Status and prospects for $B$ physics and discrete symmetries at Tevatron

Kevin Pitts
University of Illinois
Outline

- Introduction
  - $B$ physics at the Tevatron
  - Detectors & datasets

- Physics with (semi)leptonic final states
  - $B_s \rightarrow J/\psi \phi$
  - Dimuon $CP$ asymmetry
  - Rare decays: $B_s \rightarrow \mu^+\mu^-, \mu^+\mu^-\phi$

- Physics with hadronic final states
  - A bit of history
  - $B \rightarrow D^0K$
  - Charmless two-body decays ($b \rightarrow u\bar{u}d, \bar{u}u\bar{s}, s\bar{s}s$)
  - $CP$ asymmetry in $D^0 \rightarrow \pi^+\pi^-$

- A bit more on prospects

- Conclusion
**B Physics at the Tevatron**

Production is by strong interaction:

- **Pros**
  - Large cross-section
    - $\sim 3-5 \mu$ barn “reconstructable”
    - At $2 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$ $\Rightarrow$ $\sim 800 \text{Hz}$ of reconstructable $BB$!!
  - All $B$ species produced
    - $B_u, B_d, B_s, B_c, \Lambda_b, \ldots$
  - CP symmetric initial state
    - Equal numbers of $q$ and $\bar{q}$

- **Cons**
  - Large inelastic background
    - Triggering and reconstruction are challenging
    - Modes with $\pi^0$’s are tough
  - Reconstruct a $B$ hadron, $\sim 20$-$40\%$ chance $2^{nd}$ $B$ is within detector acceptance
  - $p_T$ spectrum relatively soft
    - Typical $p_T(B) \sim 10$-$15 \text{ GeV}$ for reconstructed $B$’s ($\beta\gamma \approx 2$-$3$)

---

Pros

Cons
Detectors

- Both detectors
  - silicon microvertex detectors
  - axial solenoid
  - central tracking
  - high rate trigger/DAQ system
  - calorimeter & muon systems

- DØ
  - Excellent electron & muon ID
  - Excellent tracking acceptance

- CDF
  - Silicon vertex trigger
  - Particle ID (TOF and dE/dx)
  - Excellent mass resolution
Datasets

- Tevatron performing well
  - Delivering 2.5 fb\(^{-1}\)/year

- Run II total: 10 fb\(^{-1}\) delivered
  - analyze 75–80% of delivered
  - Show 1–6 fb\(^{-1}\) results today

- Peak \(\mathcal{L}_{\text{inst}}\) 3.5-4x10\(^{32}\) cm\(^{-2}\) s\(^{-1}\)
- 6-8 interactions per crossing
- Reduced efficiency for flavor physics at high \(\mathcal{L}_{\text{inst}}\)
Currently integrating about 2.5 fb$^{-1}$ per year. Projection assumes no major luminosity improvements.

Oct 2011, 12 fb$^{-1}$ delivered

now 10 fb$^{-1}$ delivered

Three year extension: 18-19 fb$^{-1}$ delivered
⇒ 14-15 fb$^{-1}$ analysis
Trigger Strategies

- **Dimuons**
  - Clean signatures, less background
  - Get lots of $B \to J/\psi$ modes
  - Also rare decays ($B \to \mu\mu$, $\mu\mu\chi$)

- **Single electrons/muons**
  - Semileptonic decays

- **Track only**
  - Hadronic modes
Comments

- Tevatron experiments primarily contribute measurements of $B_s$, $B_c$, $b$-baryons
  - Can contribute to $B^0$ and $B^+$ in a few places
    - $B \rightarrow DK$, $A_{CP}(B^0 \rightarrow K\pi)$, $B^0 \rightarrow \mu^+\mu^-$, $B^0 \rightarrow \mu^+\mu^- K^*$,
    - $A_{CP}(B^+ \rightarrow J/\psi K^+)$, $B^+ \rightarrow \phi K^+$, $\tau_{B^+}/\tau_{B^0}$
  - In many cases (e.g. lifetimes, mixing) $B^0$ and $B^+$ are calibration or normalization modes...

- In all cases, trigger imposes a significant bias (kinematic, decay time) that must be dealt with…

- Other than a few special modes, typically require all-charged final state

- Experiments are mature, analyses have developed well beyond their original projections.
**$B_s$ Mixing**

- Mixing proceeds through “box” diagrams:

- Oscillation frequency, $\Delta m_s$
  
  $\Delta m_s \propto |V_{ts}|^2$ and $|V_{ts}|/|V_{td}| \approx 6$

- Updated CDF analysis (used for flavor tagging calibration)
  
  $\Delta m_s = 17.79 \pm 0.07 \text{ (stat) ps}^{-1}$

- What about the phase of $V_{ts}$?

---

Kevin Pitts  
*B physics and discrete symmetries at the Tevatron*
**CP Violation in $B_s \to J/\psi \phi$ Decays**

Analogous to the neutral $B^0$ system, CP violation in $B_s$ system is accessible through interference of decays with and without mixing:

$$B^0 \to J/\Psi K^0_s, \quad \bar{B}^0 \to J/\Psi \phi$$

$$\Rightarrow \sin(2\beta)$$

$$B^0_s \to J/\Psi \phi, \quad \bar{B}^0_s \to J/\Psi \phi$$

$$\Rightarrow \sin(2\beta_s)$$

- **Decay rate** ~
  - $s \to \bar{t}, c, u \to b$,
  - $W^+, W^-$

- **New Physics?**

$$\beta^S_{SM} = \text{arg}(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) \approx 0.02$$

- **CP violation phase** $\beta_s$ in SM is predicted to be very small, $O(sin^2\theta_c)$
- New physics particles running in the mixing diagram may enhance $\beta_s$
$B_s \rightarrow J/\psi \phi$

Technique:
- Use flavor tagging to determine $B_s$ vs. $\bar{B}_s$ produced
- Measure decay time and angular distributions

Decay of $B_s$ (spin 0) to $J/\psi$ (spin 1) and $\phi$ (spin 1) leads to:
- $L = 0$ (s-wave), 2 (d-wave) $\rightarrow$ CP even ($= \text{short lived or light } B_s \text{ if no CPV}$)
- $L = 1$ (p-wave) $\rightarrow$ CP odd ($= \text{long lived or heavy } B_s \text{ if no CPV}$)

Extract:
- $B_s$ lifetime $\tau_s$
- $B_{sH}, B_{sL}$ decay width difference $\Delta \Gamma_s = 1/\Gamma_{s,L} - 1/\Gamma_{s,H}$
- CP violating phase $\beta_s$
CDF + DØ combination done by the Tevatron B Working Group: http://tevbwg.fnal.gov/

Combination of 2.8 fb\(^{-1}\) analyses showed 2.1\(\sigma\) deviation from SM
**$B_s \to J/\psi \phi$ New Results**

- **CDF**
  - 6500 signal events
  - Include s-wave $KK$ component in fit.
  - Better particle ID

  *CDF Run II Preliminary, $L = 5.2\, \text{fb}^{-1}$*

  ![CDF Diagram](image)

- **DØ**
  - 3435 signal events
  - Check for s-wave $KK$ in data
  - No same-side tagging
  - Include strong phase constraints

  *Preliminary, $DØ, 6.1\, \text{fb}^{-1}$*

  ![DØ Diagram](image)

Trends are the same as before, but both experiments now see SM consistency at about $1\sigma$.

*see Louise Oakes’ talk on Friday*
**$B_s \rightarrow J/\psi K$**

- Cabibbo suppressed $b \rightarrow c\bar{c}d$
  - Smaller tree contribution larger relative penguin contribution

- $B_s \rightarrow J/\psi K^{*0}(892)$
  - Analogous to $B_s \rightarrow J/\psi \phi$

- $B_s \rightarrow J/\psi K_S$
  - $CP$ eigenstate, 100% $B_s$ heavy

- First observations, branching ratios consistent with spectator estimate
Dimuon charge asymmetry

Search for CP violation in mixing using same sign dimuon events from **semileptonic B decays**:

\[
A_{sl}^b \equiv \frac{N_{b}^{++} - N_{b}^{--}}{N_{b}^{++} + N_{b}^{--}}
\]

- \(N_{b}^{++}, N_{b}^{--}\) - number of events with two \(b\) hadrons decaying semileptonically producing two same-sign muons
  - One muon comes from direct semileptonic decay \(b \rightarrow \mu^- X\)
  - Second muon comes from direct semileptonic decay after mixing \(\bar{b} \rightarrow b \rightarrow \mu^- X\)

Derived from dimuon and inclusive muon asymmetries:

\[
A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}, \quad \text{and} \quad a \equiv \frac{n^+ - n^-}{n^+ + n^-}
\]
Experimental issues

- use one muon as the “tag” and the other as the “probe”.
- At Tevatron, both $B^0$ and $B_s$ contribute.
- Lots of subtleties, but two main issues:
  1. Asymmetric backgrounds from kaons faking $\mu$
  2. Asymmetric $\mu^+$ and $\mu^-$ acceptance/efficiency

Deal with acceptance/efficiency issue by periodically reversing polarity on central solenoid and muon toroids.
- Check residual asymmetry with data.
Fake muon backgrounds

- $\sigma(K^+N) < \sigma(K^-N)$
  - more $K^+$ get through calorimeter making fake $\mu$

- Need to know:
  - Number $K$ faking $\mu$
  - $K^+ \rightarrow \mu^+$ vs. $K^- \rightarrow \mu^-$

- Define sources of kaons:
  - $K^{*0} \rightarrow K^+\pi^-$
  - $\varphi(1020) \rightarrow K^+K^-$

- Require that the kaon is identified as a muon

- Compute asymmetry from observed $+/-$ yields

---

**Graph (a)**

- $\phi \rightarrow K^+K^-$ decay
- $\chi^2$/dof = 64/27
- $D\O, \ 6.1 \ fb^{-1}$

**Graph (b)**

- $N(K^+ \rightarrow \mu^+) + N(K^- \rightarrow \mu^-)$
- $\chi^2$/dof = 22/35
- $D\O, \ 6.1 \ fb^{-1}$

---

Kevin Pitts
DØ 6.1 fb\(^{-1}\) analysis yields:

\[ A_{s1}^b = (-0.957 \pm 0.251 \text{ (stat)} \pm 0.146 \text{ (syst)} ) \%
\]

SM prediction:

\[ A_{s1}^b (SM) = (-0.023^{+0.005}_{-0.006}) \%
\]

\( \Rightarrow \) using prediction of \( a_{s1}^d \) and \( a_{s1}^s \) from A. Lenz, U. Nierste, hep-ph/0612167

- Differs from SM by \( \sim 3.2 \sigma \)
DØ Combined results

- Result from $B_s \rightarrow J/\psi\phi$ consistent with dimuon asymmetry

![Graph showing $\Delta \Gamma_s$ vs. $\phi_s^{J/\psi\phi}$ with 68% and 95% CL regions.

$\delta_1 \equiv -0.42 \pm 0.18$
$\delta_2 \equiv 3.01 \pm 0.14$
$\Delta M_s \equiv 17.77 \pm 0.12 \text{ ps}^{-1}$

DØ, 6.1 fb$^{-1}$
$B_s^0 \rightarrow J/\psi\phi$
Projections for dimuon $A_{CP}$

- DØ dimuon $A_{CP}$ has a statistical error of 0.25% using 6.1 fb$^{-1}$

- Can CDF perform this measurement?
  - Cannot reverse magnet polarity
    - Probably not a major concern, CDF axially symmetric
    - Dominant charge bias is in central tracker at low momentum, can be measured with other modes.
  - DØ has better muon coverage at high $|\eta|$
CDF used a different technique

- Use muon impact parameter information to fit for sample composition.
- $A_{SL} = 0.0080 \pm 0.0090\text{(stat)} \pm 0.0068\text{(syst)}$

Scaling to 7 fb\(^{-1}\) would have statistical error of 0.45%

Unclear if systematics scale with statistics using CDF technique
$B_s \rightarrow \mu^+\mu^-$

- $B_s \rightarrow \mu\mu$ is highly suppressed in SM
- Some new physics models enhance BR significantly.

CDF preliminary (3.7 fb$^{-1}$)
$\text{BR}(B_s \rightarrow \mu^+\mu^-) < 4.3 \times 10^{-8} @ 95\% \text{CL}$

D0 arXiv:1006.3469 (6.1 fb$^{-1}$)
$\text{BR}(B_s \rightarrow \mu^+\mu^-) < 5.1 \times 10^{-8} @ 95\% \text{CL}$
Projection for $B_s \rightarrow \mu^+\mu^-$

CDF $\text{BR}(B_s \rightarrow \mu^+\mu^-)$ Projection

- Excluded: CDF PRL 100, 101802 (2008) (2 fb$^{-1}$)
- DØ arXiv:1006.3469 (6.1 fb$^{-1}$)
- CDF preliminary (3.7 fb$^{-1}$)
- DØ expected limit (6.1 fb$^{-1}$)

With 8 fb$^{-1}$ project 95% confidence limit of $\text{BR}(B_s \rightarrow \mu\mu) < 2 \times 10^{-8}$

SM prediction $\text{BR}(B_s \rightarrow \mu\mu) = (3.42 \pm 0.54) \times 10^{-9}$
$B_s \rightarrow \mu^+\mu^-h$

- $e^+e^- B$ factory results for $A_{fb}(B^0 \rightarrow \mu^+\mu^-K^*)$ shows interesting behavior

**Belle**

(Belle arXiv:0904.0770v1, 657M $B\bar{B}$)

**BaBar**

(BaBar PRD79,031102R(2009), 384M $B\bar{B}$)

No crossing? (i.e., opposite sign $C_7$?)

Opposite sign $C_9C_{10}$ is disfavored
CDF 4.4 fb\(^{-1}\) analysis

\(A_{fb}\) in \(B^0 \rightarrow \mu^+ \mu^- K^*\)

\(101 \pm 12\) signal events

First observation of \(B_s \rightarrow \mu^+ \mu^- \phi\)

\(27 \pm 6\) signal events

(SM expectation 31 events)

Signal significance: 6.3\(\sigma\)
Outline

- Introduction
  - $B$ physics at the Tevatron
  - Detectors & datasets
- Physics with (semi)leptonic final states
  - $B_s \rightarrow J/\psi \phi$
  - Dimuon $CP$ asymmetry
  - Rare decays: $B_s \rightarrow \mu^+\mu^-$, $\mu^+\mu^-\phi$
- Physics with hadronic final states
  - A bit of history
  - $B \rightarrow D^0K$
  - Charmless two-body decays ($b \rightarrow u\bar{u}d$, $u\bar{u}s$, $s\bar{s}s$)
  - $CP$ asymmetry in $D^0 \rightarrow \pi^+\pi^-$
- A bit more on prospects
- Conclusion
We’ve come a long way…

- Success of the Tevatron $B$ program has benefitted from:
  - More luminosity
  - Better detectors, triggers, DAQ systems
  - Better understanding of heavy flavor production
  - Improved of analysis techniques

- Two **major** transitions:
  1. silicon microvertex detector (~1991)
  2. utilizing silicon in the trigger (~2002)
The early days...

- Before silicon
- After silicon

B° mixing
F. Bedeschi, D. Lucchesi et al.
Silicon Vertex Trigger (SVT)

- SVT incorporates silicon info in the Level 2 trigger… select events with large impact parameter!
- Uses fitted beamline
- impact parameter per track
- System is "deadtimeless":
  \[ \approx 35 \mu \text{sec/event for readout} + \text{clustering} + \text{track fitting} \]
What do we get with the SVT?

Access to many new modes

without

with

inefficiency for events with low decay time

[can be accounted for e.g. $B_s$ lifetimes/mixing]
Towards CP angle $\gamma$ from $B^- \rightarrow D^0 K^-$

$\gamma$ could be extracted by exploiting the interference between the processes $\bar{b} \rightarrow \bar{c}usu$ ($B^+ \rightarrow D^0 K^+$) and $\bar{b} \rightarrow \bar{uc}s$ ($B^+ \rightarrow D^0 K^+$).

\[ A_1 \sim V_{cb} V_{us}^* \sim \lambda^3 \]

\[ A_2 \sim V_{ub} V_{cs}^* \sim \lambda^3 R_B e^{-i\delta_B} e^{-i\gamma} \]

*ADS (Atwood-Dunietz-Soni) method* ([PRL78,3257;PRD63,036005])

uses the $B^\pm \rightarrow D K^\pm$ decays with $D$ reconstructed in the doubly cabibbo suppressed $D_{DCS}^0 \rightarrow K^+ \pi^-$

Only requires extraction of yields by charge, Does not require flavor tagging or time dependent measurement
ADS analysis

- Looking for “wrong sign” $B^+ \rightarrow [K^- \pi^+]K^+$ decays from:
  - Color suppressed $B^+ \rightarrow D^0 K^+$ with $D^0 \rightarrow K^- \pi^+$
  - Cabibbo favored $B^+ \rightarrow \overline{D}^0 K^+$ with DCS $\overline{D}^0 \rightarrow K^- \pi^+$

CDF Run II Preliminary $L_{\text{int}} = 5 \text{ fb}^{-1}$

- Cabibbo favored $B^+ \rightarrow [K^+ \pi^-] \pi^+ + \text{c.c.}$
- Color suppressed + DCS D decay $B^+ \rightarrow [K^- \pi^+] \pi^+$

- Total sample about 19,000 $B^+ \rightarrow DK/D\pi$ events
$B^\pm \to D^0 K/D^0 \pi$

- Use kinematic and particle ID information to extract $D^0 K$ component
- Cabibbo favored modes:

CDF Run II Preliminary $L_{\text{int}}=1 \text{ fb}^{-1}$

$\chi^2 = 88/95$

From (PRD81:031105,2010) analysis of CP even components of GLW (Gronau- London- Wyler) method ([PLB253,483 PLB265,172]) uses the $B^\pm \to D K^\pm$ decays with $D_{CP}$ decay modes. $D_{CP+} \to \pi^+ \pi^- K^+ K^-$

Particle ID (dE/dx) information on hadron (h) from $B \to D^0 h$

CDF Run II Preliminary $L_{\text{int}}=1 \text{ fb}^{-1}$

$\chi^2 = 66/72$
ADS results

- Color suppress/doubly Cabibbo suppressed modes
- Combined significance (is there anything there?) $>5\sigma$

CDF Run II Preliminary $L_{\text{int}} = 5 \text{ fb}^{-1}$

$R_{\text{ADS}}(\pi) = 0.0041 \pm 0.0008\, (\text{stat}) \pm 0.0004\, (\text{syst})$

$A_{\text{ADS}}(\pi) = 0.22 \pm 0.18\, (\text{stat}) \pm 0.06\, (\text{syst})$

$R_{\text{ADS}}(K) = 0.0225 \pm 0.0084\, (\text{stat}) \pm 0.0079\, (\text{syst})$

$A_{\text{ADS}}(K) = -0.63 \pm 0.40\, (\text{stat}) \pm 0.23\, (\text{syst})$

see Paola Garosi’s talk on Thursday
$B_s \rightarrow \phi\phi$

CDF Run II Preliminary  
$L_{\text{int}} = 2.9 \text{ fb}^{-1}$

$BR(B_s \rightarrow \phi\phi) = (24.0 \pm 2.1(\text{stat.}) \pm 2.7(\text{sys.}) \pm 8.2(BR)) \cdot 10^{-6}$

- Penguin decay
- Normalize observed yield to $B_s \rightarrow J/\psi\phi$
- Measured BR consistent with expectation.

- $B_s \rightarrow \phi\phi$ is $P \rightarrow VV$ transition
- polarization sensitive to penguins, new physics.
- Analysis similar to $B_s \rightarrow J/\psi\phi$
**B → h⁺ h⁻**

- Charmless two-body modes
- Kinematics and particle ID

**measure:**
- BR and Direct CP asymmetry in 4 modes
  - $B^0 \rightarrow K^+ \pi^-$, $B_s \rightarrow K^- \pi^+$
  - $\Lambda_b \rightarrow p \pi^-$, $\Lambda_b \rightarrow p K^-
- BR in 2 modes
  - $B^0 \rightarrow \pi^+ \pi^-$, $B_s \rightarrow K^+ K^-$
- BR limits on 2 modes
  - $B^0 \rightarrow K^+ K^-$, $B_s \rightarrow \pi^+ \pi^-$

**Next iteration:**
- Reduced uncertainties on direct CP uncertainties
- Flavor tagged indirect CPV search

---

Kevin Pitts

B physics and discrete symmetries at the Tevatron

slide 36
Search for charm $CP$ violation

$$A_{CP}(D^0 \to \pi^+ \pi^-) = \frac{\Gamma(D^0 \to \pi^+ \pi^-) - \Gamma(\bar{D}^0 \to \pi^+ \pi^-)}{\Gamma(D^0 \to \pi^+ \pi^-) + \Gamma(\bar{D}^0 \to \pi^+ \pi^-)}$$

- Tagging the $D^0$ with $D^*$:
  $$\begin{align*}
  D^{*+} & \to D^0 \pi^+_s \\
  D^{*-} & \to \bar{D}^0 \pi^-_s
  \end{align*}$$

- $CP$ symmetric initial state ($p$-$\bar{p}$) ensures charge symmetric production

- 215,000 $D^* \to D^0 \pi$ with $D^0 \to \pi \pi$. 

CDF Run II Preliminary $\int L \, dt = 5.94 \, fb^{-1}$
Search for charm $CP$ violation

- Use tagged and untagged $D^0 \rightarrow K^- \pi^+$ (data driven) to quantify soft pion charge bias.
  - Bias significant at low $p_T$

![Graph showing asymmetry vs. $p_T$ for various decay modes.](image)

- Untagged samples:
  - $N(D^0 \rightarrow \pi^+ \pi^-) \approx 1.2 \times 10^6$
  - $N(D^0 \rightarrow K^+ K^-) \approx 3 \times 10^6$
  - $N(D^0 \rightarrow K^- \pi^+) \approx 30 \times 10^6$
**CP Asymmetry in $D^0 \rightarrow \pi^+ \pi^-$**

- **In 5.94 fb$^{-1}$ result:**

  \[
  A_{CP}(D^0 \rightarrow \pi^+ \pi^-) = (+0.22 \pm 0.24 \pm 0.11)\% \]

  \text{stat} \quad \text{syst}

- Because of displaced track trigger, CDF measures a different combination of direct and indirect CP components

- $D^0$ mixing parameters are small (x$\tau$, y$\tau$$\ll$1), then the integrated asymmetry at the first order can be written as:

  \[
  A_{CP}(D^0 \rightarrow \pi^+ \pi^-) \approx a_{CP}^{dir} + \frac{\langle t \rangle}{\tau} a_{CP}^{ind}
  \]

- **Coming:** CP asymmetry in $D^0 \rightarrow K^+K^-$

  see Fabrizio Ruffini’s talk on Friday

CDF Run II Preliminary $\int L \, dt = 5.94$ fb$^{-1}$

![Graph showing CP asymmetry with different data sets and error bands.](image-url)
Topics Not Covered (or in the pipeline…)

- **Lifetimes** (e.g. $\Lambda_b \rightarrow J/\psi \Lambda$
- **More $B_s$**
  - $B_s \rightarrow D_s D_s$
  - CPV in $B_s \rightarrow \mu D_s$
  - Other $B_s$ modes
- **Baryons**
  - Properties
  - Excited states
  - $\Omega_b$
- **$B_c$**
  - Decays
  - properties
- $D^0 \rightarrow \mu \mu$
- Production
- $X(3872), Y(4140), Z(4430)$
Conclusion

- Tevatron continuing to produce a rich program in heavy flavor physics.
  - Complementary to $e^+e^-$ machines and LHC experiments

- Many interesting results will benefit from more data.
  - Anticipate 9 fb$^{-1}$ per experiment for analysis by end of FY11
  - If run is extended, ultimate sample could be 15 fb$^{-1}$

- Results will continue beyond the end of the run
Where the Real Info Is…

- T, C, P, CP symmetries, accidental symmetries 7 (Thursday afternoon)
  - Paola Garosi
    - *First ADS analysis of $B \rightarrow DK$ in hadron collisions*

- T, C, P, CP symmetries, accidental symmetries 9 (Friday afternoon)
  - Louise Oakes
    - *Measurement of $B_s$ mixing phase and observation of suppressed $B_s$ decays at CDF*

- T, C, P, CP symmetries, accidental symmetries 10 (Friday afternoon)
  - Fabrizio Ruffini
    - *Precision measurements of direct CP violation in $D^0 \rightarrow \pi\pi$ at CDF*