time in a hadron collider: Use “long” B lifetime. Trigger on Impact Parameter at L 2 (2 tracks, IP $> 100 \mu$).
Displaced Track Trigger

900 $B \rightarrow hh$ events for 190 pb$^{-1}$
($B^0_d \rightarrow \pi\pi$, $B^0_s \rightarrow KK$, etc)

SVT Impact Parameter distribution

\[ \sigma = 48 \text{ \mu m} \text{ (includes 33\mu m beam spot)} \]
Disentangling $B \to hh$

**Challenge:** Separate $B^0_d \to \pi\pi$, $B^0_s \to KK$ and other $B \to hh$

1.16$\sigma$ $K/\pi$ sep. from $\frac{dE}{dx}$ (Data)

Mass vs $(1 - p_1/p_2) \cdot Q_1$. (Monte Carlo)
$B_d^0 \to hh$ Results for 65 pb$^{-1}$, and prospects

- First observation of $B_s \to KK$: $90 \pm 24$ out of 300 $B \to hh$ events (65 pb$^{-1}$).

- Search for CP in time-integr. rates
  \[ A_{CP} = \frac{\Gamma(\bar{B}_d^0 \to K^+\pi^-) - \Gamma(B_d^0 \to K^+\pi^-)}{\Gamma(\bar{B}_d^0 \to K^-\pi^+) + \Gamma(B_d^0 \to K^-\pi^+)} \]
  \[ = 0.02 \pm 0.15 \pm 0.017 \]

- $\frac{\Gamma(B_d^0 \to \pi^+\pi^-)}{\Gamma(B_d^0 \to K^{\pm}\pi^{\mp})} = 0.26 \pm 0.11 \pm 0.06$

- Analysed $\sim 3\times$ as much data $\to$ Improved results, soon.

- Long term: Time dependent decay rate asymmetries in $B_d \to \pi\pi$ and $B_s \to KK$ allow extraction of CP phase $\gamma$.
Loads of Charm - $D^0 \rightarrow hh$

$D^0$ from $D^{*+} \rightarrow D^0\pi$: Clean signal, distinguish $D^0$, $\bar{D}^0$. For $123 \text{ pb}^{-1}$

$$D^{*+} \rightarrow D^0(K^-\pi^+)\pi^+ \quad D^{*+} \rightarrow D^0(K^+K^-)\pi^+$$

- $A_{CP} \ KK = 
  \frac{\Gamma(\bar{D}^0\rightarrow K^+K^-) - \Gamma(D^0\rightarrow K^+K^-)}{\Gamma(\bar{D}^0\rightarrow K^-K^+) + \Gamma(D^0\rightarrow K^+K^-)}$
  $$= 2.0 \% \pm 1.2 \% \pm 0.6 \%$$

- $A_{CP} \ \pi\pi = 
  \frac{\Gamma(\bar{D}^0\rightarrow \pi^+\pi^-) - \Gamma(D^0\rightarrow \pi^+\pi^-)}{\Gamma(\bar{D}^0\rightarrow \pi^-\pi^+) + \Gamma(D^0\rightarrow \pi^+\pi^-)}$
  $$= 1.0 \% \pm 1.2 \% \pm 0.6 \%$$

$$\frac{\Gamma(D^0\rightarrow K^+K^-)}{\Gamma(D^0\rightarrow K^+\pi^+)\pi^+} = 9.96 \% \pm 0.11 \% \pm 0.12 \%$$

$$\frac{\Gamma(D^0\rightarrow K^+\pi^+)\pi^+}{\Gamma(D^0\rightarrow K^+K^-)} = 2.762 \% \pm 0.040 \% \pm 0.034 \%$$

88.3 k ± 0.3 k

8.19 k ± 0.14 k
$B_S^0 \rightarrow D_S \pi$

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

- Flavour eigenstate
- No missing momentum (unlike $B_S^0 \rightarrow D_S \ell\nu$), good time resolution ($\sigma(\tau)$ in topol. similar decays: 67 fs). Needs hadron trigger.
- CDF’s “golden mode” for mixing.
- $80 \ B_S^0 \rightarrow D_S(\phi\pi)\pi$ evt for $119 \text{ pb}^{-1}$, $S/B \sim 2$. Note: efficiency improved. Now $\sim 1.6 \text{ evts/pb}^{-1}$.

No $B_S$ mixing result, yet. B.R. instead:

$$\frac{f_s \cdot BR(B_S^0 \rightarrow D_S^{-}\pi^+)}{f_d \cdot BR(B_d^0 \rightarrow D^{-}\pi^+)} = 0.35 \pm 0.05 \pm 0.04 \pm 0.09(BR)$$
Pentaquarks
Looking for $\Xi^0(1860) \rightarrow \Xi^- \pi^+$ and $\Xi^{--} \rightarrow \Xi^- \pi^-$ with $\Xi^- \rightarrow \Lambda(p\pi)\pi^-$, found by NA49 (hep-ex/0310014)

1st Step: $\Xi^-$ reconstruction

- $\Xi^-$ is very long lived - yet another job for the displaced track trigger. Find 36,000 $\Xi^-$.  
- $\Xi^-$ lives long enough to leave hits in Si Detector. Requiring hits from the $\Xi^-$ in the Si provides extremely clean $\Xi^-$ signal.
**Pentaquarks** Looking for $\Xi(1860) \rightarrow \Xi^-\pi^\pm$

2\textsuperscript{nd} Step: Combine $\Xi^-$ with $\pi^\pm$

Normalise by known $\Xi^0(1530) \rightarrow \Xi^-\pi^+$.  

- Don’t see any $\Xi(1860)$
- It’s not statistics: (18× as many $\Xi^-$ as NA49).
- Unknown bias due to Trigger? Re-check with Jet20 data (2× NA49). Still no $\Xi(1860)$

95% UL relativ to $\Xi(1530)$:

<table>
<thead>
<tr>
<th></th>
<th>$\Xi^-\pi^+$ (search) / $\Xi(1530)$</th>
<th>$\Xi^-\pi^-$ (control) / $\Xi(1530)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.07</td>
<td>0.04</td>
</tr>
</tbody>
</table>
Summary
Plenty of B at Tevatron. Only source of $B_s$, $\Lambda_b$.

**Lepton Trigger**
- $\sigma(p\bar{p} \to bX)$
- Precise $\tau_B$ in $B \to J/\psi X$. 1st step towards $\Delta \Gamma_s$, test HQE.
- Best limits for $B_{d,s} \to \mu\mu$. Highly sensitive probe of New Physics.

**Hadron Trigger**
- Unique sample of $B \to hh$, $B \to D\pi$
- 1st observation of $B_s \to KK$.
- Lots of Charm.
- Future: $\Delta \Gamma_s$, $\Delta m_s$, $CP$ with $B_s \to KK$ & $B_d \to \pi\pi$

- Pentaquarks: Didn’t see $\Xi(1840)$
  ... will look for others, especially D or $J/\psi +$ Baryon.
Summary B Physics at DØ and CDF

Lepton Trigger
- Plenty $B \rightarrow J/\psi X$, $B \rightarrow \ell \nu X$, for $\sigma(p\bar{p} \rightarrow bX)$, B.R. $B \rightarrow D^{**}$, precise $\tau$ for $B^+, B_d, B_s, \Lambda_b$.
- Best limits for $B_{d,s} \rightarrow \mu \mu$ from CDF, DØ result with similar precision, soon. Highly sensitive probe of New Physics.
- Flavour tagging and $B_d$ mixing results from DØ.

Hadron Trigger
- Unique sample of $B \rightarrow hh$, $B \rightarrow D \pi$. 1st observation of $B_s \rightarrow KK$, Lots of Charm.
- DØ’s displaced track trigger is being commissioned.
- Pentaquarks: Didn’t see $\Xi(1840)$. Will look for others, especially D or $J/\psi +$ Baryon.

Penty of B results at both experiments. Beginning to seriously probe SM. More B physics of all flavours, soon.
BACKUP SLIDES
two cuts:
- $p(\pi^+) > 3$ GeV/c
- opening angle between $\Xi$ and $\pi$ greater than 4.5°
NA49 Digest

\begin{align}
N(\Xi^-) &= 1,640 \\
N(\bar{\Xi}^+) &= 551 \\
N(\Xi(1530)^0) &\sim 150 \\
N(\Xi(1860)) &= 67.5 \\
N(\Xi(1860)) &= 36 \\
N(\Xi(1860)^0) &= 31.5
\end{align}

\begin{align}
r_{\Xi(1860)}^{\Xi^-} &= \frac{\text{#}(\Xi(1860))}{\text{#}(\Xi(1530))} = \frac{\sigma(pp \to \Xi(1860)) \cdot Br(\Xi(1860) \to \Xi^- \pi^+) \cdot a(\Xi(1860))}{\sigma(pp \to \Xi(1530)) \cdot a(\Xi(1530))} \sim 0.21, \\
r_{\Xi(1860)}^{-\Xi^-} &= \frac{\text{#}(\Xi(1860))}{\text{#}(\Xi(1530))} = \frac{\sigma(pp \to \Xi(1860)) \cdot Br(\Xi(1860) \to \Xi^- \pi^-) \cdot a(\Xi(1860))}{\sigma(pp \to \Xi(1530)) \cdot a(\Xi(1530))} \sim 0.24, \\
r_{\Xi(1860)}^{\Xi^+} &= \frac{\text{#}(\Xi(1860))}{\text{#}(\Xi(1530))} = \frac{\sigma(pp \to \Xi(1860)) \cdot Br(\Xi(1860) \to \Xi^+ \pi^-) \cdot a(\Xi(1860))}{\sigma(pp \to \Xi(1530)) \cdot a(\Xi(1530))} \sim 0.45
\end{align}

\begin{align}
\sigma(pp \to \Xi(1860)) \cdot a(\Xi(1860)) \\
\sigma(pp \to \Xi(1530)) \cdot a(\Xi(1530))
\end{align}
The $B_s$ System

- Two CP-eigenstates with different mass and lifetime. Measure both $\Delta \Gamma_s$ and $\Delta m_s$ at CDF.
- $\Delta \Gamma_s$ from lifetimes in $B_s^0 \to D_sD_s$, $B_s^0 \to KK$, $B_s^0 \to J/\psi\phi$
- 1st step towards $\Delta \Gamma_s$: Average $\tau$ in $J/\psi\phi$ $1.33 \pm 0.14$ ps
- $\Delta m_s$ from $B_s$ oscillations.

**Status**

- $\Delta m_s = 15 - 30 \text{ ps}^{-1}$, 95% CL (Direct limit + Unitarity Triangle, from CKMFitter).
- Theory: $\frac{\Delta \Gamma_s}{\Gamma_s} = 7\% \pm 4\%$
- Exp: $\frac{\Delta \Gamma_s}{\Gamma_s} < 0.31$, 95% CL
- $\frac{\Delta \Gamma_s}{\Delta m_s} = \pi \frac{m_b^2}{2m_W^2} \left| \frac{V_{cb}V_{cs}}{V_{ts}V_{tb}} \right|^2 \times \text{QCD} \sim 2 \cdot 10^{-3}$
- Sensitive to CKM and New Physics.
Tagging Strategies and Status

flavours at creation

fully reconstructed $B$

$b$

opposite-side $B$ hadron

$\pi$

lepton Tag $b \rightarrow f^-$

Kaon Tag $b \rightarrow c \rightarrow s \rightarrow K^-$

Jet Charge $\Sigma Q$(all trks in Jet)

Same Side Tag:

$\bar{b}$

$B_s$

$K^+$

$\bar{s}$

Measured Performances in Run II.

$\varepsilon = \text{efficiency}, \ \omega = \text{wrong-tag}$

$D = 1 - 2\omega$

<table>
<thead>
<tr>
<th>Tag</th>
<th>$\varepsilon D^2$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$</td>
<td>$0.66 \pm 0.09$</td>
</tr>
<tr>
<td>$e$</td>
<td>in progress</td>
</tr>
<tr>
<td>$K_{opp}$</td>
<td>in progress</td>
</tr>
<tr>
<td>$Q_{Jet}$</td>
<td>in progress</td>
</tr>
<tr>
<td>$B_d: \pi_{same}$</td>
<td>$1.9 \pm 0.9$</td>
</tr>
<tr>
<td>$B_s: K_{same}$</td>
<td>in progress</td>
</tr>
</tbody>
</table>

N events before tagging $\sim \varepsilon D^2 \cdot N$

perfectly tagged events.

Expect great things from Kaons: $K/\pi$ sep. in Time Of Flight.
$\Delta m_s$ with $B_S^0 \rightarrow D_S \pi$

Significance =

$$\sqrt{\frac{1}{2} S \varepsilon D^2} \sqrt{\frac{S}{S + B}} \exp\left( (\Delta m_s \sigma_\tau)^2 \right)$$

Performance

<table>
<thead>
<tr>
<th>Now</th>
<th>Expected Improvements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evts/lumi</td>
<td>1.6 pb</td>
</tr>
<tr>
<td>S/B</td>
<td>$\sim 2.$</td>
</tr>
<tr>
<td>$\varepsilon D^2$</td>
<td>being studied</td>
</tr>
<tr>
<td>$\sigma(\tau)$</td>
<td>67 fs</td>
</tr>
</tbody>
</table>

Most important improvement: Better $\sigma(\tau)$ using innermost Si layer, and evt-by-evt prim. Vtx.
B production at Tevatron Run II

- p¯p collisions @ 1.96 TeV, $\sigma_{b\bar{b}} \sim 0.05$ mb

- Produce many $B^0, B_s, \Lambda_b, ...$ some picture

- Challanging: Messy environment ($\sigma(p\bar{p} inel) \sim 100$ mb)
Silicon Vertex Trigger *Impact Parameter trigger at L2*
Combines L1-tracks with Si-info to calculate IP.
\[ \sigma_{IP} = 48 \mu m = 0.35 \mu m(\text{intrinsic}) \oplus 0.33 \mu m(\text{beam-size}) \]

2-Track Hadron Trigger

**L1:** 2 XFT tracks, \( p_t > 2 \text{ GeV}, \Delta \phi < 135^\circ \), \( p_t1 + p_t2 > 5.5 \text{ GeV} \).

**L2:**
- **2-body:**
  - e.g. \( B^0_d \to \pi \pi \)
  - IP > 100 \( \mu m \)
  - \( 20^\circ < \Delta \phi < 135^\circ \)
  - \( L_{xy} > 200 \mu m \)
  - IP of B < 140 \( \mu m \)
- **Multi-body:**
  - e.g. \( B^0_s \to D_s \pi \)
  - IP > 120 \( \mu m \)
  - \( 2^\circ < \Delta \phi < 90^\circ \)
  - \( L_{xy} > 200 \mu m \)

**L3:** Same with refined tracks & mass cuts.

Finds lots of charm.
Use \( D^0 \to K\pi \) as online monitor for SVT.
Silicon Vertex Detector
Silicon Vertex Detector

- Layer 00 fully functional
- Cooling problem solved.
- Chip-failures in z-layers understood, can be prevented in future (no problems since Nov).
- Need to finalise Alignment: For now, ISL, Layer 00 and z-information not used (coming soon).

For “simple” $\tau$ measurements, SVX II in 2-D fully adequate. Improvement from L00, ISL, and z available soon, esp. for $\Delta m_s$, and to improve acceptance.
CDF Run II Semileptonic: \[ \tau(\Lambda_b) \text{ from } \Lambda_b \rightarrow \Lambda_c^+(pK^+\pi^-)\ell^-\nu \]

- Use combined particle ID from time of flight and \( \frac{dE}{dx} \) to identify protons and reduce background (see Figure).
- Find \( 590 \pm 50 \ \Lambda_c \).
- Combine \( \Lambda_c \) with \( \ell \), accept masses between \( M(\Lambda_c) \) and \( M(\Lambda_b) \).
- Statistical precision of current sample: \( \sigma(\tau_{\Lambda_b}) = 0.13 \) ps.

\[ \Lambda_c \text{ mass with and without proton ID from TOF and } \frac{dE}{dx}. \]