Observation of $\Sigma_{b}^{\pm}$ at CDF

(or states consistent with $\Sigma_{b}^{\pm}$)

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September 25, 2006

All Experimenters’ Meeting
Special Topic
**Motivation**

Why spectroscopy?

- hadron mass measurements allow to check predictions of QCD inspired quark models:
  - potential models
  - lattice QCD calculations
  - $1/N_c$ expansion models
- studies of bottom hadrons in particular test predictions of HQET
- HQET has been quite successful in describing the properties of heavy mesons. What about baryons, a more complex 3-quark system?
- experimentally it is fun to find new states
Motivation

- Tremendous progress in spectroscopy
  - $B^{**}$ is well established
  - $B_s^{**}$ observed (first observation by D0)
  - observed fully reconstructed $B_c^+ \rightarrow J/\psi \pi^+$

- Still, there is only one well established B-baryon – $\Lambda_b$

- Next readily observable B-baryon - $\Sigma_b$:
  - decays strongly $\Sigma_b \rightarrow \Lambda_b \pi$, low Q expected, narrow state(s)
  - expect significant sample of $\Lambda_b$; about 3,000 in $1 fb^{-1}$
  - CDF is in the unique position to be the first here:
    - displaced track trigger for fully hadronic modes
    - excellent track momentum resolution ($\Rightarrow$ excellent mass resolution) thanks to the 138 cm lever arm tracker in 1.4 T solenoidal field
    - precision vertexing thanks to SVXII

- expect to observe lowest lying charged $\Sigma_b$ states, measure their masses and possibly isospin splittings
What is $\Sigma_b$?

- similar to $\Sigma_c$

- $\Lambda$-type $Q \{q_1 q_2\}$ $\Sigma$-type $Q \{q_1 q_2\}$, $l_k = 0$, $l_K = 0$:
  \[
  j_l = s_l = 1
  \]

- $J = j_l \pm s_Q$

- degenerate for $m_Q \to \infty$

- mass [GeV]

- $\Lambda_c$ - type

- $\Sigma_c$ - type

- $M(\Sigma_c^+) - M(\Sigma_b) = \frac{M(B^+) - M(B)}{M(D^+) - M(D)} = 0.33$

- $M(\Sigma_c^+) - M(\Sigma_c) \sim 70$ MeV

- $M(\Sigma_b^+) - M(\Sigma_b) \sim 23$ MeV

- $M(\Sigma_b) - M(\Lambda_b) \sim 180 - 190$ MeV

- $\Gamma(\Sigma_b) \sim 8$ MeV, $\Gamma(\Sigma_b^+) \sim 17$ MeV

- $M(\Sigma_b^+) - M(\Sigma_b) = 5 - 6$ MeV
Analysis Strategy

- pre-select $\Lambda_b \rightarrow pK\pi$ candidates satisfying displaced trigger requirements (2/4 tracks) and loose vertex fit requirements
- optimize cuts to achieve best $S/\sqrt{S+B} \Lambda_b$ signal
- attach fifth track to form $\Sigma_b^\pm \rightarrow \Lambda_b^0 \pi^\pm$ candidates
- measure Q-value spectrum:
  \[
  Q = M(\Lambda_b\pi) - M(\Lambda_b) - m_\pi
  \]
to get rid of $\Lambda_b$ mass systematic uncertainty
- blind "Signal Region":
  \[
  0.03 < Q < 0.1 \text{ GeV}/c^2
  \]
  choice is based on theoretical estimates
- optimize cuts on $\Sigma_b$ candidates by scoring $S/\sqrt{1.5+B}$ in a blind fashion by taking "B" from $\Sigma_b$ extrapolated sidebands: left sideband : $0 < Q < 0.03 \text{ GeV}/c^2$
  right sideband : $0.1 < Q < 0.5 \text{ GeV}/c^2$
- take "S" from PYTHIA Monte Carlo

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**CDF II Preliminary, L = 1.1 fb⁻¹**

- **Figure:**
  - Projection of unbinned max log-likelihood fit
  - About 3,000 \( \Lambda_b \) candidates in \( \int \mathcal{L} dt = 1070 \pm 60 \, \text{pb}^{-1} \)
  - World's largest \( \Lambda_b \) sample

- **Graph:**
  - \( \Lambda_b \to \Lambda_c \rho, \Lambda_b \to \Sigma_c \pi, \) Comb. Bkgnd.
  - \( \Lambda_b \) semileptonic + other
  - B semileptonic + other
  - \( \Lambda_b \) and B 4-track decays
  - \( \Lambda_b \to \Lambda_c K \)
Blinded Q-plots

Cuts:
- $p_T(\Sigma_b) > 9.5 \text{ GeV/c}$
- $|d_0/\sigma_d| < 3$ (slow $\pi$ track)
- $\cos \theta^* > -0.35$ ($\theta^*$ angle between slow $\pi$ momentum in $\Sigma_b$ rest frame and direction of $\Sigma_b$ boost)

Backgrounds:
- "real" $\Lambda_b$ plus random soft track from $b$-quark hadronization of underlying event $\Lambda_b$ HA+UE background, a major background (Monte Carlo simulation)
- "real" $B$-meson faking $\Lambda_b$ plus random soft track from $b$-quark hadronization or underlying event $B$ HA+UE background (Monte Carlo simulation)
- Combinatorial background (estimated using upper $\Lambda_b$ sideband $5.8 < M(\Lambda_c\pi) < 6 \text{ GeV/c}^2$

Shapes and relative normalization of background contributions were determined prior to opening the box.
● count observed candidates in the signal region
● compare with background extrapolation

<table>
<thead>
<tr>
<th>Sample</th>
<th>S + B</th>
<th>B</th>
<th>S</th>
<th>S/√(S + B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_b^0\pi$</td>
<td>416</td>
<td>268</td>
<td>148</td>
<td>7.3</td>
</tr>
<tr>
<td>$\Lambda_b^0\pi^+$</td>
<td>306</td>
<td>298</td>
<td>108</td>
<td>5.4</td>
</tr>
</tbody>
</table>

● CDF does not bless $S/\sqrt{S + B}$
● there is a significant excess in the signal region in both spectra!

● proceed to fit adding signal terms:

$$G \otimes BW(Q, Q_{\Sigma_b^0}, \sigma_{\Sigma_b^0}, \Gamma_{\Sigma_b^0}) +$$
$$G \otimes BW(Q, Q_{\Sigma_b^+}, \sigma_{\Sigma_b^+}, \Gamma_{\Sigma_b^+})$$

for all four $\Sigma_b^{(*)\pm}$ states
● simultaneous unbinned maximum log-likelihood:
  ● background shapes frozen
  ● 7 floating variables – $Q_{\Sigma_b^0}, Q_{\Sigma_b^+}, Q_{\Sigma_b^+} – Q_{\Sigma_b^0}, N(\Sigma_b^-), N(\Sigma_b^{*-}), N(\Sigma_b^0), N(\Sigma_b^{*+})$
  ● detector resolutions and natural widths fixed.
Fit Result

Yields:

\[
N(\Sigma_b^-) = 60.0^{+14.8}_{-13.3}(\text{stat})^{+8.4}_{-4.0}(\text{syst})
\]

\[
N(\Sigma_b^+) = 29.0^{+12.4}_{-11.6}(\text{stat})^{+5.0}_{-3.4}(\text{syst})
\]

\[
N(\Sigma_b^{*-}) = 74.0^{+18.2}_{-17.4}(\text{stat})^{+15.6}_{-5.0}(\text{syst})
\]

\[
N(\Sigma_b^{*+}) = 74.0^{+17.2}_{-16.3}(\text{stat})^{+10.3}_{-5.7}(\text{syst})
\]
Masses

\[ M(\Sigma_b^-) - M(\Lambda_b) - M(\pi) = 55.9^{+1.0}_{-1.0}(stat) \pm 0.1(syst)\text{MeV}/c^2 \]

\[ M(\Sigma_b^+) - M(\Lambda_b) - M(\pi) = 48.4^{+2.0}_{-2.3}(stat) \pm 0.1(syst)\text{MeV}/c^2 \]

\[ M(\Sigma_b^*) - M(\Sigma_b) = 21.3^{+2.0}_{-1.9}(stat)^{+0.4}_{-0.2}(syst)\text{MeV}/c^2 \]
with $1 fb^{-1}$ of luminosity accumulated, the CDF is finally in the flavor frontier mode. Hats off to Accelerator Division and excellent CDF operations.

- collected world largest sample of $\Lambda_b \rightarrow \Lambda_c \pi$ decays
- using this sample we observe 4 new states consistent with being lowest lying charged $\Sigma_b^{(*)}$ baryons
- we report measurement of masses of the new states (reported today at Beauty 2006)

Using CDF measurement $M(\Lambda_b) = 5619.5 \pm 1.2(stat) \pm 1.2(syst) \text{ MeV}/c^2$ (Phys. Rev. Lett. 96, 202001, 2006)

\[
M(\Sigma_b^-) = 5816^{+1.0}_{-1.0}(stat) \pm 1.7(syst) \text{ MeV}/c^2 \\
M(\Sigma_b^+) = 5808^{+1.0}_{-1.0}(stat) \pm 1.7(syst) \text{ MeV}/c^2 \\
M(\Sigma_b^{*-}) = 5837^{+2.0}_{-2.3}(stat) \pm 1.7(syst) \text{ MeV}/c^2 \\
M(\Sigma_b^{*+}) = 5829^{+1.6}_{-1.8}(stat) \pm 1.7(syst) \text{ MeV}/c^2
\]

- as statistic grows, expect to measure the widths of $\Sigma_b^{(*)}$ baryons
- There will be Wine&Cheese on Oct 20 with all the gory details
Back up slides
### Systematics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tracking</th>
<th>$\Lambda_b$ Sample Comp.</th>
<th>$\Lambda_b$ Sample Norm.</th>
<th>$\Lambda_b$ HA+UE Shape</th>
<th>$\Lambda_b$ HA+UE Reweight</th>
<th>Detector Res.</th>
<th>$\Sigma_b$ Width</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{\Sigma_b}$ [MeV/c^2]</td>
<td>+0.06</td>
<td>+0.00</td>
<td>+0.009</td>
<td>+0.000</td>
<td>+0.04</td>
<td>+0.00</td>
<td>0.009</td>
<td>-0.07</td>
</tr>
<tr>
<td>$Q_{\Sigma_b^+}$ [MeV/c^2]</td>
<td>+0.06</td>
<td>+0.03</td>
<td>+0.013</td>
<td>+0.013</td>
<td>+0.00</td>
<td>+0.00</td>
<td>-0.005</td>
<td>-0.07</td>
</tr>
<tr>
<td>$Q_{\Sigma_b} - Q_{\Sigma_b^+}$</td>
<td>-0.06</td>
<td>-0.05</td>
<td>-0.13</td>
<td>-0.00</td>
<td>+0.32</td>
<td>+0.02</td>
<td>+0.07</td>
<td>+0.37</td>
</tr>
<tr>
<td>$N(\Sigma_b^-)$</td>
<td>+0.0</td>
<td>+0.7</td>
<td>+2.2</td>
<td>+0.3</td>
<td>+0.4</td>
<td>+0.3</td>
<td>+3.4</td>
<td>+8.5</td>
</tr>
<tr>
<td>$N(\Sigma_b^+)$</td>
<td>+0.0</td>
<td>+3.3</td>
<td>+2.1</td>
<td>+1.2</td>
<td>+2.3</td>
<td>+0.3</td>
<td>+3.4</td>
<td>-4.0</td>
</tr>
<tr>
<td>$N(\Sigma_b^{**})$</td>
<td>+0.0</td>
<td>+0.4</td>
<td>+4.8</td>
<td>+0.3</td>
<td>+14.7</td>
<td>+0.1</td>
<td>+1.7</td>
<td>+15.6</td>
</tr>
<tr>
<td>$N(\Sigma_b^{***})$</td>
<td>+0.0</td>
<td>+7.3</td>
<td>+4.8</td>
<td>+2.8</td>
<td>+4.6</td>
<td>+0.2</td>
<td>+0.8</td>
<td>+10.3</td>
</tr>
</tbody>
</table>

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### Fit Likelihood Ratios

**Hypothesis**

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>$\Delta$ NLL</th>
<th>$1/LR$</th>
</tr>
</thead>
<tbody>
<tr>
<td>“NULL” vs “4 peak”</td>
<td>44.7</td>
<td>$2.6 \cdot 10^{19}$</td>
</tr>
<tr>
<td>“2 Peak” vs “4 peak”</td>
<td>14.3</td>
<td>$1.6 \cdot 10^{6}$</td>
</tr>
<tr>
<td>“No $\Sigma_b$ peak”</td>
<td>10.4</td>
<td>$3.3 \cdot 10^{4}$</td>
</tr>
<tr>
<td>“No $\Sigma_b^+$ peak”</td>
<td>1.1</td>
<td>3</td>
</tr>
<tr>
<td>“No $\Sigma_b^-$ peak”</td>
<td>10.1</td>
<td>$2.4 \cdot 10^{4}$</td>
</tr>
<tr>
<td>“No $\Sigma_b^+$ peak”</td>
<td>9.8</td>
<td>$1.8 \cdot 10^{4}$</td>
</tr>
</tbody>
</table>

CDF II Preliminary, $L = 1.1 \text{ fb}^{-1}$  
Fit Prob. = 0.003%

**Diagram:**

- $\Sigma_b^-$
- $\Sigma_b^+$
- Total Fit
- $\Lambda_b^0$ Ha + UE Background

$Q = m(\Lambda_b^0) - m(\Lambda_b^0) - m_\pi$ (GeV/c$^2$)