Flavour Physics Technique at CDF and D0

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Outline

• Detector elements crucial for B Physics at hadron colliders
  - Integrated Tracking Systems
    Silicon detectors, Drift chamber, Fiber Tracker
  - Lepton Detectors
• Trigger architecture/strategies used for B Physics
  - Lepton Triggers
  - Hadron Triggers (i.e. triggering on displaced vertices)
• Clean reconstruction of complex topologies
  - Precision mass, lifetime measurements
• Particle identification from dE/dx, TOF
  - Calibration, performance, use in analysis
• Flavor tagging
• Conclusions
At Tevatron, the $b$ production cross section is much larger compared to B factories → CDF is enjoying a very rich B Physics program

Plethora of states accessible at Tevatron ($B_d$, $B_u$, $B_s$, $Λ_b$, $Ξ_b$, $Σ_b$, $Ω_b$) → Complement the B factories physics program

Total inelastic cross section at Tevatron is ~1000 larger than $b$ cross section → Large backgrounds suppressed by triggers that target specific decays
The CDF detector

- **Solenoid (1.4T)**
- **Em/Had Calor.**
- **Time-of-Flight**
- **Muon System**
  - Drift chamber/scintillator $|\eta|<1.5$ (CMU/CMP, CMX, BMU)
  - # of layers: 4/4, 8, 4
- **Electromagnetic Calorimeter**
  - Scintillator/Lead 0.11x0.26 (hxf)
  - ~20 radiation length
  - Pos detector at shower max
- **COT: 96 Layers**
- **Silicon 7-8 Layers**
The CDF Tracker

B field = 1.4 T

TIME OF FLIGHT

Axial SL
Stereo SL
The D0 Detector

2T Solenoid

Fiber Tracker: 16 Layers, $|\eta| < 2$, $R \sim 0.5$ m

Silicon Tracker: 5 Layers, $|\eta| < 3$

Muon System $|\eta| < 2$
Drift Tube/scintillator
3 layers of tubes (3-4 planes/layer)
Toroid between Layer 1-2

Electromagnetic Calorimeter
Liquid Argon/Uranium
0.1x0.1 (hxf), ~20 rad length
Preshow: scintillating strips
Shower max: 3$^{rd}$ layer

Central/Forward Muon Scintillators
CDF B Triggers

**Di-Muon (J/ψ)**
- $P_T(μ) > 1.5 \text{ GeV}$
- $J/ψ$ modes down to low $P_T(J/ψ)$ ($\sim 0 \text{ GeV}$)

**Displaced trk + lepton (e, μ)**
- $P_T(\text{lepton}) > 4 \text{ GeV}$
- $P_T(\text{trk}) > 2 \text{ GeV}$
- $IP(\text{trk}) > 100 \mu m$
- $IP(\text{trk}) > 120 \mu m$

**2-Track Trig.**
- $P_T(\text{trk}) > 2 \text{ GeV}$
- $IP(\text{trk}) > 100 \mu m$
- Fully hadronic modes

**X(3872) → J/ψππ**

**β_s in B_s → J/ψ φ,**

**Ξ_b, Ω_b Observation**

**$Λ_b → J/ψ Λ$ (masses, lifetimes)**

**B^0_{s,d} → μμ (rare decays)**

**Bc → J/ψ π (J/ψ 1X)**

**High statistics lifetime**

**Tagging studies, mixing**

$B → hh \ (CP)$

$B_S$ mixing

$D^0$ mixing

$Σ^+ → Λ_b \ π$

$Λ_b → Λ_c π$

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$B_S$ mixing

$D^0$ mixing

$Σ^+ → Λ_b \ π$

$Λ_b → Λ_c π$
CDF Trigger Architecture

Raw data, 7.6 MHz Crossing rate

- **Level 1** pipeline:
  - 42 clock cycles
  - **Level 1 Trigger**
    - 7.6 MHz Synchronous Pipeline
    - 5.5 µs Latency
    - 30 kHz accept rate

- **Level 2** buffer:
  - 4 events
  - **Level 2 Trigger**
    - Asynchronous 2 Stage Pipeline
    - 20 µs Latency
    - 1000 Hz accept rate

- **DAQ buffers**
- **L3 Farm**

**Mass Storage (~100 Hz)**

**Drift chamber tracking**
- Lepton identification

**Silicon tracking**
- Secondary vertex selection

**L3 CPU farm**
- Full event reconstruction
- with speed optimized offline code

**SVX read out after L1**

**XFT here**

**SVT here**
XFT working principle

Good hit patterns identified as segments, segments linked as tracks

$\sigma(1/p_T) = 1.7\%/\text{GeV}$

$\sigma(\phi_0) = 5 \text{ mrad}$

96% efficiency ($p_T > 1.5 \text{ GeV}$)
Lepton triggers
Match between a muon stub/calorimeter signal with an XFT track
Exploit lifetime to select $b,c$

Proton-antiproton collision point

B decay vertex

Impact parameter ($d$)

~ 1 mm

Transverse view
**Inputs:**
- L1 tracks from XFT ($\phi$, pT)
- digitized pulse heights from SVX II

**Outputs:**
- reconstructed tracks ($d$, $\phi$, pT)
**SVT Performance**

\[ \sigma = 48 \mu m = 35 \mu m \pm 33 \mu m (\text{res} \pm \text{beam}) \]

Given a fiducial offline track with SVX hits in 4/4 layers used by SVT

**Efficiency**

0.00  0.05  0.10  0.15

SVT Impact parameter (cm)

\[ \langle d \rangle = Y_{\text{beam}} \cos \phi - X_{\text{beam}} \sin \phi \]

Online impact parameter measurement requires online beam position estimate
### Hadronic B Trigger (I)

<table>
<thead>
<tr>
<th>L1</th>
<th>Two XFT tracks: $P_t &gt; 2$ GeV; $P_{t1} + P_{t2} &gt; 5.5$ GeV; $\Delta \phi &lt; 135^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Two-body decays</strong></td>
</tr>
<tr>
<td></td>
<td>$100 \ \mu m &lt; d_0 &lt; 1 mm$ for both tracks</td>
</tr>
<tr>
<td>L2</td>
<td>Validation of L1 cuts with $\Delta \phi &gt; 20^\circ$</td>
</tr>
<tr>
<td></td>
<td>$L_{xy} &gt; 200 \ \mu m$</td>
</tr>
<tr>
<td></td>
<td>$d_0(B) &lt; 140 \ \mu m$</td>
</tr>
<tr>
<td></td>
<td>$B \rightarrow h h'$</td>
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</tbody>
</table>

**Trigger collects tons of $D^0 \rightarrow K-\pi^+$**

(used as online L3 monitor)
Hadronic B Trigger (II)

- Run I collected $O(1) B_s \rightarrow D_s \pi$ in $100 \text{ pb}^{-1}$ (all $D_s$ modes)
- Run II collected $\sim 200/100 \text{ pb}^{-1} B_s \rightarrow D_s \pi \ (D_s \rightarrow \phi [\rightarrow K^+K^-] \pi)$
- Compare with only 10x integrated luminosity!

**Without SVT**

**With SVT**

![Graph showing data and categories](image)
D0 Trigger architecture

Data Acquisition rate limited to average 55Hz (up to 150Hz)

3 Level Trigger System

L1
4.2 µs

L2
100 µs

L3
50 ms

B Triggers

Di-Muon

\[ Pt1(\mu) > 3.0 \text{ GeV, } |\eta|<2 \]

\[ Pt2(\mu) > 1.5(3.0) \text{ GeV, } |\eta|<2 \]

Single Muon

\[ Pt(\mu) > 3 \text{ GeV, } |\eta|<1.5 \]
We already have \( \sim 5 \text{ fb}^{-1} \) on tape.
Example Physics Signals

We already have ~5 fb\(^{-1}\) on tape
Measure masses @sub-Mev level

Mass scale calibration with $J/\psi \rightarrow \mu\mu$

$M(B^+) = 5279.10 \pm 0.41 \pm 0.36$ MeV

$M(B^0) = 5279.63 \pm 0.53 \pm 0.33$ MeV

$M(B^0_s) = 5366.01 \pm 0.73 \pm 0.33$ MeV

$M(\Lambda^0_b) = 5619.7 \pm 1.2 \pm 1.2$ MeV
Reconstruct most complex topologies

Reconstruct lots of b species: \( B^0, B^{**0}, B^+, B^0_s, B_c, \Lambda_b, \Xi_b, \Omega_b \)

\[ \Xi_b^{-} \rightarrow J/\psi \Xi^{-} \]
Measure $\Xi_b^{-}$ mass @MeV level

CDF: $M(\Xi_b^{-}) = 5790.9 \pm 2.6 \pm 0.8$ MeV

D0: $M(\Xi_b^{-}) = 5774 \pm 11 \pm 15$ MeV

| Exp | B[T] | Radii[cm] | $|\eta|$ | Cov | # points |
|-----|------|-----------|---------|-----|---------|
| CDF | 1.4  | 1.5-137   | <2.0    | <2.0| >100    |
| D0  | 2.0  | 1.7-52    | <3.0    | <3.0| 20      |
World class b-hadron lifetime measurements

CDF II Preliminary, L=1.1 fb⁻¹

Δ_b Lifetime Measurements

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Lifetime [ps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH Δ_c l + Δ^0 ll</td>
<td>1.21 ± 0.11</td>
</tr>
<tr>
<td>OPAL Δ_c l</td>
<td>1.29 ± 0.24 ± 0.06</td>
</tr>
<tr>
<td>DELPHI Δ_c l</td>
<td>1.11 ± 0.19 ± 0.05</td>
</tr>
<tr>
<td>CDF Run I Δ_c l</td>
<td>1.32 ± 0.15 ± 0.07</td>
</tr>
<tr>
<td>D0 Run II Δ_c l</td>
<td>1.29 ± 0.120 ± 0.067</td>
</tr>
<tr>
<td>D0 Run II J/ψ Δ</td>
<td>1.218 ± 0.130 ± 0.042</td>
</tr>
<tr>
<td>CDF Run II J/ψ Δ</td>
<td>1.583 ± 0.033 ± 0.076</td>
</tr>
<tr>
<td>CDF Run II Δ_c π (PRELIMINARY)</td>
<td>1.401 ± 0.046 ± 0.035</td>
</tr>
<tr>
<td>PDG 2008</td>
<td>1.383 ± 0.049 ± 0.043</td>
</tr>
</tbody>
</table>
Silicon Detectors status

No significant degradation of offline (trigger) tracking performance expected if $S/N > 3$ (6)
PID from $dE/dx$ (Calibration)

Use large sample of $D^* \rightarrow D^0 \pi_{soft} \rightarrow [K \pi] \pi_{soft}$ (Hadronic Trigger)

Tight mass cuts: $1.84 < m(D^0) < 1.89 \text{ GeV}$, $5.3 < M(D^*) - m(D^0) - m(\pi) < 6.5 \text{ MeV}$
Correct $dE/dx$ dependencies on
- time (run number)
- track parameters $\phi$, $\eta$, $n(hits)$, luminosity

$D^0$ selected mass region after cuts - CDF Run II preliminary
K-\pi separation after calibration - CDF Run II preliminary

~$1.4\sigma$ $K/\pi$ separation
Disentangle $B^0_{(s)} \rightarrow h^+h^-'$ with $dE/dx$

Despite good mass resolution (22 MeV/$c^2$)
$B^0 \rightarrow K\pi$, $B^0 \rightarrow \pi\pi$, $B^0_s \rightarrow KK$, $B^0_s \rightarrow K\pi$
overlap in a single peak (~35 MeV/$c^2$)

Single mass assignment ($\pi\pi$) causes overlap even with perfect resolution

Determine signal composition using
- Kinematics (mass and momenta)
- Particle Identification ($dE/dx$).
Search for Handles (Kin+dE/dx)

Kinematic variables:

1) $M_{\pi\pi}$ invariant $\pi\pi$-mass
2) $\alpha = (1-p_{\text{min}}/p_{\text{max}})q_{\text{min}}$ signed $p$-imbalance
3) $p_{\text{tot}} = p_{\text{min}} + p_{\text{max}}$ scalar sum of 3-momenta

This offers good discrimination amongst modes and between $K^+\pi^-/K^-\pi^+$
Observe new $B^0_{(s)} \rightarrow h^+ h'^-$ decay modes

Tighter requirements optimized for $\Lambda_b$ selection

Clear excess in $\Lambda_b$ region

3 new rare modes observed

$N_{\text{raw}}(B^0_s \rightarrow K^- \pi^+) = 230 \pm 34 \text{ (stat.)} \pm 16 \text{ (syst.)}$

$N_{\text{raw}}(\Lambda_b^0 \rightarrow p \pi^-) = 110 \pm 18 \text{ (stat.)} \pm 16 \text{ (syst.)}$

$N_{\text{raw}}(\Lambda_b^0 \rightarrow p K^-) = 156 \pm 20 \text{ (stat.)} \pm 11 \text{ (syst.)}$
Direct CP in $B^0_{(s)} \rightarrow h^+h^-$ decay modes

ACP measurements

$A_{CP}(B^0 \rightarrow K\pi) = -0.086 \pm 0.023 \pm 0.009$

$A_{CP}(B^0_s \rightarrow K\pi) = 0.39 \pm 0.15 \pm 0.08$

$A_{CP}(\Lambda^0_b \rightarrow p\pi) = 0.03 \pm 0.17 \pm 0.05$

$A_{CP}(\Lambda^0_b \rightarrow pK) = 0.37 \pm 0.17 \pm 0.03$

Use large sample of $D^{*+} \rightarrow D^0\pi^+ \rightarrow K^-\pi^+$ and $\Lambda^0 \rightarrow p\pi^-$ to correct for asymmetric detector effects $\varepsilon(K^-\pi^+)/\varepsilon(K^+\pi^-)$ and $\varepsilon(p^-\pi^+)/\varepsilon(p\pi^-)$
D0 strategy for charge asymmetries

Asymmetric detector effects reduced by regular flipping of DØ's B fields. 
(trk(q>0)=trk(q<0) if B reversed)

World class CP measurements in semileptonic B decays

Most recent CP measurement in $B^0_s \rightarrow \mu^+ D^- s X$

$\alpha_{fs}^s = [-1.7 \pm 9.1^{+1.2}_{-2.3}] \times 10^{-3}$  
(arXiv:0904.3907)

All details in Steve Beale's Talk
Time Of Flight Detector

216 Scintillator bars, 2.8 m long, 4x4 cm$^2$
read out both ends with fine mesh PMT
Measured $\sigma_{\text{TOF}} = 100 - 130$ ps
(limited by photostatistics)

Measured quantities:
s = distance travelled
t = time of flight
p = momentum

Derived quantities:
v = s/t
m = p/$\gamma v$
Time Of Flight Detector

Measured time resolution: $\sigma_t \sim 110$ ps
Combined PID (TOF+dE/dx)

K-π separation

Typical B decay daughter momentum ~GeV
More on tools: Flavour tagging

**Opposite Side**
- **Opposite side kaon**
- **K^-**
- **D meson**
- **b hadron**
- **P.V.**

**Same Side**
- **K^+**
- **fragmentation kaon**
- **L_{xy}**

**Jet Charge**: the sum of charges of the b-Jet tracks correlated to the b-flavour

**Soft Lepton (e,\mu)**: due to b→\ellνX
- \ell charge correlated to b-flavour

**Opposite Side K**: due to b→c→s
- search for secondary K (use PID)

**Same Side Kaon**: for B_s^0 is likely to have close in ΔR a K+ from fragmentation (use PID)

Similar \(\varepsilon D^2\) for both CDF and DØ \(\sim 4.5\%\) (\(\sim 30\%\) at B factories)
(Tevatron Yellow Book -year 2001- expected \(\varepsilon D^2\) \(\sim 11\%\) at CDF)
Opposite Side Taggers

OST optimised by measuring $B_d$ mixing

- Use exclusive combination of:
  - 2 SLT ($\mu$, e)
  - 3 JQT categories
  - No OSKT

<table>
<thead>
<tr>
<th></th>
<th>HADRONIC (355 pb$^{-1}$)</th>
<th>SEMILEPTONIC (1 fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_d$</td>
<td>(0.536±0.028±0.006) ps$^{-1}$</td>
<td>(0.509±0.010±0.016) ps$^{-1}$</td>
</tr>
</tbody>
</table>
Same Side Taggers

Look for the fragmentation track charge correlated with the B

Rely on MC prediction of SSKT performance for $B_s$ mixing

- Choose the track in a cone of $\Delta R < 0.7$ around B most likely to be a K
- Make use of PID based on dE/dx and TOF information (CDF)

$\text{SST} \varepsilon D^2 = 4.0^{+0.8}_{-1.2} \% \text{ (CDF)}$

$\text{SST} \varepsilon D^2 = 1.7\pm0.6 \% \text{ (D0)}$

Tagging crucial for $\Delta m_s$ measurement
Conclusions

- CDF/DO Detectors/Triggers are well understood and show stable performance with time
- Datasets increasing smoothly, as well as physics results

![Graph showing luminosity over time](image)

- 2 fb\(^{-1}\) on tape ready for analysis
- More fb\(^{-1}\) expected
- Most analyses still use <3 fb\(^{-1}\)

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

*Delivered*  
*Acquired*