# OBSERVATION OF THE $\Sigma_b$ BARYONS AT CDF

J. PURSLEY on behalf of the CDF Collaboration
*Department of Physics and Astronomy, 366 Bloomberg Center,*
*3400 N. Charles St., Baltimore, MD 21218, USA*

We present a measurement of four new bottom baryons in proton-antiproton collisions with a center of mass energy of 1.96 TeV. Using 1.1 fb$^{-1}$ of data collected by the CDF II detector, we observe four $\Lambda_b^0\pi^\pm$ resonances in the fully reconstructed decay mode $\Lambda_b^0 \to \Lambda_c^+\pi^-$, where $\Lambda_c^+ \to pK^-\pi^+$. The probability for the background to produce a similar or larger signal is less than $8.3 \times 10^{-8}$, corresponding to a significance of greater than 5.2 $\sigma$. We interpret these baryons as the $\Sigma_b^{(*)\pm}$ states.

## 1 Introduction

The Tevatron at the Fermi National Accelerator Laboratory collides $p\bar{p}$ with a center of mass energy of 1.96 TeV. The Collider Detector at Fermilab, or CDF, experiment employs a general multipurpose detector [1] to reconstruct particle physics events from these collisions. With a $b$ hadron cross section of $\approx$ 50 $\mu$b $(|\eta| < 1.0)$, [2] CDF has collected a wealth of experimental data on $b$ hadrons. Using this data, we announce the first observation of the $\Sigma_b^{(*)\pm}$ baryons.

## 2 $\Sigma_b^{(*)}$ Theoretical Predictions

Only one $b$ baryon has been previously established, the ground state $\Lambda_b^0$, which contains $b$, $u$, and $d$ quarks with the two light quarks ($u$ and $d$) in a flavor antisymmetric diquark state. CDF uses a two displaced track trigger to select the decay of $\Lambda_b^0 \to \Lambda_c^+\pi^-$, with $\Lambda_c^+ \to pK^-\pi^+$ (inclusion of the respective charge conjugate modes is assumed throughout this paper). The two displaced track trigger requires two high $p_T$ tracks displaced from the $p\bar{p}$ interaction point; in the decay of $\Lambda_b^0$, the two tracks which satisfy the requirements are primarily the pion from the $\Lambda_b^0$ decay and the proton from the $\Lambda_c^+$ decay. Using 1.1 fb$^{-1}$ of data collected by the CDF II detector between February 2002 and March 2006, CDF possesses the world's largest sample of bottom baryons with $3180 \pm 60$ (stat.) $\Lambda_b^0 \to \Lambda_c^+\pi^-$ candidates. The reconstructed $\Lambda_b^0$ invariant mass distribution is shown in Fig. 1.

The next accessible $b$ baryons are the lowest lying $\Sigma_b^{(*)}$ states, which decay strongly to $\Lambda_b^0$ baryons by emitting pions. The $\Sigma_b^{(*)+}$ baryons contain one $b$ and two $u$ quarks, the $\Sigma_b^{(*)-}$ baryons contain one $b$ and two $d$ quarks, and the $\Sigma_b^{(*)0}$ baryons contain the $b$, $u$, and $d$ quarks. In the $\Sigma_b$ baryons, the two light quarks are in a flavor symmetric diquark state, leading to a doublet of baryons with $J^P = \frac{1}{2}^+$ ($\Sigma_b$) and $J^P = \frac{3}{2}^+$ ($\Sigma_b^*$). Because $\Sigma_b^{(*)0}$ decays to $\Lambda_b^0\pi^0$ and the CDF II detector cannot reconstruct neutral pions, we expect to observe only the charged $\Sigma_b^{(*)\pm}$ states.

There is predicted to be a hyperfine mass splitting between the doublet states $\Sigma_b$ and $\Sigma_b^*$, as well as a mass splitting between the $\Sigma_b^{(*)-}$ and $\Sigma_b^{(*)+}$ states due to strong isospin violation. Predictions for the $\Sigma_b^{(*)}$ masses exist from heavy quark effective theories, non-relativistic and relativistic potential models, $1/\mathrm{N}_c$ expansion, sum rules, and lattice Quantum Chromodynamics calculations. These predictions expect [3] $m(\Sigma_b) - m(\Lambda_b^0) \sim 180 - 210$ MeV/$c^2$, $m(\Sigma_b^*) - m(\Sigma_b) \sim 10 - 40$ MeV/$c^2$, and $m(\Sigma_b^-) - m(\Sigma_b^+) \sim 5 - 7$ MeV/$c^2$. The intrinsic width of $\Sigma_b^{(*)}$ baryons is dominated by the P-wave one-pion transition, whose partial width depends on the available phase space. [4] For the predicted range of $\Sigma_b^{(*)}$ masses, the intrinsic width varies between 2 and 20 MeV/$c^2$.

## 3 Analysis Methodology

We search for four resonant $\Lambda_b^0\pi^\pm$ states consistent with theoretical predictions for $\Sigma_b$, where $\Sigma_b$ now refers to both charged $J = \frac{1}{2}^+$ ($\Sigma_b^\pm$) and $J = \frac{3}{2}^+$ ($\Sigma_b^{*\pm}$) states. To minimize the contribution of the mass resolution of each $\Lambda_b^0$ candidate, the search is made for narrow resonances in the mass difference distribution of $Q = m(\Lambda_b^0\pi) - m(\Lambda_b^0) - m_\pi$. Events are separated into "$\Lambda_b^0\pi^-$" and "$\Lambda_b^0\pi^+$" subsamples; $\Lambda_b^0\pi^-$ contains $\Sigma_b^{(*)-}$ and $\overline{\Sigma}_b^{(*)-}$ while $\Lambda_b^0\pi^+$ contains $\Sigma_b^{(*)+}$ and $\overline{\Sigma}_b^{(*)+}$.

The $\Lambda_b^0$ candidate is combined with a prompt pion, as the $\Sigma_b$ decays strongly at the primary vertex of the $p\bar{p}$ collision. To perform an unbiased optimization of the selection criteria, we use as a background sample only those tracks far from the expected $\Sigma_b$ signal region. From theoretical predictions, the signal region is defined as $30 < Q < 100$ MeV/$c^2$. The principle sources of background in the $\Sigma_b$ $Q$ distribution are tracks from the hadronization of prompt $\Lambda_b^0$ baryons and $B$ mesons reconstructed as $\Lambda_b^0$ baryons, and combinatorial background. The percentage of each background source in the $\Sigma_b$ $Q$ distribution is fixed from the $\Lambda_b^0$ invariant mass fit shown in Fig. 1, which is 89.4% $\Lambda_b^0$ baryons, 7.3% $B$ mesons, and 3.3% combinatorial background. The $Q$ distribution of each background component is established before unblinding the signal region. The high mass region above the $\Lambda_b^0 \to \Lambda_c^+\pi^-$ signal in the $\Lambda_b^0$ mass distribution (Fig. 1) determines the combinatorial background. Reconstructing $\bar{B}^0 \to D^+\pi^-$ data as $\Lambda_b^0 \to \Lambda_c^+\pi^-$ gives the background from $B$ hadronization tracks. The largest background component, from $\Lambda_b^0$ hadronization tracks, is obtained from a $\Lambda_b^0$ PYTHIA [5] Monte Carlo simulation.

## 4 $\Sigma_b^{(*)}$ Results

After determining the background shape, we observe an excess of events over the expected background in the $\Sigma_b$ signal region. The excess in the $\Lambda_b^0\pi^-$ subsample is 118 candidates over 288 expected background candidates, while in the $\Lambda_b^0\pi^+$ subsample the excess is 91 over 313 expected background candidates. The strength of the $\Sigma_b$ hypothesis is evaluated using as a test statistic the likelihood ratio, $LR \equiv L_{\mathrm{alt}}/L$, where $L$ is the fit likelihood of the four $\Sigma_b$ signal hypothesis and $L_{\mathrm{alt}}$ is the fit likelihood of an alternate hypothesis such as the no signal hypothesis. Using simplistic Monte Carlo samples of background fluctuations, we find the probability of the no signal hypothesis to be less than $8.3 \times 10^{-8}$, corresponding to a signal significance of greater than 5.2 $\sigma$.

The subsamples are modeled with a simultaneous unbinned maximum likelihood fit comprising a signal for each expected $\Sigma_b$ state plus the background. Each signal consists of a non-relativistic Breit-Wigner distribution convoluted with a double Gaussian model of the detector resolution. The intrinsic width of the Breit-Wigner is computed from the available phase space given the central location of the signal. Due to low statistics, the constraint $m(\Sigma_b^{*+}) - m(\Sigma_b^+) = m(\Sigma_b^{*-}) - m(\Sigma_b^-) \equiv \Delta(\Sigma_b^*)$ is added. The $\Sigma_b$ signal fit to data, which has a $\chi^2$ fit probability of 76% in the range $Q \in [0, 200]$ MeV/c$^2$, is shown in Fig. 2. The majority of the systematic uncertainty on the yield measurement is due to poor knowledge of the $\Lambda_b$ hadronization background, while the majority of the systematic uncertainty on the mass measurement is due to the CDF mass scale uncertainty. The final results for the yields are $N(\Sigma_b^+) = 32^{+13}_{-12}$ (stat.)$^{+5}_{-3}$ (syst.), $N(\Sigma_b^-) = 59^{+15}_{-14}$ (stat.)$^{+9}_{-4}$ (syst.), $N(\Sigma_b^{*+}) = 77^{+17}_{-16}$ (stat.)$^{+10}_{-6}$ (syst.), and $N(\Sigma_b^{*-}) = 69^{+18}_{-17}$ (stat.)$^{+16}_{-5}$ (syst.). The signal locations are $Q(\Sigma_b^+) = 48.5^{+2.0}_{-2.2}$ (stat.)$^{+0.2}_{-0.3}$ (syst.) MeV/$c^2$, $Q(\Sigma_b^-) = 55.9 \pm 1.0$ (stat.) $\pm$ 0.2 (syst.) MeV/$c^2$, and $\Delta(\Sigma_b^*) = 21.2^{+2.0}_{-1.9}$ (stat.)$^{+0.4}_{-0.3}$ (syst.) MeV/$c^2$.

## 5 Summary

The $\Lambda_b^0\pi^\pm$ resonant states observed in 1.1 fb$^{-1}$ of CDF II data are consistent with the lowest lying charged $\Sigma_b$ baryons, and the observed properties are in agreement with theoretical predictions. Using the CDF II measurement [6] of m($\Lambda_b^0$) = 5619.7 $\pm$ 1.2 (stat.) $\pm$1.2 (syst.) MeV/$c^2$, the masses of each state are

$$\mathrm{m}(\Sigma_b^+) = 5807.8^{+2.0}_{-2.2}\ \text{(stat.)} \pm 1.7\ \text{(syst.) MeV}/c^2,$$
$$\mathrm{m}(\Sigma_b^-) = 5815.2 \pm 1.0\ \text{(stat.)} \pm 1.7\ \text{(syst.) MeV}/c^2,$$
$$\mathrm{m}(\Sigma_b^{*+}) = 5829.0^{+1.6}_{-1.8}\ \text{(stat.)}^{+1.7}_{-1.8}\ \text{(syst.) MeV}/c^2,$$
$$\mathrm{m}(\Sigma_b^{*-}) = 5836.4 \pm 2.0\ \text{(stat.)}^{+1.8}_{-1.7}\ \text{(syst.) MeV}/c^2.$$

This is the first observation of the lowest lying charged $\Sigma_b$ baryons.


## Acknowledgments

We thank T. Becher, A. Falk, D. Pirjol, J. Rosner, and D. Ebert for useful discussions. We also thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Particle Physics and Astronomy Research Council and the Royal Society, UK; the Institut National de Physique Nucleaire et Physique des Particules/CNRS; the Russian Foundation for Basic Research; the Comisión Interministerial de Ciencia y Tecnología, Spain; the European Community's Human Potential Programme under contract HPRN-CT-2002-00292; and the Academy of Finland.


## References


1. D. Acosta *et al.* (CDF Collaboration), *Phys. Rev.* D **71**, 032001 (2005).
2. The CDF II detector uses a cylindrical coordinate system with the $z$-axis along the proton beam direction. The pseudorapidity $\eta$ is defined as $\tanh^{-1}(\cos\theta)$. Transverse momentum, $p_\mathrm{T}$, is the component of the particle's momentum in the $(x, y)$ plane.
3. CDF Collaboration, CDF Public Note 8523 (2006) and references therein, http://www-cdf.fnal.gov/physics/new/bottom/060921.blessed-sigmab.
4. J. G. Körner, M. Krämer, and D. Pirjol, *Prog. Part. Nucl. Phys.* **33**, 787 (1994).
5. T. Sjöstrand, P. Eden, C. Friberg, L. Lonnblad, G. Miu, S. Mrenna, and E. Norrbin, *Comput. Phys. Commun.* **135**, 238 (2001).
6. D. Acosta *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **96**, 202001 (2006).

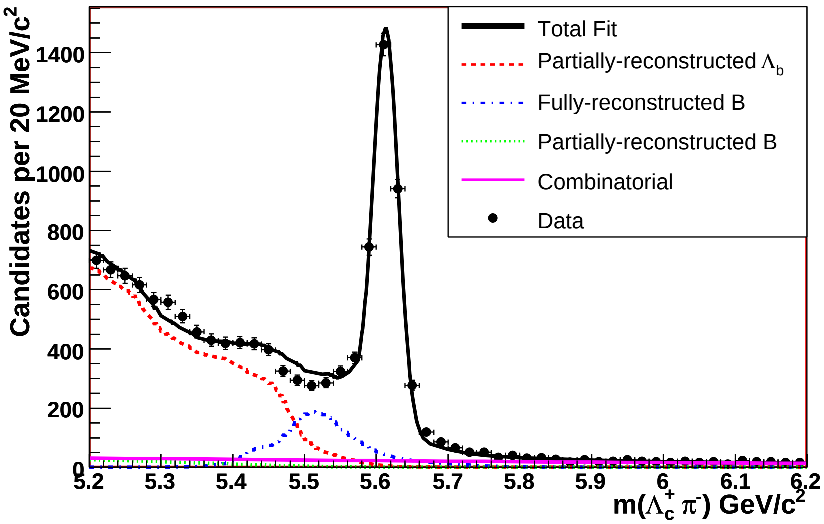


Figure 1: Unbinned maximum likelihood fit to the reconstructed invariant mass of $\Lambda_b^0 \to \Lambda_c^+\pi^-$ candidates. The fully reconstructed $\Lambda_b^0$ modes (such as $\Lambda_b^0 \to \Lambda_c^+\pi^-$ and $\Lambda_b^0 \to \Lambda_c^+K^-$) are not shown separately on the figure.

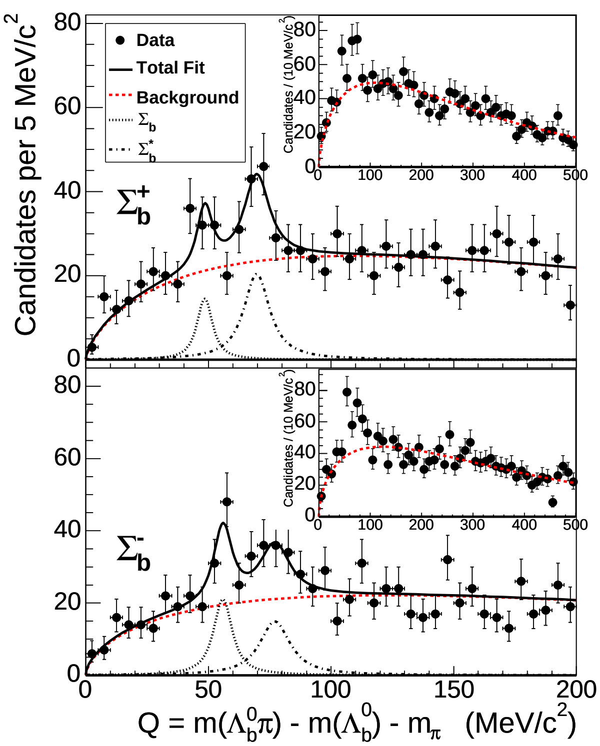


Figure 2: Unbinned maximum likelihood fit to the $\Sigma_b$ $Q$ distributions. The top plot shows the $\Lambda_b^0\pi^+$ combinations, while the bottom plot shows the $\Lambda_b^0\pi^-$ combinations. The insets show the expected background plotted on the data for $Q \in [0, 500]$ MeV/$c^2$, while the $\Sigma_b$ signal fit is shown on a reduced range of $Q \in [0, 200]$ MeV/$c^2$.