Latest results on b-spectroscopy from CDF

Elena Vataga (Univ. of New Mexico, USA)
On behalf of the CDF Collaboration
CERN- October 31, 2006
Why B spectroscopy?

- **We are not looking for New Physics** (but may find subtle discrepancy…)
- Standard Model is extraordinary. Deserves thorough elucidation.

B-quark discovered in 1977. Wealth of b-mesons is found. Only one b-baryon well established so far.

Effective theories derived from QCD needed for dynamical understanding: HQET

- $m_c, m_b, m_t >> \Lambda_{QCD} >> m_u, m_d, m_s \Rightarrow$ Heavy Quark Symmetry

HQET extensively tested for $Qq$ systems; interesting to check predictions for $Qqq$ systems
What’s new?

- Observation of orbitally excited $B_s^{**}$ mesons
- Observation and mass measurement of $B_c \rightarrow J/\psi \pi$
- Search for $\eta_b \rightarrow J/\psi J/\psi$
- Observation of new beauty baryons $\Sigma_b^{\pm(*)}$
Tevatron

- Excellent performance of Tevatron in last years
- Record Instantaneous luminosity > $2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$
- Now: delivered $\int L dt = 1.8$ fb$^{-1}$
- Good for b-physics on tape $\int L dt = 1.3$ fb$^{-1}$
The CDF II detector

96 layer drift chamber
44 < r < 132 cm, |z| < 155 cm
|\eta| \leq 1.0, 30k channels

\( r_{00} = 1.3 \div 1.6 \) cm

silicon layers:
90 cm long, |\eta| \leq 2.0

|Trigger: 3 levels|
25000 / 300 / 100 Hz
L1: COT tracks
L2: silicon tracks
dead time < 5%

|Resolution:|
\( p_T \sim 0.15\% \ p_T \)
vertex r-\( \phi \) \sim 30 \mu m; r-z \sim 80 \mu m
J/\psi \) mass \sim 14 \text{MeV/c}^2

\( \mu \) coverage
|\eta| \leq 1
84% in \phi

\( \psi \) mass \sim 14 \text{MeV/c}^2
B physics @ Tevatron

Compared to $e^+e^-$ experiments on $\Upsilon(4S)$ or $Z^0$

- **Pro:**
  - $p\bar{p} \rightarrow b\bar{b}$ x-section is $>1000$ times larger ($\sim 10 \mu b$)
  - All species of $b$-hadrons: not just $B^\pm/B^0$, also $B_s^0$, $B_c$, $\Lambda_b^0$

- **Contro:**
  - QCD background $\times 10^3$ larger than $\sigma(bb)$
  - multiple interactions, large combinatorics
  - Collision rate $\sim1.7$ MHz $\rightarrow$ tape writing limit $\sim 100$ Hz

Flavor creation (annihilation)  
Flavor creation (gluon fusion)  
Flavor excitation  
Gluon splitting
B physics @ CDF: triggers are crucial

Trigger configurations:

- **Di-muon**
- **Lepton plus displaced track**
- **2 displaced tracks**

**Secondary Vertex Trigger (SVT)** is unique to CDF!

First of its kind to trigger on fully hadronic b/c decays

BR~$10^{-5}$ visible with just trigger confirmation!

~ 42 TB in BCHARM trigger!
**$B_s$ and $\Lambda_b$ mass measurements**

**PRL 96, 202001 2006**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$M(B_s)$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delphi</td>
<td>5374. ± 16. ± 2.</td>
</tr>
<tr>
<td>Aleph</td>
<td>5368.6 ± 5.6 ± 1.5</td>
</tr>
<tr>
<td>Opal</td>
<td>5359. ± 19. ± 7.</td>
</tr>
<tr>
<td>CDF</td>
<td>5369.9 ± 2.3 ± 1.3</td>
</tr>
<tr>
<td>CDF II (this)</td>
<td>5366.01 ± 0.73 ± 0.33</td>
</tr>
<tr>
<td>World average</td>
<td>5369.6 ± 2.4</td>
</tr>
</tbody>
</table>

**Delphi**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$M(\Lambda_b)$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF</td>
<td>5668. ± 16. ± 8.</td>
</tr>
<tr>
<td>Aleph</td>
<td>5614. ± 21. ± 4.</td>
</tr>
<tr>
<td>CDF II (this)</td>
<td>5621.0 ± 4.0 ± 3.0</td>
</tr>
<tr>
<td>World average</td>
<td>5624.0 ± 9.0</td>
</tr>
</tbody>
</table>

**better precision than the current world average!**
**Lambda_b Lifetime**

- Measured with fully reconstructed $\Lambda_b \rightarrow J/\psi \Lambda^0$ decay
- 542 $\Lambda_b$ candidates
- World best $\tau(\Lambda_b)$ measurement!

\[ \tau(\Lambda_b^0) = 1.593^{+0.083}_{-0.078} \text{(stat)} \pm 0.02 \text{(syst)} \text{ ps} \]

\[ \frac{\tau(\Lambda_b^0)}{\tau(B^0)} = 1.037 \pm 0.058 \text{ (\tau(B^0) from World Average)} \]
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\[ \Lambda_b \text{ Lifetime vs theory} \]

As precise as previous world average

3.1 \sigma different though!

World Average (without this result)

(C.Tarantino et al., hep-ph/0203089)

CDF New Result

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Observation of orbitally excited (L=1) $B_s^{**}$ mesons
### Orbitally Excited $B_{sJ}$ Mesons

- **$B_{sJ}$ states have $l=0$**

<table>
<thead>
<tr>
<th>$j_q$</th>
<th>$J^p$</th>
<th>$B_{sJ}$</th>
<th>Decay</th>
<th>Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2</td>
<td>0+</td>
<td>$B_{s0}$</td>
<td>BK</td>
<td>Broad (S-wave)</td>
</tr>
<tr>
<td>1/2</td>
<td>1+</td>
<td>$B_{s1}$</td>
<td>$B^*K$</td>
<td>Broad (S-wave)</td>
</tr>
<tr>
<td>3/2</td>
<td>1+</td>
<td>$B_{s1}$</td>
<td>$B^*K$</td>
<td>Narrow (D-wave)</td>
</tr>
<tr>
<td>3/2</td>
<td>2+</td>
<td>$B_{s2}^*$</td>
<td>BK, $B^*K$</td>
<td>Narrow (D-wave)</td>
</tr>
</tbody>
</table>

- $B^{**} \rightarrow B^+\gamma$, where $\gamma$ is undetected
- Shift of possible $B_{s2}^*$, $B_{s1}$ peaks by $\Delta M(B^{**} - B^+) = 45.78$ MeV/c² (see PDG)
- Two channels: $B^+ \rightarrow J/\psi K$, $B^+ \rightarrow D\pi$
B\(^+\) sample: \(~58\ 000!\)

Use Neural Network to optimize both B\(^+\) and B\(_s\)**
Two signals:

- $B^*_{s2}$ already seen by OPAL, DELPHI and DØ
- $B^*_{s1}$ ⇒ first observation!

Orbitally Excited $B_s$-mesons
Discovery of $B_{s1}$

- $N(B^{*}_{s2}) = 94.8 \pm 23.4\text{ (stat)}$
- $N(B_{s1}) = 36.4 \pm 9.0\text{ (stat)}$

P-value from Toy MC $\sim 2 \times 10^{-7}$

Greater than 5 $\sigma$!

$m(B_{s1}) = 5829.41 \pm 0.21\text{ (stat)} \pm 0.14\text{ (syst)} \pm 0.6\text{ (PDG)} \text{ MeV/c}^2$

$m(B^{*}_{s2}) = 5839.64 \pm 0.39\text{ (stat)} \pm 0.14\text{ (syst)} \pm 0.5\text{ (PDG)} \text{ MeV/c}^2$
Observation of $B_c \rightarrow J/\psi \pi$
and mass measurement of $B_c$
$B_c^\pm \rightarrow J/\psi \pi^\pm$

- $B_c$ is not produced at B factories
- Observed in semileptonic mode
- Full reconstruction allows for precise mass measurement
- New analysis
  - Tune selection on $B^+ \rightarrow J/\psi K^+$
  - After approval, “open box”.
  - Wait for significant excess
  - Measure properties of the $B_c$
$B_c^{±} \rightarrow J/\psi \pi^{±}$

$\mathcal{N}(B_c) = 45.2 \pm 9.4, \frac{S}{\sqrt{B}} = 7.5$

$m(B_c) = 6276.5 \pm 4.0$ (stat) $\pm 2.7$ (syst) MeV/c$^2$
Search for $\eta_b \rightarrow J/\psi J/\psi$
Introduction

- Spin-singlet $b\bar{b}$ bound state
- $\sigma(p\bar{p} \rightarrow \eta_b X) \sim \mu b$ level at Tevatron energy scale
- Large uncertainty on decay branching fraction:
  - $\text{BR}(\eta_b \rightarrow J/\psi J/\psi \rightarrow \mu\mu\mu\mu) \sim 10^{-7} \div 5$
Search for $\eta_b \to J/\psi J/\psi$

- Exclusive search from CDF RunI and LEP
- Inclusive search from CLEO
  \( (\Upsilon(nS) \to \eta_b \gamma; h_b \to \eta_b \gamma) \)
- No significant evidence yet.

Run I history (80 pb\(^{-1}\)):
- 7 events observed/ 1.8 backgr. (2.2 \(\sigma\))
- Upper limit 18 pb
Results

- Expected 3.6 bkg events; observe 3 events
- Set upper limit for production cross section

\[
\frac{\sigma(p\bar{p} \rightarrow \eta_b X) \cdot Br(\eta_b \rightarrow J/\psi J/\psi)}{\sigma(p\bar{p} \rightarrow b \rightarrow J/\psi X)} < 4.98 \times 10^{-3}
\]

\[
\sigma(p\bar{p} \rightarrow \eta_b X, |y(\eta_b)| < 0.6, p_T(\eta_b) > 3 GeV) \cdot Br(\eta_b \rightarrow J/\psi J/\psi) \cdot [Br(J/\psi \rightarrow \mu\mu)]^2 < 2.6 \text{ pb}
\]
Observation of new beauty baryons $\Sigma_b^{\pm(*)}$

Bottom Baryon States with $B=1, C=0, J^P = 1/2^+, 3/2^+$

<table>
<thead>
<tr>
<th>Notation</th>
<th>Quark content</th>
<th>$J^P$</th>
<th>SU(3)</th>
<th>$(I,I_3)$</th>
<th>S</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_b^0$</td>
<td>b[ud]</td>
<td>$1/2^+$</td>
<td>3*</td>
<td>(0,0)</td>
<td>0</td>
<td>5619.7±1.2 MeV</td>
</tr>
<tr>
<td>$\Sigma_b^0$</td>
<td>b{ud}</td>
<td>$1/2^+$</td>
<td>6</td>
<td>(1,1)</td>
<td>0</td>
<td>5.82 GeV</td>
</tr>
<tr>
<td>$\Sigma_b^-$</td>
<td>b{sd}</td>
<td>$1/2^+$</td>
<td>6</td>
<td>(1,-1)</td>
<td>0</td>
<td>5.82 GeV</td>
</tr>
<tr>
<td>$\Xi_b^0$</td>
<td>b[su]</td>
<td>$1/2^+$</td>
<td>6</td>
<td>(1/2,1/2)</td>
<td>-1</td>
<td>5.80 GeV</td>
</tr>
<tr>
<td>$\Xi_b^-$</td>
<td>b[sd]</td>
<td>$1/2^+$</td>
<td>6</td>
<td>(1/2,-1/2)</td>
<td>-1</td>
<td>5.80 GeV</td>
</tr>
<tr>
<td>$\Omega_b^0$</td>
<td>bss</td>
<td>$1/2^+$</td>
<td>6</td>
<td>(0,0)</td>
<td>-2</td>
<td>6.04 GeV</td>
</tr>
<tr>
<td>$\Sigma_b^*$</td>
<td>b[uud]</td>
<td>$3/2^+$</td>
<td>6</td>
<td>(1,1)</td>
<td>0</td>
<td>5.84 GeV</td>
</tr>
<tr>
<td>$\Sigma_b^{*0}$</td>
<td>bud</td>
<td>$3/2^+$</td>
<td>6</td>
<td>(1,0)</td>
<td>0</td>
<td>5.84 GeV</td>
</tr>
<tr>
<td>$\Sigma_b^{*-}$</td>
<td>b[ddd]</td>
<td>$3/2^+$</td>
<td>6</td>
<td>(1,-1)</td>
<td>0</td>
<td>5.84 GeV</td>
</tr>
<tr>
<td>$\Xi_b^{*0}$</td>
<td>b[ud]</td>
<td>$3/2^+$</td>
<td>6</td>
<td>(1/2,1/2)</td>
<td>-1</td>
<td>5.94 GeV</td>
</tr>
<tr>
<td>$\Xi_b^{*-}$</td>
<td>b[sd]</td>
<td>$3/2^+$</td>
<td>6</td>
<td>(1/2,-1/2)</td>
<td>-1</td>
<td>5.94 GeV</td>
</tr>
<tr>
<td>$\Omega_b^{*}$</td>
<td>bss</td>
<td>$3/2^+$</td>
<td>6</td>
<td>(0,0)</td>
<td>-2</td>
<td>6.06 GeV</td>
</tr>
</tbody>
</table>

Mass predictions from hep-ph/9406359
# Predictions on Σ_b^-(*)/Σ_b^+(*) properties

<table>
<thead>
<tr>
<th>Σ_b property</th>
<th>Expected val. (MeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>m(Σ_b) − m(Λ_b)</td>
<td>180 ÷ 210</td>
</tr>
<tr>
<td>m(Σ_b^*) − m(Σ_b)</td>
<td>10 ÷ 40</td>
</tr>
<tr>
<td>m(Σ_b^-) − m(Σ_b^+)</td>
<td>5 ÷ 7</td>
</tr>
<tr>
<td>Γ(Σ_b), Γ(Σ_b^*)</td>
<td>~8, ~15</td>
</tr>
</tbody>
</table>

- NRQCD, HQET
- Potential models
- 1/N_c expansions
- Lattice QCD calculations

Strong decay with π emission:

Σ_b → Λ_b π
Methodology

Decay chain:
\[ \Sigma_b^{(*)} \rightarrow \Lambda_b^0 \pi^- \]
\[ \Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \]
\[ \Lambda_c^+ \rightarrow p K^- \pi^+ \]
Strategy

- Optimize $\Lambda_b$ yield
- Blind $\Sigma_b$ signal region
  - Check for possible reflections from other B decays
  - Evaluate different background contributions
- Optimize $\Sigma_b$ selection (MC)
- Estimate detector resolution for $\Sigma_b$ (MC)
- Measure $\Sigma_b$ yields and Masses
- Set the limit

Understanding of background is crucial!

OPEN THE BOX
Discriminating variable

- Search for narrow resonances in
  - \( Q = m(\Lambda_b\pi) - m(\Lambda_b) - m(\pi) \)
- Blinded region \( 0.03 < Q < 0.10 \) GeV/c^2
- Work with 2 distributions
  - (expect \( m(\Sigma_b^-) > m(\Sigma_b^+) \))
- Same Charge (SC):
  - \( \Sigma_b^- (*) \rightarrow \Lambda_b^0 \pi^- \rightarrow \Lambda_c^+ \pi^- \pi^- ( + c.c ) \)
- Opposite charge (OC):
  - \( \Sigma_b^+ (**) \rightarrow \Lambda_b^0 \pi^+ \rightarrow \Lambda_c^+ \pi^- \pi^+ ( + c.c ) \)

- Remove \( \Lambda_b \) resolution
- 5.787 < \( m(\Sigma_b) < 5.857 \) GeV/c^2
- \( \Sigma_b^- (bdd) \) and anti-\( \Sigma_b^- \)
- \( \Sigma_b^+ (buu) \) and anti-\( \Sigma_b^+ \)
- Two \( \pi \) have same/opposite charge

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Expected background

\[ \Sigma_b \text{ signal region} \]
(expect two narrow states)

B meson bkg
(possible peaks from \(B^{**}, D^{*}\ldots\)?)

Combinatorial background
(under control)

\[ \Lambda_b \text{ hadronization + Underlying Event} \]
(dominant bkg)
$\Lambda_b$ sample

CDF II Preliminary, $L = 1.1 \text{ fb}^{-1}$

Signal region: [5.565, 5.670]

- $\Lambda_b \rightarrow \Lambda_c \rho, \Lambda_b \rightarrow \Sigma_c \pi, \text{Comb. Bkgnd.}$
- $\Lambda_b$ semileptonic + other
- B semileptonic + other
- $\Lambda_b$ and B 4-track decays
- $\Lambda_b \rightarrow \Lambda_c K$

| $N(\Lambda_b)$ | 86 % |
| $N(B)$      | 10 % |
| comb        | 4 %  |

Largest in the World!
**Σ_b optimization**

- Cut are optimized with signal region blinded.
- Signal is taken from PYTHIA
- Background is taken from the sidebands.
- Optimization is done maximizing FOM $\varepsilon(S)/\sqrt{B}$
- No cut on $p_T (\pi_\Sigma)$

<table>
<thead>
<tr>
<th>Cut</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T (\Sigma_b)$</td>
<td>$&gt; 9.5$ GeV/c</td>
</tr>
<tr>
<td>$</td>
<td>d0/\sigma(d0)</td>
</tr>
<tr>
<td>$\cos \theta^* (\pi_\Sigma)$</td>
<td>$&gt; -0.35$</td>
</tr>
</tbody>
</table>

*cross-check on $D^* \rightarrow D^0 \pi$, included in systematic*
## Background Composition

<table>
<thead>
<tr>
<th>Background type</th>
<th>Sample</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_b$ HA+UE</td>
<td>PYTHIA</td>
<td>Dominant</td>
</tr>
<tr>
<td>Combinatorial</td>
<td>Upper $\Lambda_b$ sideband $m(\Lambda_b) \in [5.8, 7.0]$</td>
<td>Small (~ 5%)</td>
</tr>
<tr>
<td>B mesons</td>
<td>data</td>
<td>Small (~10%)</td>
</tr>
</tbody>
</table>
| B meson reflections     | $\pi_\Sigma$ from B HA+UE | PYTHIA
|                         | $\pi_\Sigma$ from B decay ($D^*$, $D^{**}$) | Inclusive BGen
|                         | $\pi_\Sigma$ from $B^{**}$ | B0 PYTHIA
|                         | $\pi_\Sigma$ from $B^{**}$ | negligible
|                         | $\pi_\Sigma$ from $B^{**}$ | negligible

The $\Lambda_b$ HA+UE background is the dominant contribution, followed by the combinatorial background and then B mesons. The B meson reflections are negligible.
Corrections to MC samples

- **PYTHIA $\Sigma_b \rightarrow \Lambda_b \pi$**
- **Do not expect perfect description for $b$-baryons** – experimental data are limited
- **Needs reweighting**
  - $P_T(\Sigma_b)$
  - $P_T(\text{soft } \pi)$
- **Included in systematic**
Fitting background

Combinatorial

B mesons

Λb HA+UE

\[ f(Q; \alpha, Q_{\text{max}}, \gamma) = \left( \frac{Q}{Q_{\text{max}}} \right)^{\alpha} e^{-\frac{\alpha}{\gamma} \left( \frac{Q}{Q_{\text{max}}} \right)^{\gamma}} \left( \frac{Q}{Q_{\text{max}}} \right)^{\gamma} - 1 \]

alternative fit shapes in systematics
Detector resolution and signal width

- Estimated detector resolution from MC generating signal with 0 natural width $\sim 2 \text{ MeV}/c^2$
- Cross-check on $D^* \rightarrow D^0\pi$ (MC)
- $\Gamma(\Sigma_b)$ is predicted by HQET:

\[ \Gamma_{\Sigma_q \rightarrow \Lambda_q\pi} = \frac{1}{6\pi} \frac{M_{\Lambda_q}}{M_{\Sigma_q}} |f_p|^2 |\vec{p}_\pi|^3 \]

- Dominated by natural width

$\Gamma_{\Sigma_q \rightarrow \Lambda_q\pi} = \frac{1}{6\pi} \frac{M_{\Lambda_q}}{M_{\Sigma_q}} |f_p|^2 |\vec{p}_\pi|^3$

$ f_p \equiv g_A / f_\pi; \quad g_A = 0.75 \pm 0.05$

hep-ph/9406359
Sum of Background Fits

- Smooth background shape in signal window
- Fixed fit parameters before opening the box
**Unblinded Q distribution**

![Graph showing Q distribution with data points and fits for different samples: SC and OC.](image)

Significant excess in both distributions!

<table>
<thead>
<tr>
<th>Sample</th>
<th>Data</th>
<th>Bkg</th>
<th>Excess</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC</td>
<td>416</td>
<td>268</td>
<td>148</td>
</tr>
<tr>
<td>OC</td>
<td>406</td>
<td>298</td>
<td>108</td>
</tr>
</tbody>
</table>

• Naïve $S/\sqrt{(S+B)} \sim 9 \sigma$
Fitting the signal

- Simultaneous unbinned NLL fit for both $\Sigma_b^{-(*)}/\Sigma_b^{+(*)}$ distributions
- Background frozen
- 4 peaks: Breit-Wigner $\otimes$ Gaussians
- $\Gamma(\Sigma_b) =$ function $(Q)$
- 7 Floating parameters:
  - Num of events in 4 peaks: $N(\Sigma_b)$
  - $Q(\Sigma_b^-)$ and $Q(\Sigma_b^+)$
  - Common parameter $Q(\Sigma_b^*) = Q(\Sigma_b)$
Fit: values and errors

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q (\Sigma_b^-) [\text{MeV/c}^2]$</td>
<td>55.9</td>
<td>-0.96, +0.99</td>
</tr>
<tr>
<td>$Q (\Sigma_b^+) [\text{MeV/c}^2]$</td>
<td>48.4</td>
<td>-2.29, +2.02</td>
</tr>
<tr>
<td>$N (\Sigma_b^-)$</td>
<td>60</td>
<td>-13.8, +14.8</td>
</tr>
<tr>
<td>$N (\Sigma_b^+)$</td>
<td>29</td>
<td>-11.6, +12.4</td>
</tr>
<tr>
<td>$N (\Sigma_b^{*-})$</td>
<td>74</td>
<td>-17.4, 18.2</td>
</tr>
<tr>
<td>$N (\Sigma_b^{*-+})$</td>
<td>74</td>
<td>-16.3, 17.2</td>
</tr>
<tr>
<td>$Q (\Sigma_b^*) - Q (\Sigma_b) [\text{MeV/c}^2]$</td>
<td>21.3</td>
<td>-1.94, 2.03</td>
</tr>
<tr>
<td>NLL</td>
<td>-24553.5</td>
<td></td>
</tr>
</tbody>
</table>
Signal significance

- Naïve: $9\sigma$
- \( P \) value calculation: $>5\sigma$ (not enough Toy MC)
- Evaluate Likelihood Ratio for different hypothesis:

$$LR \equiv \frac{L_{\text{no peak fit}}}{L_{4 \text{ peak fit}}}$$

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>( \Delta(-\ln(L)) )</th>
<th>1/LR</th>
</tr>
</thead>
<tbody>
<tr>
<td>“NULL”</td>
<td>44.7</td>
<td>2.6e19</td>
</tr>
<tr>
<td>“Two Peaks”</td>
<td>14.3</td>
<td>1.6e6</td>
</tr>
<tr>
<td>No ( \Sigma_b^- ) peak</td>
<td>10.4</td>
<td>3.3e4</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>2.4e4</td>
</tr>
<tr>
<td>No ( \Sigma_b^{++} ) peak</td>
<td>9.8</td>
<td>1.8e4</td>
</tr>
</tbody>
</table>

4 peaks are $2.6 \times 10^{19}$ more likely than no peak at all

**Background fluctuation is statistically excluded**

**Hypothesis with 4 peaks in the most favorable**
Summary

- We observe four $\Lambda_b \pi$ resonant states 240 events in total.

- The significance of the signal $> 5\sigma$.

- The signal is consistent with the lowest lying $\Sigma_b^{\pm(*)}$ states.

- We measure Q values:

  - $m(\Sigma_b^-) - m(\Lambda_b^0) - m(\pi) = 55.9^{+0.0}_{-1.0}$ (stat) $\pm 0.1$ (syst) MeV/c$^2$

  - $m(\Sigma_b^+) - m(\Lambda_b^0) - m(\pi) = 48.4^{+0.0}_{-2.3}$ (stat) $\pm 0.1$ (syst) MeV/c$^2$

  - $m(\Sigma_{b(*)}^-) - m(\Sigma_b^-) = m(\Sigma_{b(*)}^+) - m(\Sigma_b^+) = 21.3^{+0.0}_{-1.9}$ (stat) $^{+0.4}_{-0.2}$ (syst) MeV/c$^2$
Plans

- Increase statistics by
  - $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ from different triggers ($\sim 1000$)
  - $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$ ($\sim 500$)
  - $\Lambda_b^0 \rightarrow \Lambda_c^+ 3\pi$
- Measure $\Delta m = M(\Sigma_b^*) - M(\Sigma_b)$ for “+” and “−” separately
- Measure widths
Conclusions

- CDF makes fundamental contributions in b-spectroscopy
- Performing the world most precise measurements of \( \Lambda_b \ B_c \ B_s \ B^+ \ B^0 \) masses
- Discovering new particles:
  - \( \Sigma_b^{\pm(*)} \rightarrow \Lambda_b \pi \)
  - \( B_{s1} \rightarrow B^*K \)
  - \( B_c \rightarrow J/\psi \pi \)
- Setting new limits:
  - \( \eta_b \rightarrow J/\psi \ J/\psi \)
- And all these with only THE FIRST \( fb^{-1} \)!
\[ \Sigma_b^{\pm(*)} \text{ masses} \]

- Using \( m(\Lambda_b) = 5619.7 \pm 1.2 \text{(stat)} \pm 1.2 \text{(syst)} \)

\[
\begin{align*}
    m(\Sigma_b^-) &= 5816^{+1.0}_{-1.0} \text{ (stat)} \pm 1.7 \text{ (syst) MeV/c}^2 \\
    m(\Sigma_b^+) &= 5808^{+2.0}_{-2.3} \text{ (stat)} \pm 1.7 \text{ (syst) MeV/c}^2 \\
    m(\Sigma_b^{*-}) &= 5837^{+2.1}_{-1.9} \text{ (stat)} \pm 1.7 \text{ (syst) MeV/c}^2 \\
    m(\Sigma_b^{*+}) &= 5829^{+1.6}_{-1.8} \text{ (stat)} \pm 1.7 \text{ (syst) MeV/c}^2
\end{align*}
\]
## Systematic Errors

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tracking</th>
<th>$\Lambda_b$ Comp.</th>
<th>$\Lambda_b$ Norm.</th>
<th>$\Lambda_b$ Shape</th>
<th>reweight</th>
<th>Det. Res.</th>
<th>$\Sigma_b$ width</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
<td>$\Sigma_b^-$ Q (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>0.0</td>
<td>0.009</td>
<td>0.07</td>
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<td>-0.03</td>
<td>-0.002</td>
<td>-0.011</td>
<td>-0.0004</td>
<td>-0.011</td>
<td>-0.005</td>
<td>-0.07</td>
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<tr>
<td>$\Sigma_b^+$ Q (Mev/c$^2$)</td>
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<td>0.03</td>
<td>0.013</td>
<td>0.013</td>
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<td>0.01</td>
<td>0.07</td>
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<td>-0.014</td>
<td>-0.02</td>
<td>-0.13</td>
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<td>$\Sigma_b^-*\Sigma_b$ Q (Mev/c$^2$)</td>
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<td>0.05</td>
<td>0.14</td>
<td>0.04</td>
<td>0.32</td>
<td>0.02</td>
<td>0.07</td>
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<td>-0.13</td>
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<td>7.4</td>
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<td>3.4</td>
<td>8.3</td>
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<td>-2.2</td>
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<td>0.0</td>
<td>0.0</td>
<td>-3.4</td>
<td>-4.0</td>
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<tr>
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<td>3.3</td>
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<td>2.3</td>
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<td>-3.4</td>
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<td>$\Sigma_b^-$ events</td>
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<td>0.0</td>
<td>-1.7</td>
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<tr>
<td>$\Sigma_b^{*+}$ events</td>
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<td>-2.9</td>
<td>0.0</td>
<td>-0.8</td>
<td>-5.7</td>
</tr>
</tbody>
</table>
**Σ_b Motivation**

- Λ_b only established B baryon
- Enough statistics at Tevatron to probe other heavy baryons
- Next accessible baryons: Σ_b: b{qq}, q = u,d;

\[
J^P = S_Q + s_{qq} = 3/2^+ (\Sigma_b^*)
\]

\[
J^P = S_Q + s_{qq} = 1/2^+ (\Sigma_b)
\]

- HQET extensively tested for Qq systems; interesting to check predictions for Qqq systems
- Baryon spectroscopy also tests Lattice QCD and potential quark models

<table>
<thead>
<tr>
<th>Σ_b property</th>
<th>Expected values (MeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>m(Σ_b) - m(Λ_b^0)</td>
<td>180 - 210</td>
</tr>
<tr>
<td>m(Σ_b^*) - m(Σ_b)</td>
<td>10 - 40</td>
</tr>
<tr>
<td>m(Σ_b^-) - m(Σ_b^+)</td>
<td>5 - 7</td>
</tr>
<tr>
<td>Γ(Σ_b), Γ(Σ_b^*)</td>
<td>~8, ~15</td>
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</table>
Fit: correlation coeff.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Global</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
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<tbody>
<tr>
<td>1 $\Sigma_b^-$ Q</td>
<td>0.31202</td>
<td>1.000</td>
<td>0.156</td>
<td>0.175</td>
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<td>-0.114</td>
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<td>2 $\Sigma_b^-$ events</td>
<td>0.29891</td>
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<td>0.005</td>
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<td>3 $\Sigma_b^+$ Q</td>
<td>0.71323</td>
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<td>1.000</td>
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<td>6 $\Sigma_b^+$ events</td>
<td>0.19252</td>
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<td>0.006</td>
<td>-0.012</td>
<td>-0.162</td>
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<td>1.000</td>
<td>0.074</td>
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<tr>
<td>7 $\Sigma_b^*$ - $\Sigma_b$ Q</td>
<td>0.72939</td>
<td>-0.246</td>
<td>0.084</td>
<td>-0.712</td>
<td>0.057</td>
<td>-0.002</td>
<td>0.074</td>
<td>1.000</td>
</tr>
</tbody>
</table>

$\Sigma_b^+$ peak is small – relies on $\Sigma_b^*$ - $\Sigma_b$ to determine it’s mean value.
$\Sigma_b \ N-1 \ scan$

$\Sigma_b$ N-1 scan

PT ($\Sigma b$) > 9.5 GeV/c

$|d0/\sigma(d0)| < 3.$

$\cos \theta^* > -0.35$

CERN - October 31, 2006

E.Vataga - Latest results on b-spectroscopy from CDF
Why b baryons?

- B quark discovered in 1977
- Wealth of b- mesons is found
- Only one b baryon well established so far
- Finding and studying b baryons completes tests of SM
- Systematic expansion of QCD: Heavy Quark Eff. Theory:
  - $m_c, m_b, m_t \gg \Lambda_{QCD} \gg m_u, m_d, m_s \Rightarrow$ Heavy Quark Symmetry
- Masses and decay rates test HQET
- HQET extensively tested for $Qq$ systems; interesting to check predictions for $Qqq$ systems
$B_s$ mass measurement

Delphi: $5374.0 \pm 16.0 \pm 2.0$

Aleph: $5368.6 \pm 5.6 \pm 1.5$

Opal: $5359.0 \pm 19.0 \pm 7.0$

CDF: $5369.9 \pm 2.3 \pm 1.3$

CDF II (this): $5366.01 \pm 0.73 \pm 0.33$

World average: $5369.6 \pm 2.4$

better precision than the current world average!
**Λ_b mass measurements**

- Observed Λ_b decays:
  - Λ_b^0 → J/ψ Λ^0
  - Λ_b^0 → Λ_c^+π^-
  - Λ_b^0 → Λ_c^+μ^-ν_μ

**Better precision than the current world average!**

**PRL 96, 202001 2006**