Tevatron
Heavy Flavor
Physics

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Outline

Just a flavor of Tevatron flavor physics...
(...and new since last Users' Meeting)

• Motivation
• Detector
• $B_s^0$ system
  • Exploration of mixing matrix
  • $CP$ violation
• New $b$ baryons
  • $\Xi_b$
  • $\Xi_b$ and $\Xi_b$ properties
• Exotica
  • $Y(4140)$
• Rare Decays
Motivation

Why Heavy Flavor Physics? *It's got it all!*

- Electroweak symmetry breaking determines flavor structure
  
  CKM matrix, CP violation, FCNC's

- QCD Modeling: production, spectroscopy, masses, lifetimes, decays
  
  Challenges lattice gauge, Heavy Quark Effective Theory, strong symmetries

- Searches for new physics rare decays & departures in

Why at the Tevatron?

- Produce heavier states not accessible anywhere else (at least until LHC):

  \[ \bar{b} s, \bar{b} c, B_c, B_{s0}, B_s^{**}, \ldots \]

  Complementary to \( \Upsilon (4S) \) B factories

\[ \bar{b} d, B_{d0}^0, B^+, \bar{b} u \]
Motivation

Why Heavy Flavor Physics? It's got it all!

- Electroweak symmetry breaking determines flavor structure
  CKM matrix, CP violation, FCNC's

- QCD Modeling: production, spectroscopy, masses, lifetimes, decays
  Challenges lattice gauge, Heavy Quark Effective Theory, strong symmetries

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Why at the Tevatron?

- Produce heavier states not accessible anywhere else: $B^0, B_c, B^{**}, B_s^{**}, \Lambda_b, \Xi_b, \Sigma_b$ ...

- Huge production rate (but also huge backgrounds: triggers for specific target decays)
  Precision, rare decays, can also be competitive with $B$ factories in some $B^+$ and $B^0_d$ decays
Detectors

DØ Tracker: excellent coverage & vertexing
- Silicon & scintillating fiber
- Small radii, but extending to $|\eta| < 2$
- New Layer 0 silicon on beam pipe in 2006, improving impact para. resol.

Triggered muon coverage: $|\eta| < 2$
E.g.triggers: dimuons, single muons, track displacement @ L2

CDF Tracker: excellent mass resolution & vertexing
- Silicon, Layer 00
- Large radii drift chamber, many hits, excellent momentum resolution
- dE/dx (and TOF): particle id

Triggered muon coverage: $|\eta| < 1$
E.g.triggers: dimuons, lepton + displaced track, two displaced tracks

Relevant for B physics:
Why the $B_s^0$ is so great

Weak Eigenstates propagate according to Schrodinger:

$$i \frac{d}{dt} \begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix} = \begin{pmatrix} M - \frac{i M_{12}}{2} & M_{12} - \frac{i M_{12}}{2} \\ M^{*}_{12} - \frac{i M^{*}_{12}}{2} & M - \frac{i M^{*}_{12}}{2} \end{pmatrix} \begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix}$$

**Diagonalize**

CP Eigenstates:

$$|B_{s}^{\text{odd}}\rangle = |B_{s}^{0}\rangle + |\bar{B}_{s}^{0}\rangle \quad |B_{s}^{\text{even}}\rangle = |B_{s}^{0}\rangle - |\bar{B}_{s}^{0}\rangle$$

Mass Eigenstates:

$$|B_{s}^{\text{H}}\rangle = p|B_{s}^{0}\rangle + q|\bar{B}_{s}^{0}\rangle \quad |B_{s}^{\text{L}}\rangle = p|B_{s}^{0}\rangle - q|\bar{B}_{s}^{0}\rangle$$

If CP conserved in mixing, $p=q$

$$|B_{s}^{\text{H}}\rangle = |B_{s}^{\text{odd}}\rangle \quad |B_{s}^{\text{L}}\rangle = |B_{s}^{\text{even}}\rangle$$

$$m_s = M_H - M_L \sim 2 M_{12}$$

$$m_s^{CP} \sim 2 M_{12}$$

$$m_s = M_L - M_H \sim 2 M_{12} \cos \theta_s$$

$$\Delta m_s = \frac{M_L + M_H}{2} = \frac{1}{\sqrt{s}} \quad \Delta m_s^{SM} = \arg \left[ - \frac{M_{12}}{M_{12}} \right] \sim 0.004 \text{ in SM}$$
Why the $B_s^0$ is so great

Weak Eigenstates propagate according to Schrödinger:

$$i \frac{d}{dt} \begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix} = \begin{pmatrix} M - \frac{1}{2} & M_{12} - \frac{1}{2} \\ M_{12}^* - \frac{1}{2} & M - \frac{1}{2} \end{pmatrix} \begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix}$$

Diagonalize

CP Eigenstates:

$$|B_s^\text{odd}\rangle = |B_s^0\rangle + |\bar{B}_s^0\rangle \quad |B_s^\text{even}\rangle = |B_s^0\rangle - |\bar{B}_s^0\rangle$$

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$$|B_s^H\rangle = p |B_s^0\rangle + q |\bar{B}_s^0\rangle \quad |B_s^L\rangle = p |B_s^0\rangle - q |\bar{B}_s^0\rangle$$

If CP conserved in mixing, $p=q$

$$|B_s^H\rangle = |B_s^\text{odd}\rangle \quad |B_s^L\rangle = |B_s^\text{even}\rangle$$

$$m_s = M_H - M_L \sim 2 |M_{12}| = 17.77 \pm 0.12 \text{ ps}^{-1} \quad \text{(Precision! better than theory)}$$

$$\epsilon_s^{\text{CP}} = \epsilon_{\text{even}} - \epsilon_{\text{odd}} \sim 2 |M_{12}|$$

$$\epsilon_s = \epsilon_L - \epsilon_H \sim 2 |M_{12}| \cos \theta_s$$

$$\theta_s = \frac{\theta_L + \theta_H}{2} ; \quad \theta = \frac{1}{\theta_s}$$

Tiny for $B_d^0$ meson, but not for $B_s^0$! Eigenstates propagate with different lifetimes!

$$\epsilon_s^{\text{SM}} = \arg \left[ - \frac{M_{12}}{M_{12}} \right] \sim 0.004 \text{ in SM}$$
**Why the $B_s^0$ is so great**

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*Diagonalize*

CP Eigenstates:

$$|B_{s}\text{odd}\rangle = |B_{s}^0\rangle + |\bar{B}_{s}^0\rangle \quad |B_{s}\text{even}\rangle = |B_{s}^0\rangle - |\bar{B}_{s}^0\rangle$$

Mass Eigenstates:

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If CP conserved in mixing, $p=q$

$$|B_{s}^H\rangle = |B_{s}\text{odd}\rangle \quad |B_{s}^L\rangle = |B_{s}\text{even}\rangle$$

$$m_s = M_H \Delta M_L \sim 2 \frac{|M_{12}|}{\frac{1}{\Delta s}} \quad \text{Sensitive to new physics}$$

$$\Delta s^{CP} = \Delta_{\text{even}} \Delta_{\text{odd}} \sim 2 \frac{|M_{12}|}{\frac{1}{\Delta s}} \quad \text{Not sensitive to new physics}$$

$$\Delta s = \Delta_L \Delta_H \sim 2 \frac{|M_{12}|}{\frac{1}{\Delta s}} \cos \frac{\Delta s}{\Delta s} \quad \text{Very sensitive to new physics}$$

$$\Delta s = \frac{\Delta_L + \Delta_H}{2} ; \quad \Delta = \frac{1}{\Delta s}$$

$$\Delta_{SM} = \text{arg} \left[ - \frac{M_{12}}{\frac{1}{\Delta s}} \right] \sim 0.004 \text{ in SM}$$
First assuming no $CP$ violation in $B_s$ mixing, $\Delta s \sim 0$

Mass and $CP$ eigenstates the same

- Heavy ($H$, $CP$-odd) and Light ($L$, $CP$-even) $B_s$ states
  
  \[ \Delta s = \Delta L \Delta H ; \quad \Delta s = \left( \Delta L + \Delta H \right)/2 ; \quad \Delta s = \frac{1}{\Delta s} \]

Not "flavor-specific", predicted to be more $CP$-even than odd

- Decays into two vector mesons that are either $CP$-odd ($L=1$) or $CP$-even ($L=0,2$)

- Time-dependent angular distributions allow separation of components

- Simultaneous fit to lifetime and three angles "transversity basis"
First assuming no CP violation in $B_s$ mixing, $\Delta s \sim 0$
Mass and CP eigenstates the same

- Heavy ($H$, CP-odd) and Light ($L$, CP-even) $B_s$ states
  $$\Delta s = \Delta L \Delta H ; \quad \Delta s = (\Delta L + \Delta H)/2 ; \quad \Delta s = \frac{1}{\Delta s}$$
  Not "flavor-specific", predicted to be more CP-even than odd

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Update of 1.3 fb$^{-1}$ published analysis to 2.8 fb$^{-1}$:
CDF Run II Preliminary $L = 2.8 \text{ fb}^{-1}$
3.2k signal candidates
DØ: ~2k signal candidates
First assuming no CP violation in $B_s$ mixing, $\Delta s \sim 0$

Mass and CP eigenstates the same

- Heavy ($H$, CP-odd) and Light ($L$, CP-even) $B_s$ states

\[
\Delta s = \Delta L \Delta H; \quad \Delta s = (\Delta L + \Delta H)/2; \quad \Delta s = \frac{1}{2}
\]

- Decays into two vector mesons that are either CP-odd ($L=1$) or CP-even ($L=0,2$)

- Time-dependent angular distributions allow separation of components

- Simultaneous fit to lifetime and three angles "transversity basis"
First assuming no CP violation in $B_s$ mixing, $\Delta m_s \sim 0$
Mass and CP eigenstates the same

CDF Run II Preliminary $2.8 \text{ fb}^{-1}$

$\Delta \Gamma_s = 0.02 \pm 0.05 \pm 0.01 \text{ ps}^{-1}$

$\bar{\tau}_s = 1.53 \pm 0.04 \pm 0.01 \text{ ps}$

No flavor tag

$\bar{\tau}_s = \frac{1}{\Gamma_s} = \frac{2}{\Gamma_H + \Gamma_L}$

c.f. $\Delta \Gamma_s^{SM, pred} = 0.088 \pm 0.017 \text{ ps}^{-1}$ (hep-ph/0612167)

$0.096 \pm 0.039 \text{ ps}^{-1}$ if don't use $\Delta m_s^{\text{meas.}}$

**CP Violation**

Three kinds:

- **In decay:** \( |A_f|^2 \neq |\bar{A}_f|^2 \) (explored previously both CDF & DØ)
- **In mixing:** \( |q/p|^2 \neq 1 \) (update by DØ)
- **In interference of decay and mixing amplitudes**  (CDF & DØ)

\[ \phi_s \neq 0 \text{ or } \pi \]
**CP Violation**

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix} =
\begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
\]

- CP violation in SM occurs in complex phases in unitary CKM matrix; new physics: plenty of new phases!!

\[B_d\text{ unitarity condition} \quad V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0\]

(43 in MSSM)

Golden mode, \(B\) factories

\[B^0 \rightarrow J/\psi K_S^0\]

Area of triangle prop. to level of CP violation

\[\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\]

\[\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\]

CP violation through interference of diagrams with and w/o mixing

1
**CP Violation in $B_s^0$ System**

\[
\begin{pmatrix}
    d' \\
    s' \\
    b'
\end{pmatrix} =
\begin{pmatrix}
    V_{ud} & V_{us} & V_{ub} \\
    V_{cd} & V_{cs} & V_{cb} \\
    V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
    d \\
    s \\
    b
\end{pmatrix}
\]

- CP violation in SM occurs in complex phases in unitary CKM matrix; new physics: plenty of new phases!!

$B_s$ unitarity condition

\[V_{us} V_{ub}^* + V_{cs} V_{cb}^* + V_{ts} V_{tb}^* = 0\]

Golden mode, **Tevatron**

\[B_s^0 \rightarrow J/\psi \phi\]

"Squashed" Triangle

\[
\begin{pmatrix}
    \Box \\
    \Box \\
    \Box_s
\end{pmatrix}
\]

CP violation through interference of diagrams with and w/o mixing
**CP Violation in $B_s^0$ System**

Explore new part of matrix!

\[
\begin{pmatrix}
  d'' \\
  s' \\
  b'
\end{pmatrix} = \begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & \_ \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix} \begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
\]

- CP violation in SM occurs in complex phases in unitary CKM matrix; new physics: plenty of new phases!!

**$B_s$ unitarity condition**

\[ V_{us} V_{ub}^* + V_{cs} V_{cb}^* + V_{ts} V_{tb}^* = 0 \]

\[ \beta_{s}^{SM} = \arg[-V_{ts} V_{tb}^*/V_{cs} V_{cb}^*] \approx 0.02 \quad \text{Tiny!} \]

"Squashed" Triangle

\[ (\Box, \Box) \quad \frac{V_{ts}}{V_{cs}} \frac{V_{tb}}{V_{cb}} \quad \Box_s \]
**CP Violation in $B_s^0$ System**

- How could new physics affect these phases?

\[
2\beta_s^{SM} = 2 \arg[-V_{ts}V_{tb}^{*}/V_{cs}V_{cb}^{*}] \rightarrow 2\beta_s^{SM} - \phi_s^{NP} \\
\phi_s^{SM} = \arg[-M_{12}/\Gamma_{12}] \rightarrow \phi_s^{SM} + \phi_s^{NP} \\
\approx 0.04 \quad \approx 0.004
\]

Subtracts from one, adds to other

- Both DØ and CDF also measure/observe the phase responsible for CP violation in $B_s^0 \rightarrow J/\psi \phi$ decays

\[
\phi_s = -2\beta_s \approx \phi_s^{NP}
\]

DØ CDF If large

- Use flavor tagging to identify initial flavor, $B_s^0$ or $\bar{B}_s^0 \rightarrow J/\psi \phi$

(and known value of $m_s$)

*Flings the window open wide...*
**CP Violation in $B^0_s \rightarrow J/\psi \phi$**

- Now using initial state flavor tagging

![Graph showing CP violation](image)

**Ambiguities:**

$$2\beta_s^{J/\psi\phi} \rightarrow \pi - 2\beta_s^{J/\psi\phi} \quad \Delta \Gamma_s \rightarrow -\Delta \Gamma_s \quad \delta_\parallel \rightarrow 2\pi - \delta_\parallel \quad \delta_\perp \rightarrow \pi - \delta_\perp$$
**CP Violation in $B_s^0 \rightarrow J/\psi \phi$**

- Now using initial state flavor tagging

![Graph showing CP violation in $B_s^0 \rightarrow J/\psi \phi$](image)

**CDF Run II Preliminary**  
$L = 2.8 \text{ fb}^{-1}$

**Ambiguities:**

$$2\beta_{s/J/\psi \phi} \rightarrow \pi - 2\beta_{s/J/\psi \phi} \quad \Delta \Gamma_{s} \rightarrow -\Delta \Gamma_{s}$$

- Add weak constraints on strong phases, $\beta_j$
  - (angles between polarization amplitudes in $B_s^0 \rightarrow J/\psi \phi$ decays)

Constrain based on $B_s^0$ observations

$$\delta_{||} \rightarrow 2\pi - \delta_{||} \quad \delta_{\perp} \rightarrow \pi - \delta_{\perp}$$

**DØ**  
"Flipped"  
PRL 101, 241801 (2008)

- $M_s = 17.77 \text{ ps}^{-1}$
- $90\% \text{ CL}$
**CP Violation in $B_s^0 \rightarrow J/\psi\phi$**

Justification for DØ constraining $\phi$?
Separate, *new* DØ analysis (w/o flavor tag)

- Same phases? (SU(3) symmetry?)


Strong phases $\delta_{\perp}$ and $\delta_{\parallel}$ should be equal within 10 degrees for $B_s^0$ and $B_d^0$
**CP Violation in $B_s^0 \rightarrow J/\psi \phi$**

- **Same phases? (SU(3) symmetry?)**

```
\[ |A_\parallel|^2 \quad |A_\perp|^2 \]
```


  strong phases $\delta_\perp$ and $\delta_\parallel$ should be equal within 10 degrees for the two states.
CDF & DØ sharing two-dim. likelihoods, adjust to same statistical coverage, DØ releasing constraints on $\beta$ for comparison/combin.

Stay tuned for
- Full combination
- Updates with more data

From publication: PRL 101, 241801 (2008);
DØ Note 5933-CONF

- DØ releasing weak constraints on strong phases
- Systematic uncertainties in 2-dim. likelihood (pub. had syst. unc. on 1-dim point estimates only)
Search for \( CP \) Violation in Semileptonic \( B_s^0 \) Decay

\[
A_{SL}^s = \frac{N(\bar{B}_s^0(t) \rightarrow \ell^+ \nu_\ell X) - N(B_s^0(t) \rightarrow \ell^- \bar{\nu}_\ell X)}{N(\bar{B}_s^0(t) \rightarrow \ell^+ \nu_\ell X) + N(B_s^0(t) \rightarrow \ell^- \bar{\nu}_\ell X)} = \frac{|p/q|^2_s - |q/p|^2_s}{|p/q|^2_s + |q/p|^2_s} = |q/p|^2 
eq 1
\]

Experimentally, fit to:

- **Unmixed**
  \[
  \Gamma(B_s^0 \rightarrow \mu^+ X) \propto \exp(-\Gamma_s t)[\cosh(\Delta \Gamma_s t/2) + \cos(\Delta m_s t)]
  \]
  \[
  \Gamma(\bar{B}_s^0 \rightarrow \mu^- X)
  \]

- **Mixed**
  \[
  \Gamma(\bar{B}_s^0 \rightarrow \mu^+ X) \propto (1 + A_{SL}^s) \exp(-\Gamma_s t)[\cosh(\Delta \Gamma_s t/2) - \cos(\Delta m_s t)]
  \]
  \[
  \Gamma(B_s^0 \rightarrow \mu^- X) \propto (1 - A_{SL}^s) \exp(-\Gamma_s t)[\cosh(\Delta \Gamma_s t/2) - \cos(\Delta m_s t)]
  \]

Flavor tag

\[
\bar{B}_s^0 \rightarrow D_s \mu \nu
\]

Two decay modes

- \( \pi^+ / K^+ \)
- \( K^- \)
- \( K^+ / \pi^+ \)
Search for \( CP \) Violation in Semileptonic \( B_s^0 \) Decay

\( \sim 115k \) total \( B_s^0 \rightarrow D_s \mu \nu \) decays

- DØ toroid and solenoid polarities flipped regularly; control & measure detector asymmetries (and then correct, some as large as 3%)

\[
A_{SL} = -0.0017 \pm 0.0091^{+0.0012}_{-0.0023}
\]
Search for CP Violation in Semileptonic $B_s^0$ Decay

$$A_{SL}^s = \frac{\Delta \Gamma_s}{\Delta m_s} \tan \phi_s$$

- Green band is region allowed in new physics models given by

$$\Delta \Gamma_s = 2|\Gamma_{12}| \cos \phi_s$$
Search for CP Violation in $B_s^0$ System

$$\tau(B_s^0)_{fs} = \frac{1}{1 + \left( \frac{\Delta \Gamma_{s}}{2 \Gamma_{s}} \right)^2}$$

- World average value of $B_s^0$ flavor-specific lifetime of $1.456 \pm 0.030$ ps (HFAG)
  (50% CP-even, 50% CP-odd @ $t=0$)

- $p$-value of SM point = 10%
- Again, goal to combine w/ CDF

(shown as special talk S.Youn last Users' Mtg.)

$\mathcal{B}(B_s^0 \to D_s^*(\pi^0)D_s^{(*)-}) = 0.035 \pm 0.015$
New $b$-Flavored Baryons

- Until 2006, ground state $\Lambda_b$ was the only directly observed $b$ baryon

$$J = \frac{1}{2} \ b \text{ Baryons}$$

- More statistics, can look for more states

$$J = \frac{3}{2} \ b \text{ Baryons}$$

$L=0$ "atomic" system, heavy quark and light diquark

$\Lambda_b^0 = |bud\rangle$ DØ, CDF

$\Sigma_b^- = |bqq\rangle, q = u, d$ CDF

$\Xi_b^- = |bds\rangle$ DØ, CDF
New $b$-Flavored Baryons

- Until 2006, ground state $\Lambda_b$ was the only directly observed $b$ baryon

- More statistics, can look for more states

$L=0$ "atomic" system, heavy quark and light diquark

$\Omega_b^- = |bss\rangle$

Spin-0: $\Lambda_b$
Spin-1: $\Sigma_b$

$\Lambda_b^0 = |bud\rangle$
$\Sigma_b^- = |bqq\rangle, q = u, d$
$\Xi_b^- = |bds\rangle$
**Ω_b Baryon**

...doubly strange \( |bss\rangle \)

- Summer 2008, DØ analysis, 1.3 fb\(^{-1}\) building on previous \( \Xi_b^- \) observation

PRL 101, 232002 (2008)

- Yield 17.8 ± 4.9 ± 0.8 candidates

- Likelihood ratio, stat. significance = 5.4

- After special track reprocessing, large impact parameter tracks

\[ \Omega_b \rightarrow J/\psi \Omega \]
Baryon Decay lengths consistent with weakly decaying $b$ state

- Decay lengths consistent with weakly decaying $b$ state
- Rate with respect to $\Xi^{-}_b$ also measured (later comparison)

Mass measurements in MC samples

Variation of selection criteria

Comparison of data fitted masses of $\Lambda^0_b$ and $\Xi^-_b$ consistent w/ PDG

PRL 101, 232002 (2008)

$M(\Omega_b) = 6165 \pm 10 \pm 13$ MeV

(expect 5.94 – 6.12 GeV back then)

Greater than expected values, careful checks:
- Mass measurements in MC samples
- Variation of selection criteria
- Comparison of data fitted masses of $\Lambda^0_b$ and $\Xi^-_b$ consistent w/ PDG

$\Xi^{-}_b$ Mass

DØ
PRL 99, 052001 (2007)

CDF
PRL 99, 052002 (2007)
**New result from CDF, 4.2 fb\(^{-1}\), comprehensive reconstruction of \(b\) hadrons into \(J/\Psi\)**

- **Yield:** \(16^{+6}_{-4}\) evts.
- **Significance:** \(5.5\) (mass and lifetime info, likelihood ratio and toy MC's)

**Long decay lengths (cm) of charged**

\(\Xi^-/\Omega^-\) can use silicon tracking to improve impact parameter resolution (acceptance low for \(\Omega^-\))
\( \Omega_b \) Baryon (plus \( \Omega_b \) and \( \Xi_b^- \) Properties)

- Masses from fit to sample with \( c\tau > 100 \ \text{fm} \)
- Lifetime from yield in bins of \( c\tau \) (no need to model background)

\[
m(\Xi_b^-) = 5790.9 \pm 2.6 \pm 0.9 \text{ MeV} \\
\tau(\Xi_b^-) = 1.56^{+0.27}_{-0.25} \pm 0.02 \text{ ps}
\]

\( \downarrow \) First exclusive \( \Xi_b^- \) lifetime!

\[
m(\Omega_b^-) = 6054.4 \pm 6.8 \pm 0.9 \text{ MeV} \\
\tau(\Omega_b^-) = 1.13^{+0.53}_{-0.40} \pm 0.02 \text{ ps}
\]

\( \downarrow \) First ever!

- Relative rates \( 6 < p_T(b \text{baryon}) < 20 \text{ GeV} \)

\[
\frac{\sigma(\Xi_b^-)B(\Xi_b^- \rightarrow J/\psi\Xi^-)}{\sigma(\Lambda_b^0)B(\Lambda_b^- \rightarrow J/\psi\Xi^-)} = 0.167^{+0.037}_{-0.025} \pm 0.012 ; \\
\frac{\sigma(\Omega_b^-)B(\Omega^-_b \rightarrow J/\psi\Xi^-)}{\sigma(\Lambda_b^0)B(\Lambda_b^- \rightarrow J/\psi\Xi^-)} = 0.045^{+0.017}_{-0.012} \pm 0.004
\]
\( \Omega_b \) Baryon: Comparison

Difference of measured masses:

\[
m(\Omega_b^-)^{DØ} - m(\Omega_b^-)^{CDF} = 111 \pm 12 \pm 14 \text{ MeV}
\]

Significant (~6\( \sigma \)) disagreement!

- DØ's largest mass systematic unc. is 10 times less than this difference
- DØ is working on an update of this measurement with an increased data set that may help address discrepancy.

Relative rates:

DØ:

\[
\frac{f(b \to \Omega_b^-) \cdot B(\Omega_b^- \to J/\psi \Omega^-)}{f(b \to \Xi_b^-) \cdot B(\Xi_b^- \to J/\psi \Xi^-)} = 0.80 \pm 0.32^{+0.14}_{-0.22}
\]

1.3\( \sigma \) difference (assuming Gaussian unc.)

CDF:

\[
\frac{\sigma \cdot B(\Omega_b^- \to J/\psi \Omega^-)}{\sigma \cdot B(\Xi_b^- \to J/\psi \Xi^-)} = 0.27 \pm 0.12 \pm 0.01
\]
"Alphabet Soup" ...of charmonium-like states

- $X(3872) \rightarrow J/\psi \pi^+ \pi^-$ 2003, confirmed by CDF & DØ
  
  $J^{PC} = 1^{++} \text{ or } 2^{--}$

  (New prelim. CDF measurement of $X(3872)$ mass, best in world: $3871.61 \pm 0.16 \pm 0.19 \text{ MeV}$)

B Factories:

- $Y(3940) \rightarrow J/\psi \omega$ 2005
  
  $J^{PC} = 1^{--}$

- $Y(4260) \rightarrow J/\psi \pi^+ \pi^-$

- $\vdots$

- $Z(4330)^+ \rightarrow \psi(2S)\pi^+$ 2008
  
  $J^{PC} = 2^{++}$

- Why weird? Above $D\bar{D}$ and $D\bar{D}^*$ thresholds: should decay to open charm and have tiny $Br$'s to the above modes
Exotic Mesons

...of charmonium-like states

- Molecular states: loosely bound pair of charm states
- Tetraquarks: tightly bound diquark-antidiquark
- Charmonium hybrid states: excited gluonic degrees of freedom
- $c\bar{c}$ tightly bound inside light hadronic matter
- Threshold effects?
Exotica in $B$ Decays

CDF in 2.7 fb$^{-1}$, arXiv:0903.2229, submitted to PRL

$B^+ \rightarrow J/\psi \phi K^+$

Search for structure in $J/\psi \phi$ mass spectrum inside $B^+$ mass window

(...since $Y(3940) \rightarrow J/\psi \omega$ ...)

$B^+$ mass peak before cuts
Exotica in $B$ Decays

CDF in 2.7 fb$^{-1}$, arXiv:0903.2229, submitted to PRL

$B^+ \rightarrow J/\psi \phi K^+$

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Search for structure in $J/\psi \phi$ mass spectrum inside $B^+$ mass window

$B$ decays provide a "clean laboratory"
Exotica in $B$ Decays

CDF II Preliminary, 2.7 fb$^{-1}$

$\Delta M = M(\mu^+\mu^-K^+K^-) - M(\mu^+\mu^-)$ [GeV]

- Significance (toy MC):
  - 5.3\$, simple
  - 4.3\$, absence of prior mass and width prediction
  - 3.8\$, conservative background

$B_s^0 \rightarrow \psi(2S)\phi \rightarrow (J/\psi\pi^+\pi^-)\phi$

$Y(4140)$

Yield = 14 $\pm$ 5

$\Delta m = 1046.3$ $\pm$ 2.9 $\pm$ 1.2 MeV

$m = 4143.0$ $\pm$ 2.9 $\pm$ 1.2 MeV

Width = $11.7^{+8.3}_{-5.0}$ $\pm$ 3.7 MeV

(strong decay)

arXiv:0903.2229, submitted to PRL


- Should also decay to open charm
- Molecular state?
Rare Decays

- The usual: \( B_s^0, B_d^0 \rightarrow \mu^+ \mu^- \)
  Helicity suppressed in SM

  DØ, improved analysis, in 5 fb :
  \[ \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)_{\text{expect.}} < 4.3 \times 10^{-8} \text{ at } 90\% \text{ CL} \]

  Further: adding single muon trigger

- Helicity suppression and lepton-flavor violating
  \( B_s^0, B_d^0 \rightarrow \mu^+ e^-, e^+ e^- \)

  CDF in 2 fb\(^{-1}\): (prel., CDF Note 9413)
  \[ \mathcal{B}(B_s^0 \rightarrow e\mu) < 2.0 \times 10^{-7} \text{ at } 90\% \text{ CL} \]
  \[ M(LQ) > 47.4 \text{ TeV} \]
  \[ \mathcal{B}(B_d^0 \rightarrow e\mu) < 6.4 \times 10^{-8} \]
  \[ M(LQ) > 58.6 \text{ TeV} \]
Regrets...

- $\Lambda_b$ lifetime in $\Lambda_b \rightarrow \Lambda_c \pi$ decays
- $\sigma(B_c) \cdot \mathcal{B}(B_c \rightarrow J/\psi \mu \nu)$
- Search for narrow resonances below $\Upsilon$ mesons
- $B^+$ lifetime in $B^+ \rightarrow D^0 \pi^+$
- Update $B^0_s$ lifetime in $B^0_s \rightarrow D_s \pi$ decays
- $\mathcal{B}(B^0_s \rightarrow D_s^{(*)} D_s^{(*)})$ and a measurement of $\Delta \Gamma^{CP} / \Gamma_s$
- Mass in $B_c \rightarrow J/\psi \pi$ (finalized)
- $B_c$ lifetime (finalized)
- $\Upsilon(1S), \Upsilon(2S)$ polarization
- Search for FCNC $D$ meson decays
- Relative rate of $B \rightarrow \psi(2S), J/\psi$
- Search for excess dimuons in $1.6 < r < 10$ cm

DØ: http://www-d0.fnal.gov/Run2Physics/WWW/results/b.htm
Conclusions & Prospects

- Diverse physics program at the Tevatron resulting in continued large gains in understanding of $B$ physics
- Complementary to and competitive with the $B$ factories
- $B^0_s$ system and CP studies opening a powerful new window: possibly already providing hints of new phenomena?
- Renaissance of spectroscopy (and properties) as new heavy states continue to flood in
- Continue to push on rare decays

- Tevatron doing very well, expect to come close to \textit{doubling} our analyzed data-set by the end of running; \textit{still statistics limited on most analyses!}
Backup Slides
CDF 1.35 fb$^{-1}$ + DØ 2.8 fb$^{-1}$

$\Delta \Gamma_s [\text{ps}^{-1}]$

$\phi_s^{J/\psi\phi} = -2\beta_s^{J/\psi\phi} [\text{rad}]$

$p$-value = 0.031

2.2 $\sigma$ from SM

68% CL
95% CL
99% CL
99.7% CL

HFAG 2008
$$2\mathcal{B}(B_s^0 \rightarrow D_s^{(*)+} + D_s^{(*)-}) \approx \frac{\Delta \Gamma_s}{\Gamma_s \cos \phi_s} \left[ \frac{1}{1 - 2x_f} - \frac{\Delta \Gamma_s \cos \phi_s}{2\Gamma_s} \right]$$

Black hatched: Lattice;
Blue boxed: SU(3) symmetry breaking, 1/mq, 1/Nc, expansion (Jenkins et al.)
X(3872) Mass Measurements

- Belle
  3872.00 ± 0.60 ± 0.50 MeV/c²
- BaBar (B⁺)
  3871.30 ± 0.60 ± 0.10 MeV/c²
- BaBar (B⁰)
  3868.60 ± 1.20 ± 0.20 MeV/c²
- D0
  3871.80 ± 3.10 ± 3.00 MeV/c²
- CDF old
  3871.30 ± 0.70 ± 0.40 MeV/c²
- CDF new (preliminary)
  3871.61 ± 0.16 ± 0.19 MeV/c²
- old average
  3871.20 ± 0.39 MeV/c²
- new average
  3871.51 ± 0.22 MeV/c²
- m(D⁰)+m(D⁰*)
  3871.81 ± 0.36 MeV/c²

- (New) average is below, but within uncertainties of the D⁺D threshold. The explanation of the X(3872) as a bound D⁺D system is therefore still an option.
\( \tau_b \) Lifetime Measurements

- **CDF RunII**: \( 0.035 \pm 0.046 \pm 1.401 \)
- **CDF RunI**: \( 0.070 \pm 0.15 \pm 1.32 \)
- **DELPHI**: \( 0.050 \pm 0.18 \pm 1.11 \)
- **OPAL**: \( 0.033 \pm 0.078 + 0.083 \)
- **D0 RunII**: \( 0.042 \pm 0.115 + 0.130 \)
- **D0 RunII J/\Psi**: \( 1.290 \pm 0.120 + 0.087 \pm 0.110 - 0.091 \)
- **CDF RunII J/\Psi**: \( 1.218 \pm 0.130 \pm 0.042 \)
- **ALEPH**: \( 1.21 \pm 0.11 \)
- **DELPHI**: \( 1.11 \pm 0.19 \pm 0.05 \)
- **CDF RunI**: \( 1.32 \pm 0.15 \pm 0.07 \)
- **PDG 2009**: \( 1.383 \pm 0.049 \pm 0.048 \)

**New**: CDF RunII \( \tau_b \) Lifetime Measurement (PRELIMINARY)
Search for Excess Dimuon Production $1.6 < r < 10$ cm

DØ Note 5905-CONF

- Motivated as response to recent release of CDF multimuon ("ghost muon") result (arXiv:0810.5357 [hep-ex])
- Current DØ study limited to searching for dimuons in which one or both muons are produced at large radial distances ($1.6 < r < 10$ cm) from primary vertex

Overview

- Sample of dimuons selected to approximately match the sample used by CDF. Termed "loose" events
- Info from first layer (L0) of silicon detector used to find a subsample of these where we know both muons are produced within $r < 1.6$ cm - "tight" events
- Measure the efficiency and find the number of expected loose events, assuming no muons are produced beyond 1.6 cm (although know that there are regular sources of such muons such as decay-in-flight of $\pi$'s and $K$'s)
- Excess is measured as difference between observed and expected number of loose events
Search for Excess Dimuon Production $1.6 < r < 10$ cm

- Dataset corresponding to $\sim 1$ fb$^{-1}$, primarily on single or dimuon triggers
- Dimuon events selected according to:

<table>
<thead>
<tr>
<th>Requirement</th>
<th>$CDF$</th>
<th>$DØ$</th>
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</thead>
<tbody>
<tr>
<td>$p_T(\mu)$</td>
<td>$\geq 3$ GeV</td>
<td>$\geq 3$ GeV</td>
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<tr>
<td>$</td>
<td>\eta</td>
<td>$</td>
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<tr>
<td>$\Delta z_0$</td>
<td>$&lt; 1.5$ cm</td>
<td>$&lt; 1.5$ cm</td>
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<td>Cosmic Veto</td>
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<td>\Delta \phi</td>
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<tr>
<td>Timing</td>
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<td>$</td>
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<tr>
<td>$M(\mu\mu)$</td>
<td>$5 &lt; M(\mu\mu) &lt; 80$ GeV</td>
<td>$5 &lt; M(\mu\mu) &lt; 80$ GeV</td>
</tr>
</tbody>
</table>

(Remove back-to-back tracks)
(time diff. scintillator to beam crossing, inherent in trigger)
Search for Excess Dimuon Production $1.6 < r < 10 \text{ cm}$

DØ Silicon Microvertex Detector

<table>
<thead>
<tr>
<th>Requirement</th>
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<th>DØ</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Loose&quot; Selection</td>
<td>Hits in $\geq 3$ silicon layers (of 7 avail.)</td>
<td>$\geq 3$ silicon hits</td>
</tr>
<tr>
<td>&quot;Tight&quot; Selection</td>
<td>Hits in two innermost silicon layers &amp; $\geq 2$ other silicon hits</td>
<td>Hits in L0 &amp; $\geq 2$ other silicon hits</td>
</tr>
</tbody>
</table>

DØ Run IIb, Preliminary ($L = 0.9 \text{ fb}^{-1}$)
Search for Excess Dimuon Production $1.6 < r < 10$ cm

Results

\[ N^{\text{obs}}(\text{loose}) = 177,535 \]
\[ N^{\text{obs}}(\text{tight}) = 149,161 \]

- Using \( N^{\text{obs}}(\text{tight}) \) and known efficiency:

\[ N^{\text{expect}}(\text{loose}) = 176,823 \pm 504 \]

DØ Note 5905-CONF

\[ N(\text{excess}) = 712 \pm 462 \pm 942 \]
\[ N(\text{excess})/N^{\text{obs}}(\text{loose}) = (0.40 \pm 0.26 \pm 0.53)\% \]

(c.f. \~12\% CDF)

- Expect a small excess from known sources of radially displaced muons
  (punch-through, cosmic rays, decays-in-flight: \( K \to \mu\nu \), \( \pi \to \mu\nu \))