B Physics at the Tevatron

- Introduction
- Startup of Run II
- B Hadron Producers
- B Physics at the Tevatron
- Selected Run II Results from CDF & D0
- Conclusion
A Brief History of Time

First fully reconstructed B mesons at a hadron collider:

\( B^+ \rightarrow J/\psi K^+ \)

CDF 1992 (2.6 pb\(^{-1}\))
PRL 68, 3403 (1992)

Nowadays

Fully hadronic B decay
Fermilab

Some more history:
1967: Fermilab founded
1978: Laboratory decision to build pp= collider
1985: First collisions in Tevatron
Run I: 1992-1996 data taking period
Run II: Started March 01 after major upgrades of CDF & D0

The Fermilab site
The Upgraded Tevatron

\[ E_{\text{CMS}} = 1.96 \text{ TeV} \quad (\text{was } 1.8 \text{ TeV}) \]

Main Injector (150 GeV proton storage ring) replaces Main Ring

Luminosity goal: \(1-2 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}\) (x10 - Run I)

Bunch crossing time: 396 ns (x10 - Run I)

(132 ns upgrade indefinitely postponed)

36x36 bunch operation (was 6x6)

Presently: \(\sim 1-2\) interaction/bunch crossing (expect up to 10 in future)

Interaction region:

\(\sim 30 \ \mu\text{m}\) transverse size

\(\sim 30 \text{ cm}\) long,

Run II started March 2001
The Startup of Run II

Tevatron operations:

Delivered so far: \(~270\, {pb}^{-1}\)
Recorded to tape: \(~210\, {pb}^{-1}\)
Usable for analyses: \(~140\, {pb}^{-1}\) (most results shown use \(~70\, {pb}^{-1}\))
Data taking efficiency: \(~80-95\%\)

Initial luminosities:
Peak so far: \(4.7 \times 10^{31} \, {cm}^{-2}\, {s}^{-1}\)

Delivered To tape

Still factor 2 below nominal
The Startup of Run II

The Upgraded CDF Detector:

- **Tracking upgrade:**
  - Silicon:
    - Beampipe layer + 5 layers + 2/1 outer (forward) layers (radial 1.5 - 28 cm)
    - Full coverage of luminous region; Si tracking up to \(|\eta| < 2\)
  - Central Outer Tracker:
    - 30,200 sense wires (44 - 132 cm)
    - 96 dE/dx samples

- **New endplug calorimeter**

- **Improved muon coverage**

- **Trigger/DAQ upgrade**
  - Fully pipelined
  - All digital (132 ns)
  - Silicon trigger at L2

- **New frontend electronics**

- **Time-of-flight system**
The CDF Experiment
What’s new at D0:

- **New detector elements:**
  - solenoid,
  - silicon tracker,
  - fiber tracker
  - new preshower detector

- **Improved muon system**
- **Enhanced trigger system**
- **Extra shielding around beamlines**
Overview of B Hadron Producers:

\[ \Upsilon(4S): \ e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B \bar{B} \]

ARGUS:

The Players:
ARGUS & CLEO (Pioneers)
BaBar & Belle (B Factories)
B Hadron Producers

$Z^0$: $e^+ e^- \rightarrow Z^0 \rightarrow b\bar{b}$

The Players:
ALEPH, DELPHI, L3, OPAL, SLD
**B Hadron Producers**

**Tevatron:** $p\bar{p} \rightarrow b\bar{b}X$

- Lowest order $\mathcal{O}(\alpha_s^2)$ diagrams for $b\bar{b}$ production
  - (a)-(c) gluon-gluon fusion
  - (d) quark-antiquark annihilation

**CDF:**

**The Players:**
CDF & D0

**Other B producers:** Hera-B, FNAL fixed target

**The Future:** Atlas, CMS, LHCb, BTeV
Why do we have so many (✈😢♂♂♀♩♫) B factories these days?
Why the (✈️😃♂️🚀✨💥) do we want to do B physics at Fermilab?
**B Physics at the Tevatron**

- Advantages of $B$ Physics at the Tevatron:
  - All $B$ hadrons are produced: $B^0, B^+, B_S^0, B_c^+, \Lambda_b^0$
  - Enormous cross section
    * at $\Upsilon(4S)$: $\sigma(B\bar{B}) \approx 1 \text{ nb}$
    * at Tevatron: $\sigma(p\bar{p} \to b\bar{b}) \approx 50 \mu\text{b}$
  - $\approx 5 \cdot 10^9 b\bar{b}$ pairs produced in Run I during 1992-96

- Compare yield of $B$ mesons:
  
  **CLEO:** $\mathcal{L} = 3100 \text{ pb}^{-1}$
  
  $N(B^+ \to J/\psi K^+) = 198 \pm 15$

  **CDF:** $\mathcal{L} = 110 \text{ pb}^{-1}$
  
  $N(B^+ \to J/\psi K^+) = 998 \pm 51$
**B Physics at the Tevatron**

**Comparison with charm production**

![Graph showing total inelastic cross section](image)

- **Total inelastic cross section:**
  \( \sigma(\text{total}) / \sigma(b) \approx 1000 \)

→ **It's all about the trigger!**

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**CDF's 3-level trigger system:**

- **Level 1 Trigger**
  - 7.6 MHz Crossing Rate
  - 132 ns Clock Cycle
  - L1 Storage Pipeline:
    - 42 Clock Cycles Deep
  - L1 Accept

- **Level 2 Trigger**
  - 7.6 MHz Synchronous Pipeline
  - 5544 ns = 42 x 132 ns
  - Latency < 50 kHz
  - Accept Rate
  - Asynchronous 2-stage Pipeline
  - \( \sim 20 \mu s = 1/50 \text{ kHz} \)
  - Latency 300 Hz
  - Accept Rate
  - L1+L2 Rejection factor: 25,000

- **Level 3 System**
  - DAQ Buffers / Event Builder
  - Accept rate < 75 Hz
  - Rejection factor: > 4

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**B Trigger at CDF**

- **Run I:** B trigger based on leptons
  - Dilepton trigger: J/ψ, mixing
  - Single lepton: semileptonic B decays
- **Run II:** Hadronic track trigger
  (exploit 'long' B lifetime)

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**Example: Run I single electron trigger**

- **Level 1:** Fast track trigger (XFT) finds charged track with $p_T > 1.5$ GeV/
- **Level 2:** Link tracks into silicon; require track impact parameter $> 100 \, \mu$m (SVT)

**Access to hadronic B decays**

$\Rightarrow$ B physics program fully competitive with B factories

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**SVT impact parameter resolution:**

- $\sigma = 47 \, \mu$m
- Includes $33 \, \mu$m beamspot

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Trigger at D0

- **Run II**: B trigger
  - Dilepton trigger: J/ψ, mixing
  - Single lepton: semileptonic B decays
  - Commissioning of new hadronic track trigger
    (note, no pipeline)
- **Current trigger rates:**
  - L1 rate: 1 kHz
  - L2 rate: 600 Hz
  - L3 rate: 50 Hz
- **Data taking efficiency:**
  ~85% overall
B Physics in Run I

Successful B physics program at Tevatron in Run I:

- **B lifetimes**
  - $\tau(B^0)$: $1.51 \pm 0.05$ ps
  - $\tau(B^+)$: $1.66 \pm 0.05$ ps
  - $\tau(B^0_s)$: $1.36 \pm 0.10$ ps
  - $\tau(\Lambda_b)$: $1.32 \pm 0.17$ ps
  - $\tau(B_c)$: $0.46 \pm 0.17$ ps
  - Inc. $\tau(b)$: $1.53 \pm 0.04$ ps
  - $\tau(B^+)/(\tau(B^0))$: $1.09 \pm 0.05$

- **B mixing**
  - $D^0/lep$, $\Delta m_d$ Results:
    - $D^0/lep$: $0.516 \pm 0.099 + 0.028 - 0.035$ ps$^{-1}$
    - $e/\mu$: $0.562 \pm 0.068 + 0.041 - 0.050$ ps$^{-1}$
    - $\mu/\mu$: $0.450 \pm 0.045 \pm 0.051$ ps$^{-1}$
    - Average: $0.489 \pm 0.025 \pm 0.024$ ps$^{-1}$

- **B Cross Sections**
  - $\sigma(pp\rightarrow bX, \sqrt{s}=1.8$ TeV, $|y|<1$

- **Discovery of $B_c$ meson**

- **Evidence for $\sin2\beta \neq 0$**
Selected Run II Results

Average B Lifetime:

$J/\psi \rightarrow \mu \mu$ signal: $\sim 75,000$ events (40 pb$^{-1}$)

Average B lifetime from $B \rightarrow J/\psi X$:

$\tau(b) = (1.561 \pm 0.024 \pm 0.074)$ ps

$\lambda_B = 468 \pm 7\text{(stat)} \pm 22\text{(syst)}$ $\mu$m
Selected Run II Results

Exclusive B Decays:

(a) $B^+ \rightarrow J/\psi \ K^+$ (N=500)
(b) $B^0 \rightarrow J/\psi \ K_S$ (N=65)
(c) $B^0 \rightarrow J/\psi \ K^*$ (N=190)
(d) $B_S \rightarrow J/\psi \ \phi$ (N=62)
\[ \tau(B^+) = (1.76 \pm 0.24) \text{ ps (stat.)} \]

\[ \Lambda_b \rightarrow J/\psi \Lambda \]

\[ \text{DØ Run II Preliminary} \]
\[ \#\text{Sig.} = 40.7 \pm 10.7 \]
\[ M = 5604 \pm 18 \text{ MeV} \]
\[ \sigma = 63 \pm 18 \text{ MeV} \]
Where does charm come from?
- Prompt charm: $d_0 = 0$
- $B \rightarrow$ charm: $d_0 \neq 0$

Direct Production
- $D$ points back to PV

Secondary Production
- $D$ has finite impact parameter

CDF is collecting large amounts of direct charm!
Selected Run II Results

Direct charm cross sections:

\[ \sigma(D^0, p_T > 5.5 \text{ GeV}) = (13.3 \pm 0.2 \pm 1.5) \mu\text{b} \]

\[ \sigma(D^{*+}, p_T > 6.0 \text{ GeV}) = (5.2 \pm 0.1 \pm 0.8) \mu\text{b} \]

\[ \sigma(D^+, p_T > 6.0 \text{ GeV}) = (4.3 \pm 0.1 \pm 0.7) \mu\text{b} \]

\[ \sigma(D_S, p_T > 8.0 \text{ GeV}) = (0.75 \pm 0.05 \pm 0.22) \mu\text{b} \]
Selected Run II Results

**J/ψ cross section:**

Lower muon threshold of $p_T > 1.5$ GeV/c in Run II

$=>$ measure $J/ψ$

cross section
down to $p_T$ of zero
at hadron collider

$$\sigma(p_T > 0.0 \text{ GeV, } |\eta|<0.6) = (240 \pm 1 \pm 35/28) \text{ nb}$$
Reconstruction of fully hadronic B decays:

Measurement of B branching ratios:
Compare search mode to kinematically similar mode:

\[
\frac{\sigma_b \cdot f_S \cdot BR(B_S^0 \rightarrow D_S^- \pi^+)}{\sigma_b \cdot f_d \cdot BR(B^0 \rightarrow D^- \pi^+)} = \frac{\epsilon_{B^0} \cdot N_{B^0} \cdot BR(D^- \rightarrow K^+ \pi^+ \pi^+)}{\epsilon_{B_S^0} \cdot N_{B_S^0} \cdot BR(D_S^- \rightarrow K^- K^+ \pi^+)}
\]

Advantage: Cancellation of
- $\sigma_b$
- systematics in trigger and reconstruction efficiency

Normalization mode: $B^0 \rightarrow D^- \pi^+$

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Reconstruction of hadronic B decays:

First observation of $B_S^0 \rightarrow D_S \pi^+$

$$\frac{f_s \times BR(B_s \rightarrow D_s \pi)}{f_d \times BR(B_d \rightarrow D \pi)} = 0.44 \pm 0.11(\text{stat}) \pm 0.11(\text{BR}) \pm 0.07(\text{syst})$$
Two-Body Charmless B decays:

- Use hadronic track trigger
- Find \( \sim 300 \) events in 65 pb\(^{-1}\)
- \( S : N = 2 : 1 \) (expected 1:1)
- Signal is mix of \( B^0 / B_S^0 \to \pi\pi, K\pi, KK \)
- Use dE/dx & kinematics to disentangle

\[
\text{BR}(B^0 \to \pi\pi) / \text{BR}(B^0 \to K\pi) = 0.26 \pm 0.11 \pm 0.055
\]

- Significant \( B_S^0 \to KK \) contribution: \( 90 \pm 17 \pm 17 \) events
- Fraction of \( B^0 \to K\pi \): \( 0.53 \pm 0.06 \)
  \( B^0 \to \pi\pi \): \( 0.14 \pm 0.05 \)
  \( B_S^0 \to KK \): \( 0.32 \pm 0.06 \)
  \( B_S^0 \to K\pi \): \( 0.01 \pm 0.04 \)
Conclusions

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- Start-up of Run II
- Tour of B producers
- How to do B Physics at a Hadron Collider => Trigger
- Some Run II Results from D0:
  - Exclusive B decays modes & Lifetimes
- Some Run II Results from CDF:
  - Charm & J/Psi cross sections
  - Reconstruction of hadronic B decay modes
    (CDF's hadronic track trigger working well)
- More to expect with more luminosity
  (see talk on Bs mixing prospects by Stephanie Menzemer)
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"Anyone who keeps the ability to see beauty never grows old."
Franz Kafka
(born in Prague 1883)