B Physics at the TeVatron

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Fermilab Tevatron

- $p\bar{p}$ collisions at 1.96 TeV
- 1.7MHz collision rate (396 ns bunch spacing)
- Peak luminosity $3.5\times10^{32}\text{cm}^{-2}\text{s}^{-1}$
  - Average $\sim 6\ p\bar{p}$ interactions per bunch crossing.
- $\sim 8\ \text{fb}^{-1}$ “good” data on tape per experiment.
- End of operation by September 2011.

Results today on 1.6-7 fb$^{-1}$ of data collected.
B-Physics program

BSM

A_{FB}(B \rightarrow K\mu\mu)
B \rightarrow \mu\mu
D \rightarrow \mu\mu

CKM

\sin(2\beta_s)
B_s \rightarrow D_s D_s
A_{SL}
B \rightarrow hh
B \rightarrow DK

QCD

XY... mesons
D mixing
D \rightarrow hh
B_s \rightarrow \phi\phi

B-production
c-baryons
b-baryons
ψ & Y production

Lifetimes
$B^0_s \rightarrow \mu^+\mu^-$

$B^0_s \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ are the most studied FCNC processes. CKM, GIM and helicity suppression in SM lead to:

\[
\text{BR}(B^0_s \rightarrow \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9} \quad (|V_{ts}|^2)
\]

\[
\text{BR}(B^0 \rightarrow \mu^+\mu^-) = (1.0 \pm 0.1) \times 10^{-10} \quad (|V_{td}|^2)
\]

NP can enhance up to 100× MSSM: $\text{BR} \propto \tan^6(\beta)$.

RPV SUSY enhances also at low $\tan(\beta)$.

Very hot! Either observation or null result provides crucial information.
**B⁰_s → μ⁺μ⁻ - Results**

World’s best from 3.7 fb⁻¹
BR(B⁰_s → μ⁺μ⁻) < 4.3×10⁻⁸ @ 95 %CL
BR(B⁰_s → μ⁺μ⁻) < 7.6×10⁻⁹ @ 95%CL

Most recent results on 6.1 fb⁻¹
BR(B⁰_s → μ⁺μ⁻) < 5.1×10⁻⁸ @ 95%CL

CDF Single Event Sensitivity = 3.2×10⁻⁹ → expected 1.2 SM events, 0.7 in v_NN>0.995 ~10*SM with 3.7 fb⁻¹.
Plenty of NP models already excluded.

CDF-Pub-9892, 3.7 fb⁻¹

Phys. Lett. B 693, 539 (2010), 6.1 fb⁻¹
**$B^0_s \rightarrow \mu^+\mu^-$ - Prospect**

is working to update analysis on $7fb^{-1}$:

- 2x in statistics ($3.7 \rightarrow 7 fb^{-1}$),
- increased muon acceptance,
- better signal efficiency from new ANN,
- more accurate background estimate.

The expected limit is:
$\text{BR}(B^0_s \rightarrow \mu^+\mu^-) < 2 \times 10^{-8} @ 95\% \text{ CL}$

New strong player in the game on $35 Pb^{-1}$
$\text{BR}(B^0_s \rightarrow \mu^+\mu^-) < 5.6\times10^{-8} @ 95\% \text{ CL}$
$\text{BR}(B^0 \rightarrow \mu^+\mu^-) < 1.5\times10^{-8} @ 95\% \text{ CL}$
\[ \beta_s \text{ from } B^0_s \rightarrow J/\psi \phi - \text{ status} \]

- CP violation in \( B^0_s \rightarrow J/\psi \phi \) occurs through interference of decays with and without mixing.
- SM predicts small value for the mixing phase \( 2\beta_s = -\phi_s \).
- New particles could enter weak mixing box diagrams and enhance CP violation.
- Time evolution \( (\Gamma_L, \Gamma_H, \Delta \Gamma, \beta_s) \) very sensitive to NP contributions.
- Trends are the same as in the past, both experiments now see SM consistency at about 1\( \sigma \) level.

CDF-Pub-10206

D0Note 6098-CONF
$B^0_s \rightarrow J/\psi f_0(980)$

- This is a CP=+1 eigenstate
  - Unambiguous measure of lifetime $1/\Gamma_H$
  - Clean measure $B^0_s$ mixing phase $\beta_s$
  - $B^0_s \rightarrow J/\psi \phi$ requires complex angular analysis for vector-vector final state
  - Understand S-wave contributions to $\beta_s$ measurement in $B_s \rightarrow J/\psi \phi$

- BR measurement
  - Neural Net Selection
  - Use identical selection for $B_s \rightarrow J/\psi \phi$ reference mode
  - Simultaneous log-likelihood fit to signal and normalization mode.
BR( $B^0_s \rightarrow J/\psi f_0(980)$ )

$\sim 18\sigma$ significant (CDF-Pub-10404):

$$\frac{BR(B^0_s \rightarrow J/\psi f_0, f_0 \rightarrow \pi^+ \pi^-)}{BR(B^0_s \rightarrow J/\psi \phi, \phi \rightarrow K^+ K^-)} = 0.292 \pm 0.020(stat) \pm 0.017(syst)$$

$$BR(B^0_s \rightarrow J/\psi f_0(980)) \cdot BR(f_0(980) \rightarrow \pi^+ \pi^-) = (1.85 \pm 0.13 \pm 0.57) \times 10^{-4}$$

- First observation from LHCb [PLB 698,115,2011.]
  $$\frac{BR(B^0_s \rightarrow J/\psi f_0, f_0 \rightarrow \pi^+ \pi^-)}{BR(B^0_s \rightarrow J/\psi \phi, \phi \rightarrow K^+ K^-)} = 0.252^{+0.046+0.027}_{-0.032-0.033}$$

- Confirmed by Belle [PRL106,121802,2011]:
  $$BR(B^0_s \rightarrow J/\psi f_0, f_0 \rightarrow \pi^+ \pi^-) = (1.15^{+0.31+0.15+0.26}_{-0.19-0.17+0.18}) \times 10^{-4}$$
Di-muon charge asymmetry

- Search for CP Violation in mixing using same sign dimuon events from semileptonic B decays:

  \[ A_{sl}^b = \frac{N^{++} - N^{--}}{N^{++} + N^{--}} \]

- \( N_b^{++} \) and \( N_b^{--} \) are the 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 \( \bar{b} \rightarrow b \rightarrow \mu^- X \)
  - At the Tevatron, both \( B^0_s \) and \( B^0 \) contribute.

- Lots of subtleties in the analysis, but two main experimental issues:
  - Asymmetric backgrounds from kaons faking \( \mu \)
  - Asymmetric \( \mu^+ \) and \( \mu^- \) acceptance/efficiency
Di-muon charge asymmetry

- In 6 fb\(^{-1}\) DØ measures:
  \[ A_{sl}^{b} = (-0.957 \pm 0.251 \pm 0.146)\% \]

- SM prediction is:
  - Using prediction of \(a_{sl}^{d}\) and \(a_{sl}^{s}\) from *JHEP 0706, 072 (2007)*
  \[ A_{sl}^{b} = (-0.023^{+0.005}_{-0.006})\% \]

- Differs from SM by \(\sim 3.2\sigma\)

- Results from \(B_{s}^{0} \rightarrow J/\psi \phi\) consistent with dimuon asymmetry.
Di-muon charge asymmetry

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Green band from \(A_{sl}^b\)
What about CDF?

- CDF cannot reverse magnet polarity.
  - Probably not a major concern.
  - Dominant charge biases can be measured with data.

- DØ has better muon coverage at high $|\eta|$.

- Scaling statistical uncertainty of previous CDF measurement 0.9% ([CDF-Pub-9015](#)) on 1.6 fb$^{-1}$, on 7 fb$^{-1}$ we expect $\sim$0.3-0.4%

- The main point is the systematic uncertainty! In the meanwhile.....
Time integrated mixing probability of B mesons

Defined as: \[
\bar{\chi} = \frac{\Gamma(B^0 \rightarrow \bar{B}^0 \rightarrow l^+X)}{\Gamma(B \rightarrow l^X)} = f_d \cdot \chi_d + f_s \chi_s
\]
where the numerator includes $B^0_d$ and $B^0_s$. It derives from the measurement of the ratio $R$:

\[
R = \frac{N(\mu^+\mu^+) + N(\mu^-\mu^-)}{N(\mu^+\mu^-)}
\]

Use impact parameter (d) to identify source of muons: b, c, prompt components
2D fit of impact parameter using MC templates.

$R = 0.472 \pm 0.011 \pm 0.007 \Rightarrow \bar{\chi} = 0.126 \pm 0.008$

In agreement with LEP measurement: 0.1259±0.0042.

Fit projection of impact parameter
CPV in $D^0 \rightarrow h^+h^-$

- Charm is a unique because it probes up-quark sector (unaccessible through $t$ or $u$ quarks).
- Negligible penguin contribution the charm decays in SM
  - CPV in charm would point to NP

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

Time-integrated → $A_{CP} = a_{CP}^{dir} + \frac{<t>}{\tau} a_{CP}^{ind}$
The main challenge: suppressing detector charge asymmetries at the per mille level.

Fully data driven technique using huge sample of Cabibbo-favored tagged and untagged $D^0 \rightarrow K^-\pi^+$

Basic assumption: ppbar strong interactions are charge symmetric.

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

$$A_{CP}(D^0 \rightarrow K^+K^-) = [-0.24 \pm 0.22 \pm 0.10] \%$$

World’s best measurements.

— CDF very sensitive to mixing induced effects, because of impact parameter requirements.

Fully consistent with small CP violation.
\( \gamma \) from \( B \to DK \)

- Study of \( B \to DK \) is the cleanest way to access \( \gamma \).
  - From the interference between \( b \to c \bar{u} \bar{b} s \) (\( B^- \to D^0 K^- \)) and \( b \to u \bar{c} \bar{b} s \) (\( B^- \to \text{anti}D^0 K^- \)) with the \( D^0 \) and \( \bar{D}^0 \) decay in the same final state.

- Several methods to extract \( \gamma \).
  - No tagging or time-dependent analysis required.

- ADS method (\( \text{PRL78,3257;PRD63,036005} \)) uses Doubly Cabibbo Suppressed \( D^0 \to K^+ \pi^- \) decays.

- Simultaneous ML fit combining mass and PID estimates:
  - \( N(B \to D_{\text{DCS}} K) = 34 \pm 14 \)
  - \( N(B \to D_{\text{DCS}} \pi) = 73 \pm 16 \)
  - Significance \( (D_{\text{DCS}} \pi + D_{\text{DCS}} K) > 5\sigma \)
Observables: $R_{ADS}$ and $A_{ADS}$

$$R_{ADS} = \frac{BR(B^- \rightarrow [K^+\pi^-]_{D^0}K^-) + BR(B^+ \rightarrow [K^-\pi^+]_{D^0}K^+)}{BR(B^- \rightarrow [K^-\pi^+]_{D^0}K^-) + BR(B^+ \rightarrow [K^+\pi^-]_{D^0}K^+)}$$

$$A_{ADS} = \frac{BR(B^- \rightarrow [K^+\pi^-]_{D^0}K^-) - BR(B^+ \rightarrow [K^-\pi^+]_{D^0}K^-)}{BR(B^- \rightarrow [K^-\pi^+]_{D^0}K^-) + BR(B^+ \rightarrow [K^+\pi^-]_{D^0}K^+)}$$

- $R_{ADS}$ and $A_{ADS}$ are functions of $\gamma$ angle.
- First measurements of these quantities at hadron collisions.
- Results in agreement and competitive with other experiments.
- Analysis on $7 fb^{-1}$ is in progress. $D_{DCS}K$ significance $>3\sigma$.

See P. Garosi’s talk for more details.
Conclusions

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

- Many interesting results will benefit from more data.
  - Anticipate $\sim 10\text{fb}^{-1}$ per experiment for analysis by the end of this year.

- Results will continue beyond the end of the Run.
Topic not covered here
(or in the pipeline)

- $A_{FB}(b\rightarrow s\mu\mu)$
- World’s most precise lifetime measurements (e.g. $\Lambda_b \rightarrow J/\psi \Lambda$)
- BR&ACP in $B \rightarrow hh$
- $\gamma$ from GLW $B \rightarrow DK$
- $D^0$-mixing and $D^0 \rightarrow \mu\mu$ search (in general Charm Physics).
- More $B^0_s$ ($B^0_s \rightarrow D_s D_s$, $B^0_s \rightarrow J/\psi K_s$, $B^0_s \rightarrow J/\psi K^*$, CPV in $B_s \rightarrow \mu D_s$, $B^0_s \rightarrow \phi\phi$, ....)
- Baryons (Properties, Decays, Excited states, $\Omega_b$, ....)
  - For instance see P.Barria’s poster on $\Lambda_b \rightarrow \Lambda_c \pi\pi\pi$
- $B_c$ (decays, properties)
- Production measurements
- $X(3872)$, $Y(4140)$, $Y(4274)$ ...
- ... and many others.
Backup
CDFII detector

- Central Drift Chamber
  - \( \delta p_T/p_T \sim 0.0015 \text{ (GeV/c)}^{-1} p_T \)

- Silicon Vertex Detector
  - Silicon Vertex Trigger

- Particle identification
  - \( dE/dX \) and TOF

- Good electron and muon identification by calorimeters and muon chambers.
DØ detector

- Excellent coverage of Tracking and Muon Systems
- Excellent calorimetry and electron ID
- 2 T Solenoid, polarity reversed weekly
- High efficiency muon trigger with muon $p_T$ measurement at Level1 by toroids
**B Physics at the Tevatron**

Mechanisms for b production in ppbar collisions at 1.96 TeV:

- At Tevatron, large b production cross section
- Plethora of states accessible: B^0_s, B_c, Λ^0_b, Ξ_b, Σ_b...
- Total σ(inelastic) at Tevatron is ~1000 larger that b cross section
  — large backgrounds suppressed by triggers that target specific decays.
B Triggers

**J/ψ**
- $p_T(\mu)>1.5\text{GeV}$
- J/ψ mass requirement
- Opposite charge

**Dimuon**
- $p_T(\mu)>1.5$ or $2\text{ GeV}$
- Triggers with/without charge requirement

**Displaced Track**
- $p_T(\text{track})>2\text{ GeV}$
- IP(track)$>80$ or $120\text{ μm}$
- Opposite charge

$B^0 \rightarrow J/ψ K^0*$
$B^+ \rightarrow J/ψ K^+$
$Λ_b \rightarrow J/ψ Λ$
$B_c \rightarrow J/ψ π$
$B^0_s \rightarrow J/ψ φ$
$Ξ_b, B^{**}$

$B \rightarrow μμ+\text{hadrons}$
$B \rightarrow μμ$
$bb \rightarrow μμ$
$cc \rightarrow μμ$
$D \rightarrow hh$
$Λ_b \rightarrow ph$
$D \rightarrow hh$

IFAE 2011 - M.J. Morello
$B_{s}^{0} \rightarrow J/\psi f_{0}(980)$

- CP=+1 eigenstate
- Unambiguous measure of lifetime $1/\Gamma_{H}$
- Clean measure of CP violating parameter $\beta_{s}$
  - $B_{s} \rightarrow J/\psi \phi$ requires complex angular analysis for vector-vector final state
- Understand S-wave contributions to $\beta_{s}$ measurement in $B_{s} \rightarrow J/\psi \phi$
Start with loose selection of $\mu\mu\pi\pi$ candidates
- $f_0$ is wide, so $0.85 < M(\pi\pi) < 1.2$ GeV

Neural Net Selection

Kinematic variables, track & vertex displacement, isolation

High-mass sideband only for background model

Use identical selection for $B_s \rightarrow J/\psi \phi$ reference mode

Physics backgrounds from Monte Carlo
Di-pion mass distribution consistent with $f_0$. Shape parameters from BES.

Helicity angles consistent with P→PV decay
After efficiency correction
$B^0_s \rightarrow \phi \phi$ at the TeVatron

- First measurement of BR (CDF-Pub-10064) and first measurement of polarization (CDF-Pub-10120).
  - Found large transverse polarization $(|A_{||}|^2 + |A_{\perp}|^2)/|A_0|^2 = 1.9 \pm 0.2$ in disagreement with SM, naïvely $<< 1$

- CP violation expected very tiny, however NP could enhance it.

- The best hard way: full tagged and time-dependent analysis, but statistics still too small.

- However Triple Products (TP) Asymmetries are expected zero in SM. NP could affect those.


\[ A_{TP} = \frac{\Gamma(\vec{p} \cdot (\vec{\varepsilon}_1 \times \vec{\varepsilon}_2) > 0) - \Gamma(\vec{p} \cdot (\vec{\varepsilon}_1 \times \vec{\varepsilon}_2) < 0)}{\Gamma(\vec{p} \cdot (\vec{\varepsilon}_1 \times \vec{\varepsilon}_2) > 0) + \Gamma(\vec{p} \cdot (\vec{\varepsilon}_1 \times \vec{\varepsilon}_2) < 0)}. \]

$u = \cos \Phi \sin \Phi \quad A_{|| A_{\perp}}$

$\begin{align*}
u &= \begin{cases} 
\sin \Phi & \text{if } \cos \vartheta_1 \cos \vartheta_2 > 0 \\
\sin(-\Phi) & \text{if } \cos \vartheta_1 \cos \vartheta_2 < 0
\end{cases} \quad A_0 A_{\perp}
\end{align*}$
First measurement of CPV in $B^0_s \to \phi\phi$

- No tagging and time-dependent analysis is required.
- Unbinned ML fit:
  - Signal asymmetry enter directly the Likelihood.
  - Backg. Asymmetry consistent with 0.

$$A_u = (-0.8 \pm 6.4 \pm 1.8)\%$$
$$A_v = (-12.0 \pm 6.4 \pm 1.6)\%$$

- Sensitive to CP Violation both in mixing and decay.
\( \chi \): New CDF Measurement

- Dimuon data sample
  - 1.4 fb\(^{-1}\)
  - Use impact parameter to identify source of muons: \( b, c, \) prompt
    - Same technique as \( bb \) cross-section measurement
    - 2D fit of \( d_0 \) using templates from Monte Carlo
    - Constraints on \( b,c \rightarrow K,\pi \rightarrow \mu \) also from MC
    - Much tighter selection than earlier measurements
      - Requires hit in silicon layer 1.7cm far from beam
Extracting $\bar{\chi}$

- Many sources of dimuons in $bb$ events
  - $b$ semileptonic decay
  - $b \rightarrow c \rightarrow \mu$ sequentials
  - $b \rightarrow \psi \rightarrow \mu$
  - Hadron fakes

- Use MC to derive wrong-charge fraction

- Result: $\bar{\chi} = 0.127 \pm 0.008$
  - Includes systematic uncertainty on wrong-charge correction
  - Compare to LEP: $0.126 \pm 0.004$
CPV in $D^0 \rightarrow h^+h^-$

- The main challenge: suppressing detector charge asymmetries at the per mille level.
- Fully data driven technique using huge sample of Cabibbo-favored tagged and untagged $D^0 \rightarrow K^-\pi^+$
- Basic assumption: ppbar strong interactions are charge symmetric.

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

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- World’s best measurements.
  - CDF very sensitive to mixing induced effects, because of impact parameter requirements.
- Fully consistent with small CP violation.
BR($B_s^0 \rightarrow \mu^+\mu^-$) is obtained by normalizing to the number of $B^+ \rightarrow J/\psi K^+ \rightarrow [\mu^+\mu^-]K^+$ where $\mu^+\mu^-$ vertex is reconstructed in the "same" manner (similar for $B^0$).

$B^0 \rightarrow \mu^+\mu^-$ decays at 95%CL

$B^+ \rightarrow J/\psi K^+$ decays from data

From PDG08
B\rightarrow\mu^+\mu^- - Selection

Selection based on following kinematics discriminating variables:

Transverse momentum of candidate \( p_{T}\mu^+\mu^- (>4\text{GeV}) \)
Transverse lower momentum of muon track \( p_T \)
Proper decay time \( \lambda=L_{3D}\times M_{\mu\mu}/|p_{\mu^+\mu^-}| \)
Significance of proper decay time \( \lambda/\sigma_{\lambda} (>2) \)
3D opening angle \( \Delta\alpha (<0.7 \text{ rad}) \)
Isolation of B candidate \( I (>0.5) \)