Baryon Spectroscopy
Results
at the Tevatron

Rick Van Kooten
Indiana University
(Representing the CDF & DØ Collaborations)
Spectroscopy

Spectroscopy at the Tevatron

- Highest effective collisions energies in world (at least for a little while longer...)
- Great deal of program focuses on high $p_T$ physics
- Spectroscopy? Rate
  - Access to large masses Focus here
    (rate still huge for heavy quarks, i.e., $c$ and $b$ quarks)
    (however, need to use relatively rare decays or rare decays of products to ensure that clean enough)
Motivation

Why Heavy Quark Hadron Spectroscopy?

- Heavy quark hadrons are the "hydrogen atom" of QCD, and $b$ hadrons offer the heaviest quarks in bound systems
- Very sensitive tests of potential models, HQET, and all regimes of QCD in general, including lattice gauge calculations
- Decays into heavy quarkonia rich ground for exotics

Why at the Tevatron?

- Decent rates for exotics: $X(...), Y(...), [Z(...)]$
- Produce heavier states not accessible anywhere else: $B_s^0, B_c, B^{**}, B_s^{**}, \Lambda_b, \Xi_b, \Sigma_b, \Omega_b ...$

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

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Previous talk: Kai Yi

Heavy Mesons
- $B_s^0$, $B_s^*$, $B_c$, $B^{**}$, $B_s^{**}$, ...
- $X(...)$, $Y(...)$

Outline:

Heavy Baryons
- $b\bar{u}\bar{d}$, $b\bar{u}\bar{u}$, $b\bar{s}\bar{d}$, $b\bar{s}\bar{s}$, ...
- $\Lambda_b$, $\Sigma_b$, $\Xi_b$, $\Omega_b$, ...
- $d\bar{d}$

(not reporting on pentaquarks from ~2004...)
(apologies to theorists if not comparing to their favorite model)
Detectors

Relevant for B physics:

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 parameter resolution.

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
• Tevatron doing very well, collected $> 7 \text{ fb}^{-1}$, expect to more than double our analyzed data set by end of running in 2011
Until recently, ground state $\Lambda_b$ was the only directly observed $b$ baryon.

$\Lambda_b^0 = |bud\rangle$  DØ, CDF
New $b$-Flavored Baryons

$J = 1/2 \ b$ Baryons

- Until recently, ground state $\Lambda_b$ was the only directly observed $b$ baryon
- More statistics, look for other $b$ baryon states

$J = 3/2 \ b$ Baryons

\[
\begin{align*}
\Lambda_b^0 &= |bud\rangle \quad \text{DØ, CDF} \\
\Sigma_b^\pm &= |bqq\rangle, q = u, d \quad \text{CDF} \\
\Xi_b^- &= |bds\rangle \quad \text{DØ, CDF} \\
\Omega_b^- &= |bss\rangle \quad \text{DØ, CDF}
\end{align*}
\]
Heavy Baryon

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

- Predictions from HQET, Lattice QCD, potential models, sum rules:

<table>
<thead>
<tr>
<th>Property</th>
<th>Expected Values (MeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diquark spin alignment</td>
<td>$m(\Sigma_b) - m(\Lambda_b^0)$</td>
</tr>
<tr>
<td>Hyperfine mass splitting</td>
<td>$m(\Sigma_b^*) - m(\Sigma_b)$</td>
</tr>
<tr>
<td>Isospin ($u, d$ diff.)</td>
<td>$m(\Sigma_b^-) - m(\Sigma_b^+)$</td>
</tr>
<tr>
<td></td>
<td>$\Gamma(\Sigma_b), \Gamma(\Sigma_b^*)$</td>
</tr>
</tbody>
</table>
Heavy Baryon

- Form a large optimized sample of $\Lambda_b^0 \rightarrow \Lambda_c^\pm \pi^\mp$

CDF 1.1 fb$^{-1}$

$\Lambda_b^0 \rightarrow \Lambda_c^\pm \pi^\mp$

$N(\Lambda_b^0) = 3180 \pm 60$

$\sum_b^{(*)} \rightarrow \Lambda_b^0 \pi^\pm$;
$\Lambda_b^0 \rightarrow \Lambda_c^\pm \pi^\mp$;
$\Lambda_c \rightarrow pK\pi$

- Then add a pion

- Estimate backgrounds:
  - $\Lambda_b^0$ with random hadronization tracks (89%)  
  - other $b$ hadrons (~7%)  
  - combinatorics (~3%)

- Fit for $Q$ values and no. of events
• Constrain $m(\Sigma_b^{*+}) - m(\Sigma_b^+) = m(\Sigma_b^{*-}) - m(\Sigma_b^-)$

• Two peaks for each charge, 5.2σ significance w.r.t. no signal

• Use CDF II measurement of
$m(\Lambda_b^0) = 5619.7 \pm 1.2 \pm 1.2 \text{ MeV}$
to get absolute masses:

$m(\Sigma_b^+) = 5807.8^{+2.0}_{-2.2} \pm 1.7 \text{ MeV}$
$m(\Sigma_b^-) = 5815.2 \pm 1.0 \pm 1.7 \text{ MeV}$
$m(\Sigma_b^{*+}) = 5829.0^{+1.6+1.7}_{-1.8-1.8} \text{ MeV}$
$m(\Sigma_b^{*-}) = 5836.4 \pm 2.0^{+1.8}_{-1.7} \text{ MeV}$
### $b$ Heavy Baryon

- **Splittings?**

<table>
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<tr>
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<th>Values (MeV/$c^2$)</th>
</tr>
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<tbody>
<tr>
<td><strong>Diquark spin alignment</strong></td>
<td>Expected</td>
</tr>
<tr>
<td>$m(\Sigma_b^+) - m(\Lambda_0^0)$</td>
<td>180 – 210</td>
</tr>
<tr>
<td>$m(\Sigma_b^-) - m(\Lambda_0^0)$</td>
<td>180 – 210</td>
</tr>
<tr>
<td><strong>(Isospin averaged)</strong></td>
<td>Measured (CDF)</td>
</tr>
<tr>
<td>$m(\Sigma_b) - m(\Lambda_0^0)$</td>
<td>194 [1]</td>
</tr>
<tr>
<td><strong>Hyperfine mass splitting</strong></td>
<td>192</td>
</tr>
<tr>
<td>$m(\Sigma_b^*) - m(\Sigma_b)$</td>
<td>10 – 40</td>
</tr>
<tr>
<td>$m(\Sigma_b^*) - m(\Sigma_b)$</td>
<td>20.0 ± 0.3 [2]</td>
</tr>
<tr>
<td><strong>Isospin (u, d diff.)</strong></td>
<td>7.4$^{+2.2}_{-2.4}$*</td>
</tr>
<tr>
<td>$m(\Sigma_b^-) - m(\Sigma_b^+)$</td>
<td>5 – 7</td>
</tr>
<tr>
<td>$\Gamma(\Sigma_b), \Gamma(\Sigma_b^*)$</td>
<td>$\sim$ 8, $\sim$ 15</td>
</tr>
</tbody>
</table>

*PRL 99, 202001 (2007)*


Weakly Decaying $b$ Baryons

Heavy $b$ baryon

$q$ $s$ $b$ $W$ $q$ $s$ $c$ $\bar{c}$

$J/\Psi \rightarrow \mu^+ \mu^-$

Baryon
Heavy Baryon

- Quark content:
  \[ \Xi^0_b : bsu \]
  \[ \Xi^-_b : bsd \]

- Decays weakly, dominated by \( b \) quark
  - Lifetime should be comparable to other \( b \) hadrons
  - DELPHI measured \( \tau(\Xi_b) = 1.39^{+0.34}_{-0.28} \) ps from excess of \( \Xi^- \ell^- \nu_\ell X \) events

Challenging for track reco.
- DØ reprocesses tracks using special settings to improve effic. of high-impact parameter tracks
- CDF vertexing software needed modifications

CDF uses silicon-only tracking for charged \( b \) (first time at a hadron collider)
**Heavy Baryon**

- **Quark content:**
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- **CDF, DØ**
  - $\Xi_b^0 \rightarrow \Xi_c^0 \pi^0$  
  - $\Xi_b^0 \rightarrow D^0 \Lambda$  
  - $\Xi_b^\pm \rightarrow J/\psi \Xi^\pm$  
  - $\Xi_b^\pm \rightarrow \Xi_c^0 \pi^\pm$

---

- **Graphical Representation**
  - Dimuons!  
  - CDF uses silicon-only tracking for charged particles ct ~ 5 cm
  - CDF measured $\Xi^- \ell^- \nu_\ell X$ events

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- **CDF**
  - Events/(0.002 GeV)
  - CDF, DØ, 1.3 fb$^{-1}$ (a)
  - Right-sign, wrong-sign

---

- **CDF**
  - M(\Xi^-) = (1321.37 ± 0.04) MeV/c$^2$
  - Yield = 23,500 ± 340
  - L ~ 1.9 fb$^{-1}$
\(b\) Heavy Baryon

"Strangely Beautiful Baryon"  
"Triple Scoop Baryon"

- Selection: cuts on momenta, vertex quality, \textit{decay length}
- DØ: boosted decision tree, opt. based on wrong-sign data, signal MC
- CDF: use \(B^+ \rightarrow J/\psi K^+\) as control sample, replace \(K\) with \(\Xi\)

CDF

DØ

Run 179200, Event 55278820, \(M(b) = 5.788\) GeV
**Heavy Baryon**

- **DØ**: many checks that no signal in wrong-sign $\Lambda\pi$ combinations, $\Xi$ sidebands, $J/\psi$ sidebands
- **CDF** has signal in $\Xi_b^\pm \rightarrow \Xi_c^0 \pi^\pm$ channel
- **DØ**: lifetime consistent with expectations:

\[
\begin{align*}
M(\Xi_b) &= 5792.9 \pm 2.4 \pm 1.7 \text{ MeV} \\
M(\Xi_b) &= 5774 \pm 11 \pm 15 \text{ MeV}
\end{align*}
\]
$\Xi_b$ Heavy Baryon

$\Xi_b$ Mass

DØ
PRL99, 052001 (2007)

CDF
PRL99, 052002 (2007)

Theory prediction

- Jenkins
  PRD54, 4515

- Karliner et al
  hep-ph/0706.2163

$m(\Xi_b^-) \ [\text{GeV/c}^2]$
**Ω_b Baryon**

...doubly strange \( |bss⟩ \)

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

Veto

Likelihood ratio, stat. significance = 5.4\(s\)

Remains > 5\(s\) with syst. checks

Yield 17.8 ± 4.9 ± 0.8 candidates

Likelihood ratio, stat. significance = 5.4\(s\)
Include "trials" factor, significance = 5.05\(s\)
Remains > 5\(s\) with syst. checks

After special track reprocessing, large impact parameter tracks
\( \Omega_b \) Baryon

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 \( \Lambda_b^0 \) and \( \Xi_b^- \) consistent w/ PDG

PRL 101, 232002 (2008)

\[ M(\Omega_b) = 6165 \pm 10 \pm 13 \text{ MeV} \]

(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 \( \Lambda_b^0 \) and \( \Xi_b^- \) consistent w/ PDG
$\Omega_b$ Baryon

Run 203929, Event 22881065, $M(\Omega_b) = 6.158$ GeV
**Ω_b Baryon (plus Ω_b and Ξ_b⁻ Properties)**

- **Result from CDF, 4.2 fb⁻¹, comprehensive reconstruction of b hadrons into J/ψ**

  - **Control/check**
    - $B^0 \rightarrow J/\psi K^{*0}$
    - $B^0 \rightarrow J/\psi K^0_S$
    - $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$

  - **Measure**
    - $\Xi_b^- \rightarrow J/\psi \Xi^-$
    - $\Omega_b^- \rightarrow J/\psi \Omega^-$
    - $\pi^-/K^-$

- **Yield:** $16^{+6}_{-4}$ evts.

- **Significance:** $5.5\sigma$
  (mass and lifetime info, likelihood ratio and toy MC's)

- **Long decay lengths (cm) of charged**
  $\Xi^-/\Omega^-\rightarrow$ can use silicon tracking to improve impact parameter resolution
  (acceptance low for $\Omega^-$)

**CT > 100 µm**
\( \Omega_b \) Baryon (plus \( \Omega_b \) and \( \Xi_b^- \) Properties)

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

![Graphs showing \( \Xi_b^- \) and \( \Omega_b^- \) decays](image)

- **Updated**

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

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

- **First exclusive \( \Xi_b^- \) lifetime!**
- **First ever!**

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

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

### Difference of measured masses:

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

**Significant (~6σ) 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:

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

Using ratio of decay partial widths from PRD **56**, 2799 (1997) + CDF lifetime ratio,

\[
\frac{f(b \rightarrow \Omega_b^-)}{f(b \rightarrow \Xi_b^-)} \approx 0.10
\]
**Ω_b Baryon: Comparison**

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\]

1.3σ difference (assuming Gaussian unc.)

**CDF:**

\[
\frac{\sigma \cdot B(\Omega_b^- \rightarrow J/\psi \Omega^-)}{\sigma \cdot B(\Xi_b^- \rightarrow J/\psi \Xi^-)} = 0.27 \pm 0.12 \pm 0.01
\]
$\Omega_b$ Baryon: Comparison

CDF, 4.2 fb$^{-1}$

DØ Mass

CDF

4.2 fb$^{-1}$

Data

Fit

DØ

1.3 fb$^{-1}$

CDF

Mass

Events/(0.04 GeV)

M($J/\psi\Omega^-$), ct $>$ 100 $\mu$m GeV/c$^2$
Summary & Prospects

- Renaissance of heavy quark hadron spectroscopy (and properties) as new massive states continue to be discovered
- Excellent data-theory agreement for most new heavy $b$ baryons
- $> 5\sigma$ discrepancy between DØ and CDF $\Omega_b$ mass measurements; CDF measurement consistent with predictions
- Providing useful input and comparisons to potential models, HQET, lattice gauge calculations, other QCD models: outstanding prospects for continued precision predictions (e.g., $\sum_b^{(*)}$ inputs for $\Xi_b$)
- Heavy quark and light quark spectroscopy can benefit each other
Conclusions & Prospects

- Next good experimental prospects for baryon spectroscopy?
  Possibility of double heavy baryons:
  \[ \Xi_{bc} \rightarrow J/\psi \Lambda_c \]
  \[ \Xi^0_b \rightarrow \Xi^+_c \pi^- \]
  among others...

- Tevatron doing very well, collected > 7 fb\(^{-1}\), expect to more than double our analyzed data set by end of running in 2011

Still statistics limited on most analyses!

LHCb, ATLAS, CMS

ATLAS beam gas event, beam energy 1.18 TeV from yesterday
Backup
Slides

Black hatched: Lattice;
Blue boxed: SU(3) symmetry breaking, $1/m_q$, $1/N_c$, expansion (Jenkins et al.)