New Bottom Baryons at CDF

Dmitry Litvintsev (Fermilab)

for CDF Collaboration

September 13, 2007

LBNL Research Progress Meetings series
Introduction
- Source of data: Tevatron
- Source of data: CDF detector
- Heavy flavor in $p\bar{p}$ collisions

Search for $\Sigma^*_b$

Search for $\Xi_b$

Conclusion
Source of data: Tevatron
Heavy Flavor Production at Tevatron

LO Heavy quark production

NLO Heavy quark production

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>PEPII, KEK</th>
<th>Tevatron</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(b\bar{b})$</td>
<td>1 nb</td>
<td>$100 \mu b$ ($10 \mu b \</td>
</tr>
<tr>
<td>$\sigma(b\bar{b}) : \sigma(had)$</td>
<td>0.26</td>
<td>0.001</td>
</tr>
<tr>
<td>Production</td>
<td>$e^+e^- \rightarrow \gamma(4S) \rightarrow B\bar{B}$</td>
<td>$p\bar{p} \rightarrow b\bar{b}X$</td>
</tr>
<tr>
<td>Environment</td>
<td>clean</td>
<td>messy</td>
</tr>
<tr>
<td>Hadrons produced</td>
<td>$B^0, B^+$</td>
<td>all</td>
</tr>
<tr>
<td>Boost</td>
<td>0.5</td>
<td>2-4</td>
</tr>
<tr>
<td>Kinematics</td>
<td>forward boost</td>
<td>$b\bar{b}$ not back-to-back, second $b$ usually lost</td>
</tr>
<tr>
<td>pile-up</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Trigger</td>
<td>inclusive</td>
<td>selective</td>
</tr>
<tr>
<td>Beam energy constraint</td>
<td>yes</td>
<td>no</td>
</tr>
</tbody>
</table>

Dedicated triggers are pre-requisite to efficient extraction of heavy flavor signals from the data
Completely reconstructed $\Upsilon(4S) \rightarrow B^0 \bar{B}^0$ event with $B^0 - \bar{B}^0$ mixing in ARGUS Experiment (Phys. Lett. B55 (1991), 297)

$B^0_s - \bar{B}^0_s$ mixing candidate event in CDF II, 2006
tracking
- Drift Chamber – Central Outer Chamber
- Layer00 + SVXII + ISL

new plug calorimeter

extended muon coverage, |\( \eta \) < 1.5

ToF system, (100 ps @ 150 cm)

improved DAQ and trigger systems
- new frontend electronics
- Level 1 all digital synch. h/w trigger. 132 ns pip
- 40kHz/1kHz/100 Hz
- COT Tracks @ Level 1
- Si Tracks @ Level 2
- Full analysis @ Level 3
- First hadronic B-trigger
  - Silicon vertex trigger (SVT)
  - PID with ToF and dE/dx
  - Excellent mass resolution
di-muon triggers ($B \rightarrow \mu \mu X$):

- $J/\psi$ trigger – di-muon events with masses around $J/\psi, \psi(2S)$ (two CMU muons or 1 CMU and 1 CMX muon)
- Rare B trigger – di-muon events with masses in expanded mass range from 0 to 6 GeV with tighter cuts.
  - Either two CMU muons
  - or CMU muon and CMX muon plus lateral displacement of di-muon intersect w.r.t. primary vertex, and $\Sigma(p_T)$ cut
- $b\bar{b}$ trigger – di-muon events with masses in expanded mass range from 5 to 12 GeV. Both muons must be CMUP muons.
- Upsilon trigger: di-Muon events in a mass range around the Upsilon. Either a CMU or CMX muon and a CMUP muon.
Displaced track triggers

- New displaced track triggers (two track and \(\ell\)+track) exploit \(b\)-quark lifetime.
  - Level 1
    - \(\checkmark\) XFT tracking in COT \((r - \phi)\)
    - \(\checkmark\) opposite charged track pair with \(p_T > 2\) GeV/c each
    - \(\checkmark\) \(\Sigma p_T > 5.5\) GeV/c
    - \(\checkmark\) \(\Delta \phi < 90^\circ\)
  - Level 2
    - \(\checkmark\) XFT track seeds SVT boards, that perform fast \((r - \phi)\) track fit
    - \(\checkmark\) repeat Level 1 cuts
    - \(\checkmark\) require tracks impact parameter to be \(0.012 < |d_0| < 0.1\) cm
    - \(\checkmark\) require \(L_{xy} > 0.02\) cm
  - \(\ell\)+track uses slightly different set of cuts

\[\sigma(d_0)_{SVT} = 47\ \mu m\ (including\ \sigma(beam) = 33\ \mu m)\]
Heavy Baryons

- $q = u, d, s; Q = c, b; m_Q \gg \Lambda_{QCD}$

- $\vec{k} = \frac{1}{2}(\vec{p}_1 - \vec{p}_2)$
  $\vec{K} = \frac{1}{2}(\vec{p}_1 + \vec{p}_2 - 2\vec{p}_3)$

- Convenient to consider that $q_1, q_2$ form a diquark, in SU(3):
  $\mathbf{3} \otimes \mathbf{3} = \mathbf{\bar{3}} \oplus \mathbf{6}$.

- $\Lambda$-type $Q[q_1q_2]$ $\Sigma$-type $Q\{q_1q_2\}$,

- ground states $l_k = 0, l_K = 0$:
  - $j_{qq} = s_{qq} = 0$
    
    $$J = j_{qq} \otimes s_Q = \frac{1^+}{2} \{\Lambda_c, \Xi_c, \Lambda_b, \Xi_b\}$$
  - $j_{qq} = s_{qq} = 1$
    
    $$J = j_{qq} \otimes s_Q \longrightarrow \frac{3^+}{2} \left\{ \begin{array}{c}
\Sigma^*, \Xi_c^*, \Sigma^*_b, \Xi^*_b, \Omega^*_b \\
\Sigma_c, \Xi_c^*, \Sigma_b, \Xi_b^*, \Omega_b
\end{array} \right\}$$

- $\Lambda$-like P-wave excitations $l_k = 0, l_K = 1$:
  - $j_{qq} = 1, s_{qq} = 0$
    
    $$J = j_{qq} \pm s_Q \longrightarrow \frac{3^-}{2} \left\{ \Lambda_c(2625), \Lambda_{b3/2}^* \right\}$$
  - $j_{qq} = 1, s_{qq} = 1$
    
    $$J = j_{qq} \pm s_Q \longrightarrow \frac{1^-}{2} \left\{ \Lambda_c(2593), \Lambda_{b1/2}^* \right\}$$

- In HQS limit $m_Q \rightarrow \infty j_{qq}$ and $s_Q$ are conserved separately allowing predictions for decay patterns.
potential quark modes:

- 3-quark Hamiltonian

\[ H = H_0 + H_{hyp} \]

where

\[ H_0 = \sum_i^3 \left( m_i + \frac{\vec{p}_i^2}{2m_i} \right) + \sum_{i<j} V_{conf}^{ij}(r_{ij}) \]

is perturbed by spin-spin interactions induced by gluon exchange hyper-fine term:

\[ H_{hyp} = \sum_{i<j} \frac{16\pi\alpha_s}{9m_im_j} \vec{s}_i \cdot \vec{s}_j \delta^3(\vec{r}_i - \vec{r}_j) \]


- gives reasonable description of baryon masses
HQET, $B_Q(Q q q)$:

$$M(B_Q) = M_Q + m_{qq} - \frac{1}{2 m_Q} (\lambda_1 + d_M \lambda_2) + O \left( \frac{1}{m_Q^2} \right)$$

$\lambda_1$ – kinetic energy of Q and $\lambda_2$ – chromomagnetic energy in HQS limit

$d_M$ is spin-orbit interaction term:

0 for $J^P = \frac{1}{2}^+$, 3 states ($\Lambda_Q, \Xi_Q$)

1 for $J^P = \frac{1}{2}^+$, 6 states ($\Sigma_Q, \Xi'_Q, \Omega_Q$)

$-\frac{1}{2}$ for $J^P = \frac{3}{2}^+$, 6 states ($\Sigma^*_Q, \Xi^*_Q, \Omega^*_Q$)

Lattice QCD

Calculate baryon masses from the first principles. Model independent results.
Bottom Baryon Masses

masses taken from latest works by Karliner, Lipkin and Rosner

$M_{\Xi_b} < M_{\Sigma_b}$ (Jenkins PRD 55,(1997),R10)
Heavy quark spin doublet \( \{ \Sigma_b, \Sigma_b^* \} \)
(degenerate if \( m_b \rightarrow \infty \))

Related to well established \( \Sigma^{(*)}_c \):
\[
\frac{M(\Sigma_b^*) - M(\Sigma_b)}{M(\Sigma_b^*) - M(\Sigma_c)} = \left( \frac{m_c}{m_b} \right) \approx 0.33,
\]
\[
\frac{70 \text{ MeV}}{M(\Sigma_b^*) - M(\Sigma_b)} \approx 23 \text{ MeV}
\]
\[
M(\Sigma_b) - M(\Lambda_b) \approx 180 - 190 \text{ MeV}
\]

P-wave pion emission:
\[
\Gamma_{\Sigma_b \rightarrow \Lambda_b \pi} = \frac{1}{6\pi} \frac{M_{\Lambda_b}}{M_{\Sigma_b}} \left| \frac{g_A}{f_\pi} \right|^2 |\vec{p}(\pi)|_{CM}^3
\]
\( g_A = 0.75, f_\pi = 92 \text{ MeV} \)
\( \Gamma(\Sigma_b) \sim 8 \text{ MeV}, \Gamma(\Sigma_b^*) \sim 17 \text{ MeV} \)

Two iso-spin triplets:
\[
\Sigma_b(bdd), \Sigma^0_b(bdu), \Sigma_b^+(buu)
\]
\[
\Sigma_b^*(bdd), \Sigma^*_b(bdu), \Sigma_b^{*+}(buu)
\]
\[
M(\Sigma_b^-) - M(\Sigma_b^+) = 5 - 6 \text{ MeV}
\]

Charged states are detectable via pion transitions:
\[
\Sigma_b^{\pm(*)} \rightarrow \Lambda_b^0 \pi_{soft}^{\pm}
\]
\[
\leftrightarrow \Lambda_c^+ \pi^-
\]
\[
\leftrightarrow p K^- \pi^+
\]

with \( \Lambda_b^0 \) decay product satisfying displaced track trigger conditions.

we look for 2 pairs of close narrow states near threshold
Analysis Strategy

- \( \Lambda_b \) candidates:
  - pre-select \( \Lambda_b \rightarrow \Lambda_c \pi \); \( \Lambda_c \rightarrow pK \) \( \pi^+ \)
    requiring 2-tracks (out of 4) to match SVT-tracks and satisfy two-track trigger requirements
  - tighten the cuts to achieve the best \( S/\sqrt{S+B} \) for \( \Lambda_b \) signal

- \( \Sigma_b \) candidates:
  - study Q-value spectrum:
    \[
    Q = M(\Lambda_b\pi) - M(\Lambda_b) - m_\pi
    \]
  - optimize cuts on \( \Sigma_b \) candidates by scoring \( S/\sqrt{1.5+B} \) where "B" is background obtained from sidebands:
    left sideband: \( 0 < Q < 0.03 \) GeV/c\(^2\)
    right sideband: \( 0.1 < Q < 0.5 \) GeV/c\(^2\)
  - take "S" from PYTHIA Monte Carlo
  - keep Signal Region blind:
    \[
    0.03 < Q < 0.1 \text{ GeV/c}^2
    \]
$\Lambda_b$ Signal in 1 fb$^{-1}$

- 3180 ± 60 $\Lambda_b$ candidates
- Backgrounds in signal window
  \[ 5.565 < |m(\Lambda_c \pi) - M(\Lambda_b)_{PDG}| < 5.67 \]
  - 86.4% of $\Lambda_b$ (all decays)
  - 9.3% of $B$-mesons (all decays)
  - 4.3% combinatorial
- Backgrounds under $\Sigma_b$ will be normalized using these numbers.
- Shape of background – from PYTHIA

projection of unbinned max log-likelihood fit

September 13, 2007

Dmitry Litvintsev, Fermilab, CDF
Blinded Q-plots

- **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)
    \[ 5.8 < M(\Lambda_c \pi) < 6 \text{ GeV/c}^2 \]

- **Fit Function**: Shapes and relative normalization of background contributions were determined prior to opening the box
  \[ (Q, \alpha, Q_{max}, \gamma) = \left( \frac{Q}{Q_{max}} \right)^\alpha e^{-\frac{\alpha}{\gamma} \left( \frac{Q}{Q_{max}} \right)^\gamma - 1} \]

- $p_T$ spectrum of soft tracks in PYTHIA re-weighted to reproduce data
- 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>$S/\sqrt{S + B}$</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>

- there is a significant excess in the signal region in both spectra!

- proceed to fit adding signal terms:

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

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

for all four $\Sigma_b^{(*)\pm}$ states

- simultaneous unbinned maximum log-likelihood:
  - background shapes frozen
  - 7 floating variables: $Q_{\Sigma^-}$, $Q_{\Sigma^+}$, $Q_{\Sigma^*}$, $Q_{\Sigma_b}$, $N(\Sigma_b)$, $N(\Sigma_b^*)$, $N(\Sigma_b^{*+})$
  - detector resolutions and natural widths fixed.
Yields:

\[ N(\Sigma_b^-) = 59^{+15}_{-14}(\text{stat})^{+9}_{-4}(\text{syst}) \]
\[ N(\Sigma_b^+) = 32^{+13}_{-12}(\text{stat})^{+5}_{-3}(\text{syst}) \]
\[ N(\Sigma_b^{*-}) = 69^{+18}_{-17}(\text{stat})^{+16}_{-5}(\text{syst}) \]
\[ N(\Sigma_b^{*+}) = 77^{+17}_{-16}(\text{stat})^{+10}_{-6}(\text{syst}) \]

Q-values:

\[ Q(\Sigma_b^-) = (55.9 \pm 1.0 \pm 0.2) \text{ MeV}/c^2 \]
\[ Q(\Sigma_b^+) = (48.5^{+2.0+0.2}_{-2.2-0.3}) \text{ MeV}/c^2 \]
\[ Q(\Sigma_b^{*-}) - Q(\Sigma_b) = (21.2^{+2.0+0.4}_{-1.9-0.3}) \text{ MeV}/c^2 \]
Weak Decays of Bottom Baryons

- $J/\psi$ trigger:
  \[ \Xi_b \rightarrow J/\psi \Xi^- + n\pi , \quad \Omega_b \rightarrow J/\psi \Omega^- + n\pi \]
  \[ \leftrightarrow \Lambda\pi^- \quad \leftrightarrow \Lambda K^- \]

- Displaced track trigger:
  \[ \Xi_b \rightarrow \Xi_c + n\pi , \quad \Omega_b \rightarrow \Omega_c + n\pi \]
  \[ \leftrightarrow \Xi^- + n\pi \quad \leftrightarrow \Omega^- + n\pi \]
  \[ \Xi_b \rightarrow D^0\Lambda , \quad \Omega_b \rightarrow D^0\Xi^- \]
  \[ \Xi_b \rightarrow \Lambda_c K + n\pi , \quad \Omega_b \rightarrow \Xi_c K + n\pi \]

- SVT+lepton trigger:
  \[ \Xi_b \rightarrow \Xi_c + \ell^-X , \quad \Omega_b \rightarrow \Omega_c + \ell^-X \]
  \[ \leftrightarrow \Xi^- + n\pi \quad \leftrightarrow \Omega^- + n\pi \]

Expected lifetime pattern:
\[ \tau(B^+) \sim \tau(\Xi_b^-) \sim \tau(\Omega_b^-) \geq \tau(\Lambda_b^0) \geq \tau(\Xi_b^0) \]

Decays of bottom-strange baryon involve long lived hyperons as decay products.

=> start with reconstruction of long lived hyperons
Cascades at CDF

- $\Lambda^-$ long lived ($cT = 4.91\, cm$) & charged.
- Can be tracked in SVX (previously done at LEP)
- CDF developed tracking of $\Lambda^-$. 1st in hadron collider experiment.
  - Find and form V0: $\Lambda \rightarrow p\pi^-$
  - Attach pion to $\Lambda$, form $\Xi$ candidate, do vertex fit.
  - Convert $\Xi$ momentum and vertex position into helix in CDF track parameter ($cu, \phi_0, d_0, \lambda, z_0$) basis and convert elements of Vertex fit error matrix into track $5 \times 5$ error matrix
  - Use this track to seed Outside In (OI)Z Silicon tracking.
  - Attach silicon hits starting from vertex point and going to PV.
  - Store SVX $\Xi$ tracks in the event record on the file for subsequent analysis.
  - The $\Xi^-$-track is used in analysis as any “normal” track but it is also a “loaded” track as it “remembers” its history (has pointers to vertex fits and parent tracks)

Φ pentaquarks search was based on this technique (Phys.Rev.D75:032003,2007)
Cascade Tracked!

Event Display of generated Hyperons Tracked in Silicon

\[ \Xi_b \rightarrow \Xi_c^+ \pi^- \quad \Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^- \quad \Xi^- \rightarrow \Lambda \pi_2^- \quad \Lambda \rightarrow p \pi_1^- \]
Benefits of Hyperon Tracking

- **Clean $\Xi$ samples:**

  - $L = 220 \text{pb}^{-1}$
  - $\Xi$ track found in SVX
  - $N = 36,000$

  ![Graph showing $M(\Lambda \pi)$ distribution](image)

- **Good efficiency (total $\sim 40\%$):**

  ![Graph showing relative tracking efficiency](image) (plateau at 91%)

- **Improvement in $\Xi$ impact parameter resolution:**

  - $\sigma(d_0) \sim 60\mu m$

  ![Graph showing impact parameter resolution](image)

- **Can track $\Omega^-$ too**

  ![Graph showing $M(\Lambda K)$ distribution](image) ($\Omega$ track found in SVX)

- **Track found in SVX**

  ![Graph showing $M(\Xi, K)$ distribution](image) ($\Xi$ in TTT)

- **Can track $\Omega^-$ too**

  ![Graph showing $M(\Xi, K)$ distribution](image) ($\Xi$ in TTT)
$\Xi_b^- \rightarrow J/\psi \Xi^-$
Look for $\Xi_b^-$ as $\Xi_b^0 \rightarrow \Xi^0 J/\psi$ is lost ($\pi^0$ in the final state)

- Production rate w.r.t. $\Lambda_b$:
  - Assuming $B(\Lambda_b \rightarrow J/\psi \Lambda) = B(\Xi_b^- \rightarrow J/\psi \Xi)$:

$$N(\Xi_b^- \rightarrow J/\psi \Xi) \sim \frac{N(\Lambda_b \rightarrow J/\psi \Lambda)}{8} \cdot 0.9 \cdot \epsilon_{kink} \cdot \pi \cdot \epsilon_{SVX} \sim \frac{N(\Lambda_b \rightarrow J/\psi \Lambda)}{30} \sim 15-20$$

- If $\epsilon_{kink-\pi} = 0.8$ and $\epsilon_{SVX} = 0.4$
Use silicon $\Xi$ tracks to look for $\Xi_b \rightarrow J/\psi \Xi$.

- Collapse 3-track $\Xi$ candidate to 1-track.

- $\Xi_b \rightarrow J/\psi \Xi$ becomes like $B^+ \rightarrow J/\psi K^+$. Use $B^+ \rightarrow J/\psi K^+$ as control sample.

- Selection is completely data driven & independent of signal under study.

- Optimize cuts for best $B^+ \rightarrow J/\psi K^+$ signal. Apply same cuts to $\Xi_b \rightarrow J/\psi \Xi$ candidates.

- Approach is based on assumption “$B^+ \rightarrow J/\psi K^+$ look similar to $\Xi_b \rightarrow J/\psi \Xi$”. Validated assumption with Simulation.

- Same approach used to discover $B_c \rightarrow J/\psi \pi$. Should work even better for $\Xi_b \rightarrow J/\psi \Xi$.
$J/\psi \rightarrow \mu\mu$

CDF Run II Preliminary

$N(J/\psi) = 15M$

$15M J/\psi$s using sideband subtraction counting
Cascade Yield in $J/\psi$ trigger

- $\Lambda^0$ candidates:
  - No $p_T$ cuts on daughter tracks
  - $p_T(\pi) > p_T(\pi)$
  - $|d_0(\pi)| > 0.05$ cm
  - $|d_0(\pi)| > 0.05$ cm
  - $|\Delta z(p, \pi)| < 5$ cm (at the 2-track intersection point)
  - 2-track vertex fit, $\chi^2(2D) < 49$
  - $|m(p\pi) - M(\Lambda)| < 10$ MeV/c$^2$
  - $L_{xy} \geq 1$ cm

- $\Xi^-$ candidates:
  - No $p_T$ cuts on daughter tracks
  - Vertex and mass constrained fit (both $\Lambda^0$ and $\Xi^-$)
    - $|m(\Lambda\pi) - M(\Xi)| < 10$ MeV/c$^2$
    - $R(\Xi)_{vtx} < R(\Lambda)_{vtx} + 1$

- $\Xi^-$ tracks:
  - $|d_0(\Xi)| < 0.1$ cm
  - $N_{SVX}(r - \phi) \geq 2$

- 23.5K events
- Mass is consistent with PDG
$B^+ \rightarrow J/\psi K^+$ selection variables

- Displacement of B-vertex w.r.t P.V.:
  - $ct = L_{xy} \frac{M(B)}{p_T(B)} > 80 \mu m$
  - $L_{xy} = \vec{d}_{VTX} \cdot \vec{p}_T(B)/p_T(B)$
  - $\delta[ct(B)] < 30 \mu m$
  - $d_0(K)/\sigma(d_0(K)) > 2.5$

- Kinematics & fit quality:
  - $p_T(B) > 5$ GeV/c
  - $p_T(K) > 1.7$ GeV/c
  - $prob(\chi^2(3D)) > 10^{-3}$

- Pointing of B-candidate to P.V.:
  - $\alpha < 0.4$ radians
  - $|d_0(B)| < 75 \mu m$; $\vec{d}_0(B) = \vec{d}_{VTX} \times \vec{p}_T(B)/p_T(B)$

- Require Kaon IP w.r.t. B-vertex be small:
  - $|d_0(K) (w.r.t. B_{vertex})| < 100 \mu m$
Two step procedure

<table>
<thead>
<tr>
<th>Selection variable</th>
<th>Optimization A</th>
<th>Optimization B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(K/\Xi)$ [GeV/c]</td>
<td>$&gt; 1.7$</td>
<td>$&gt; 2.5$</td>
</tr>
<tr>
<td>$p_T(J/\psi K/\Xi)$ [GeV/c]</td>
<td>$&gt; 5.$</td>
<td>$&gt; 6.$</td>
</tr>
<tr>
<td>$ct(J/\psi K/\Xi)$ [cm]</td>
<td>$&gt; 0.008$</td>
<td>$&gt; 0.01$</td>
</tr>
<tr>
<td>$\delta[ct(J/\psi K/\Xi)]$ [cm]</td>
<td>$&lt; 0.003$</td>
<td>$&lt; 0.0025$</td>
</tr>
<tr>
<td>Pointing angle</td>
<td>$&lt; 0.4$ radians</td>
<td>$&lt; 0.3$ radians</td>
</tr>
<tr>
<td>$prob(\chi^2(3D))$</td>
<td>$&gt; 10^{-3}$</td>
<td>$&gt; 10^{-2}$</td>
</tr>
<tr>
<td>$</td>
<td>d_0(J/\psi K/\Xi)</td>
<td>$ [cm] (w.r.t p.v.)</td>
</tr>
<tr>
<td>$</td>
<td>d_0(K/\Xi)_{sig}</td>
<td>$ (w.r.t p. v.)</td>
</tr>
<tr>
<td>$</td>
<td>d_0(K/\Xi)</td>
<td>$ [cm] (w.r.t sec. vtx.)</td>
</tr>
</tbody>
</table>

- Apply Optimization A. If candidate fails just one cut, apply Optimization B. Accept if it does not fail any other cuts in Optimization B.
- Any single cut of Optimization A has almost 90% signal efficiency
$B^+ \rightarrow J/\psi K^+$

CDF Run II Preliminary

$L \sim 1.9 \text{fb}^{-1}$

Yield = 31652 $\pm$ 567
$M = (5278.0 \pm 0.2) \text{MeV}/c^2$
$\sigma = (11.2 \pm 0.2) \text{MeV}/c^2$
prob = 54.4%

$S = |M(J/\psi K^+) - M(B^+)| < 3\sigma$
$SB = 7\sigma < |M(J/\psi K^+) - M(B^+)| < 10\sigma$

Loose cuts – 31K $B^+$

Optimized cuts 16K $B^+$.

Signal efficiency 52%, background reduced by factor of 500

September 13, 2007

Dmitry Litvintsev, Fermilab, CDF
## The yields

<table>
<thead>
<tr>
<th>parameter</th>
<th>Optimization A</th>
<th>Optimization B</th>
<th>Optimization A+B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N(J/\psi K^+)$</td>
<td>12,185 ± 115</td>
<td>3,837 ± 67</td>
<td>16,044 ± 134</td>
</tr>
<tr>
<td>$N(J/\psi \pi^+)$</td>
<td>447 ± 29</td>
<td>134 ± 18</td>
<td>572 ± 34</td>
</tr>
<tr>
<td>$M(B^+)$ [MeV/c$^2$]</td>
<td>5,278.3 ± 0.1</td>
<td>5,278.3 ± 0.2</td>
<td>5,278.3 ± 0.1</td>
</tr>
<tr>
<td>$\sigma_1$ [MeV/c$^2$]</td>
<td>28.6 ± 1.4</td>
<td>26.5 ± 2.2</td>
<td>27.8 ± 1.2</td>
</tr>
<tr>
<td>$\sigma_2$ [MeV/c$^2$]</td>
<td>11.0 ± 0.1</td>
<td>10.3 ± 0.1</td>
<td>10.8 ± 0.1</td>
</tr>
<tr>
<td>$R$ (fraction of wide Gaussian)</td>
<td>0.17 ± 0.02</td>
<td>0.24 ± 0.05</td>
<td>0.19 ± 0.02</td>
</tr>
</tbody>
</table>

Optimization B “recovers” 24% of signal events

Apply the same procedure to $J/\psi \Xi^-$ candidates (replace $K^+$ with $\Xi^-$)
Cross-checks

✓ $J/\psi$ and $\Xi$ sidebands
✓ Wrong charge $J/\psi \Xi^+$ where "$\Xi^+ \rightarrow \Lambda \pi^+$"
✓ Checked number of $\Xi_b$ and $\bar{\Xi}_b$ candidates – 50/50
✓ Signal is robust against cut variations
✓ No existing B-hadron can produce a signal in $M(J/\psi \Xi^-)$ spectrum at $M \sim 5.8$ GeV/c$^2$

Signal is consistent with $\Xi_b$
Event Display 2

Event: 11415004 Run: 185281

$\Xi^- \rightarrow J/\psi \Xi^-$ candidate

$M(\Xi^-) = 5,787 \pm 3 \text{ MeV}/c^2$
### Expected Mass resolution

<table>
<thead>
<tr>
<th>Channel</th>
<th>yield</th>
<th>mass resolution(s) MeV/c²</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow J/\psi K^+$</td>
<td>$27, 108 \pm 166$</td>
<td>$11.01 \pm 0.09$</td>
</tr>
<tr>
<td>$\Lambda_b^0 \rightarrow J/\psi \Lambda^0$</td>
<td>$5, 033 \pm 71$</td>
<td>$12.5 \pm 0.2$</td>
</tr>
<tr>
<td>$\Xi^-_b \rightarrow J/\psi \Xi^-$ (3-track fit)</td>
<td>$1, 955 \pm 43$</td>
<td>$14.3 \pm 0.2$</td>
</tr>
<tr>
<td>$\Xi^-_b \rightarrow J/\psi \Xi^-$ (5-track fit)</td>
<td>$1, 996 \pm 45$</td>
<td>$12.3 \pm 0.2$</td>
</tr>
</tbody>
</table>

- Full 5-track vertex fit gives 15% better mass resolution compared to 3-track vertex fit.
- But in order for it to work we had to fix our Vertex Fit software to handle charged vertices.

---

Full 5-track vertex fit is applied to previously selected 3-track candidates by utilizing properties of “loaded” $\Xi$-track.
The Fit Result

Unbinned fit uses estimate of mass uncertainty of each candidate to improve mass resolution. Constant background. Gaussian Signal

CDF Run II Preliminary

L ~ 1.9 fb⁻¹

\[ \text{yield} = 17.5 \pm 4.3 \]

\[ M = (5,792.9 \pm 2.5) \text{MeV/c}^2 \]

Yield \hspace{1cm} Mass
\[ 17.5 \pm 4.3 \] \[ (5,792.9 \pm 2.5) \text{ MeV/c}^2 \]
Signal Significance

- Assume flat distribution of events in the mass region $[5.7 - 6.5] \text{ GeV}/c^2$.

- The p-value is defined as probability to toss $N_{total} = 23$ events contained in this interval, so that there are $N_{signal} = 17$ observed events in 60 MeV/$c^2$ signal range ($\pm 2\sigma$).

$$p = 1 - \sum_{i=0}^{N_{signal}-1} B(i, N_{total}, \frac{60}{800})$$

- Putting in the numbers we get $4.1 \times 10^{-15}$ which corresponds to $7.8\sigma$ Gaussian significance.
Projection of the unbinned fit
Mass Systematics

- check on large samples in TTT that $\Xi$ tracking does not introduce any additional tracking systematics.

- projected shift at $\Xi_b$ mass is $\delta m = (-1.69 \pm 1.54)$ MeV/c$^2$. Not significant.
Mass Calibration

Mass calibration offset

CDF Run II Preliminary

Comparison with CDF B-mass PRL

Event by event difference between B-mass in $B^+ \rightarrow J/\psi K^+$ channel and CDF B-mass PRL events.

mean = $-0.6 \pm 0.2 \text{MeV/c}^2$

$\sigma = 9.6 \pm 0.2 \text{MeV/c}^2$
Tracking Momentum Scale

\[ \delta m = 1.09 \times 10^{-4} \cdot Q + 0.25 [\text{MeV}] \]

## Fit model variation

<table>
<thead>
<tr>
<th>Fit</th>
<th>yield</th>
<th>mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>base</td>
<td>17.5</td>
<td>(5, 792.9) MeV/c²</td>
</tr>
<tr>
<td>free sigma</td>
<td>17.4</td>
<td>(5, 791.8) MeV/c²</td>
</tr>
<tr>
<td>double Gaussian</td>
<td>18.1</td>
<td>(5, 794.4) MeV/c²</td>
</tr>
</tbody>
</table>

- Reasonable variation of background function and fit range does not change parameters of the peak appreciably
- Take maximum deviation as ±1.5 MeV/c²
### Summary Systematics

<table>
<thead>
<tr>
<th>Error source</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking Momentum scale</td>
<td>$\delta m = \pm 0.4 \text{ MeV}/c^2$</td>
</tr>
<tr>
<td>PDG Masses($J/\psi$, $\Xi$)</td>
<td>$\delta m = \pm 0.14 \text{ MeV}/c^2$</td>
</tr>
<tr>
<td>Mass scale calibration</td>
<td>$\delta m = \pm 0.6 \text{ MeV}/c^2$</td>
</tr>
<tr>
<td>Fit model/resolution</td>
<td>$\delta m = \pm 1.5 \text{ MeV}/c^2$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$\delta m = \pm 1.7 \text{ MeV}/c^2$</td>
</tr>
</tbody>
</table>

\[
M(\Xi^0) = (5,792.9 \pm 2.5(\text{stat.}) \pm 1.7(\text{syst.})) \text{ MeV}/c^2
\]
$\Xi_b^- \rightarrow \Xi_c^0 \pi^-$

Displaced track trigger (a.k.a. TTT)

See signal at the same mass. Processing the full $2.5fb^{-1}$ sample to have a shot at $\Xi_b^0 \rightarrow \Xi_c^+ \pi^-$
CDF observes $\Xi_b$. Significance is 7.8$\sigma$.

The $\Xi_b$ mass is measured to be

$$M(\Xi_b^-) = (5,792.9 \pm 2.5\text{(stat.)} \pm 1.7\text{(syst.)}) \text{ MeV}/c^2$$

- Weighted mean mass $5792 \pm 3$ MeV/$c^2$. 
CDF observes $\Sigma^\pm_b$ - 4 new particles!: $Q$-values:

\[
Q(\Sigma^-_b) = (55.9 \pm 1.0 \pm 0.2) \text{ MeV} / c^2 \\
Q(\Sigma^+_b) = (48.5^{+2.0}_{-2.2}^{+0.2}_{-0.3}) \text{ MeV} / c^2 \\
Q(\Sigma^*_b) - Q(\Sigma_b) = (21.2^{+2.0}_{-1.9}^{+0.4}_{-0.3}) \text{ MeV} / c^2
\]

Masses:

\[
M(\Sigma^-_b) = (5815.2 \pm 1.0 \pm 1.7) \text{ MeV} / c^2 \\
M(\Sigma^+_b) = (5807.8^{+2.0}_{-2.2} \pm 1.7) \text{ MeV} / c^2 \\
M(\Sigma^*_b^-) = (5836.4 \pm 2.0^{+1.8}_{-1.7}) \text{ MeV} / c^2 \\
M(\Sigma^*_b^+) = (5829.0^{+1.6}_{-1.8}^{+1.7}_{-1.8}) \text{ MeV} / c^2
\]

Paper submitted to PRL (arXiv:0706.3868 [hep-exp])

Measured masses of $\Sigma^\pm_b$, and $\Xi^-_b$ are in agreement with theory.
Precision mass measurement of $\Xi_b^-$ mass by CDF provides constraints on model parameters (c.f. arXiv:0708.4027 [hep-ph])

The progress has happened within last 1.5 years. Basically we just started with broad B-physics program (recall $\Delta m_s$ measurement in 2006)

CDF can do wonders with its tracking system. The $\Xi$-tracking enables us to broaden our reach in B-physics. Expect more to come very soon:

- Completion of $\Xi_b^0 \to \Xi_c^+ \pi^-$ and $\Xi_b^- \to \Xi_c^0 \pi^-$ analyses in TTT data
- Measurement of $\Xi_b^-$ lifetime
- Measurement of $\sigma(p\bar{p} \to \Xi_b^0 \chi)/\sigma(p\bar{p} \to \Lambda_b \chi)$
- A shot at $\Omega_b \to D^0 \Xi$
- Search for $\Xi_{cc}$

Fermilab makes case for running Tevatron till 2010. The results presented today, and the planned analyses will contribute to making the decision in a positive way.
Backup Slides
### $\sum_b$ Significance

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>$LR$</th>
<th>$p$-value</th>
<th>Significance ($\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Signal</td>
<td>$2.6 \times 10^{18}$</td>
<td>$&lt; 8.3 \times 10^{-8}$</td>
<td>$&gt; 5.2$</td>
</tr>
<tr>
<td>Two $\sum_b$ States</td>
<td>$4.4 \times 10^{6}$</td>
<td>$9.2 \times 10^{-5}$</td>
<td>3.7</td>
</tr>
<tr>
<td>No $\sum_b^-$ Signal</td>
<td>$1.2 \times 10^{5}$</td>
<td>$3.2 \times 10^{-4}$</td>
<td>3.4</td>
</tr>
<tr>
<td>No $\sum_b^+$ Signal</td>
<td>49</td>
<td>$9.0 \times 10^{-3}$</td>
<td>2.4</td>
</tr>
<tr>
<td>No $\sum_b^{-+}$ Signal</td>
<td>$4.9 \times 10^{4}$</td>
<td>$6.4 \times 10^{-4}$</td>
<td>3.2</td>
</tr>
<tr>
<td>No $\sum_b^{++}$ Signal</td>
<td>$8.1 \times 10^{4}$</td>
<td>$6.0 \times 10^{-4}$</td>
<td>3.2</td>
</tr>
</tbody>
</table>
## $\Sigma_b$ Systematics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mass Scale</th>
<th>$\Lambda_b$ Comp</th>
<th>$\Lambda_b$ Norm</th>
<th>$\Lambda_b$ Shape</th>
<th>Reweight</th>
<th>Reso</th>
<th>$\Sigma_b$ Width</th>
<th>$\Delta_\sigma$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Sigma_b$ $Q$</td>
<td>0.22</td>
<td>0.0</td>
<td>0.009</td>
<td>0.0</td>
<td>0.04</td>
<td>0.0</td>
<td>0.009</td>
<td>0.06</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>-0.22</td>
<td>-0.03</td>
<td>-0.002</td>
<td>-0.011</td>
<td>-0.004</td>
<td>-0.011</td>
<td>-0.005</td>
<td>0.0</td>
<td>-0.22</td>
</tr>
<tr>
<td>$\Sigma_b$ events</td>
<td>0.0</td>
<td>0.7</td>
<td>2.2</td>
<td>0.3</td>
<td>7.4</td>
<td>0.3</td>
<td>3.4</td>
<td>0.0</td>
<td>8.5</td>
</tr>
<tr>
<td></td>
<td>0.0</td>
<td>0.0</td>
<td>-2.2</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>-3.4</td>
<td>-0.08</td>
<td>-4.1</td>
</tr>
<tr>
<td>$\Sigma^+_b$ $Q$</td>
<td>0.19</td>
<td>0.03</td>
<td>0.013</td>
<td>0.013</td>
<td>0.0</td>
<td>0.0</td>
<td>0.014</td>
<td>0.0</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>-0.19</td>
<td>0.0</td>
<td>-0.013</td>
<td>0.0</td>
<td>-0.11</td>
<td>0.0</td>
<td>-0.02</td>
<td>-0.11</td>
<td>-0.25</td>
</tr>
<tr>
<td>$\Sigma^+_b$ events</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>1.8</td>
<td>0.0</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>0.0</td>
<td>0.0</td>
<td>-2.1</td>
<td>0.0</td>
<td>-1.8</td>
<td>0.0</td>
<td>-2.0</td>
<td>-0.004</td>
<td>-3.4</td>
</tr>
<tr>
<td>$\Sigma^{+-}_b$ events</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>0.0</td>
<td>15.6</td>
</tr>
<tr>
<td></td>
<td>0.0</td>
<td>0.0</td>
<td>-4.7</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>-1.7</td>
<td>-0.16</td>
<td>-5.0</td>
</tr>
<tr>
<td>$\Sigma^{++}_b$ events</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>0.16</td>
<td>10.3</td>
</tr>
<tr>
<td></td>
<td>0.0</td>
<td>0.0</td>
<td>-4.8</td>
<td>0.0</td>
<td>-2.9</td>
<td>0.0</td>
<td>-0.8</td>
<td>0.0</td>
<td>-5.7</td>
</tr>
<tr>
<td>$\Sigma^+_b - \Sigma_b$ $Q$</td>
<td>0.10</td>
<td>0.05</td>
<td>0.14</td>
<td>0.04</td>
<td>0.32</td>
<td>0.02</td>
<td>0.07</td>
<td>0.0</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>-0.10</td>
<td>0.0</td>
<td>-0.13</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>-0.07</td>
<td>-0.26</td>
<td>-0.32</td>
</tr>
<tr>
<td>$\Sigma^{+-}_b$ $Q$</td>
<td>0.28</td>
<td>0.02</td>
<td>0.13</td>
<td>0.03</td>
<td>0.32</td>
<td>0.003</td>
<td>0.08</td>
<td>0.0</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>-0.28</td>
<td>0.0</td>
<td>-0.13</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>-0.07</td>
<td>-0.184</td>
<td>-0.37</td>
</tr>
<tr>
<td>$\Sigma^{++}_b$ $Q$</td>
<td>0.32</td>
<td>0.09</td>
<td>0.12</td>
<td>0.05</td>
<td>0.17</td>
<td>0.001</td>
<td>0.05</td>
<td>0.0</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>-0.32</td>
<td>0.0</td>
<td>-0.13</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>-0.06</td>
<td>-0.39</td>
<td>-0.52</td>
</tr>
<tr>
<td>$\Sigma_b - \Sigma^+_b$ $Q$</td>
<td>0.03</td>
<td>0.0</td>
<td>0.01</td>
<td>0.0</td>
<td>0.14</td>
<td>0.003</td>
<td>0.04</td>
<td>0.19</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>-0.03</td>
<td>-0.07</td>
<td>-0.005</td>
<td>-0.03</td>
<td>0.0</td>
<td>-0.003</td>
<td>-0.02</td>
<td>0.0</td>
<td>-0.09</td>
</tr>
</tbody>
</table>

September 13, 2007

Dmitry Litvintsev, Fermilab, CDF