

## Observation of the Heavy Baryons $\Sigma_b$ and $\Sigma_b^*$

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We report an observation of new bottom baryons produced in  $p\bar{p}$  collisions at the Tevatron. Using  $1.1 \text{ fb}^{-1}$  of data collected by the CDF II detector, we observe four  $\Lambda_b^0 \pi^\pm$  resonances in the fully reconstructed decay mode  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ , where  $\Lambda_c^+ \rightarrow pK^- \pi^+$ . We interpret these states as the  $\Sigma_b^{(*)\pm}$  baryons and measure the following masses:  $m_{\Sigma_b^+} = 5807.8_{-2.2}^{+2.0}(\text{stat.}) \pm 1.7(\text{syst.}) \text{ MeV}/c^2$ ,  $m_{\Sigma_b^-} = 5815.2 \pm 1.0(\text{stat.}) \pm 1.7(\text{syst.}) \text{ MeV}/c^2$ , and  $m(\Sigma_b^*) - m(\Sigma_b) = 21.2_{-1.9}^{+2.0}(\text{stat.})_{-0.3}^{+0.4}(\text{syst.}) \text{ MeV}/c^2$ .

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Recently the CDF II detector at the Fermilab Tevatron has accumulated the world's largest sample of fully reconstructed  $\Lambda_b^0$  baryons, which consist of the  $u$ ,  $d$ , and  $b$  quarks, with  $3180 \pm 60$  (stat.)  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$  candidates. This is made possible by the large  $b\bar{b}$  production cross section in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96 \text{ TeV}$  and the ability of the CDF II experiment to select fully hadronic decays of  $b$  hadrons with a specialized trigger system. In this Letter, we present an observation of four  $\Lambda_b^0 \pi^\pm$  resonances, where

$\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$  and  $\Lambda_c^+ \rightarrow pK^- \pi^+$ , using  $1.1 \text{ fb}^{-1}$  of data. The  $\Lambda_b^0 \pi$  states are interpreted as the lowest-lying charged  $\Sigma_b$  baryons and will be labeled  $\Sigma_b^{(*)}$ . The symbol  $\Sigma_b$  refers to  $\Sigma_b^\pm$ , while  $\Sigma_b^*$  refers to  $\Sigma_b^{*\pm}$ . Any reference to a specific charge state implies the antiparticle state as well.

The  $\Sigma_b^{(*)+}$  baryons contain one  $b$  and two  $u$  quarks, while the  $\Sigma_b^{(*)-}$  baryons contain one  $b$  and two  $d$  quarks; these states are expected to exist but have not been ob-

served. Baryons containing one bottom quark and two light quarks can be described by heavy quark effective theory (HQET) [1]. In HQET, a bottom baryon consists of a  $b$  quark acting as a static source of the color field surrounded by a diquark system comprised of the two light quarks. In the lowest-lying  $\Sigma_b^{(*)}$  states, the diquark system has strong isospin  $I = 1$  and  $J^P = 1^+$ , which couple to the heavy quark spin and result in a doublet of baryons with  $J^P = \frac{1}{2}^+$  ( $\Sigma_b$ ) and  $J^P = \frac{3}{2}^+$  ( $\Sigma_b^*$ ). This doublet is degenerate for infinite  $b$  quark mass. As the  $b$  quark mass is finite, there is a hyperfine mass splitting between the  $\frac{3}{2}^+$  and  $\frac{1}{2}^+$  states. There is also an isospin mass splitting between the  $\Sigma_b^{(*)-}$  and  $\Sigma_b^{(*)+}$  states.

Predictions for the  $\Sigma_b^{(*)}$  masses come from nonrelativistic and relativistic potential quark models [2],  $1/N_c$  expansion [3], quark models in the HQET approximation [4], sum rules [5], and lattice quantum chromodynamics calculations [6]. On the basis of [2–6], we expect  $m(\Sigma_b) - m(\Lambda_b^0) \sim 180\text{--}210 \text{ MeV}/c^2$ ,  $m(\Sigma_b^*) - m(\Sigma_b) \sim 10\text{--}40 \text{ MeV}/c^2$ , and  $m(\Sigma_b^{(*)-}) - m(\Sigma_b^{(*)+}) \sim 5\text{--}7 \text{ MeV}/c^2$ . The difference between the isospin mass splittings of the  $\Sigma_b^*$  and  $\Sigma_b$  multiplets is predicted to be  $[m(\Sigma_b^{*+}) - m(\Sigma_b^{*-})] - [m(\Sigma_b^+) - m(\Sigma_b^-)] = 0.40 \pm 0.07 \text{ MeV}/c^2$  [7]. The natural width of  $\Sigma_b^{(*)}$  baryons is expected to be dominated by the  $P$ -wave one pion transition  $\Sigma_b^{(*)} \rightarrow \Lambda_b^0 \pi$ , whose partial width depends on the available phase space and the pion coupling to a constituent quark. Using an HQET prediction [8], the natural widths for the expected  $\Sigma_b^{(*)}$  masses are  $\Gamma(\Sigma_b^\pm) \approx 7 \text{ MeV}/c^2$  and  $\Gamma(\Sigma_b^{*\pm}) \approx 13 \text{ MeV}/c^2$ .

The CDF II detector is described in detail elsewhere [9]. Its components and capabilities most relevant to this analysis are the tracking system [10] and a displaced track trigger which is employed to select bottom and charmed hadrons [11].

In reconstructing the decays  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$  and  $\Lambda_c^+ \rightarrow p K^- \pi^+$ , the proton from the  $\Lambda_c^+$  decay and the  $\pi^-$  from the  $\Lambda_b^0$  decay both must have  $p_T > 2 \text{ GeV}/c$  [12], while the  $K^-$  and  $\pi^+$  candidates have  $p_T > 0.5 \text{ GeV}/c$ . We also require  $p_T(p) > p_T(\pi^+)$  to suppress  $\Lambda_c^+$  combinatorial background. No particle identification is used in this analysis. All particle hypotheses consistent with the candidate decay structure are considered. In a 3-D kinematic fit, the  $\Lambda_c^+$  daughter tracks are constrained to originate from a single point. The  $\Lambda_c^+$  candidate is constrained to the known  $\Lambda_c^+$  mass, and the  $\Lambda_c^+$  momentum vector is extrapolated to intersect the  $\pi^-$  momentum vector to form the  $\Lambda_b^0$  vertex. The probability of the 3-D  $\Lambda_b^0$  kinematic vertex fit must exceed 0.1%, and the  $\Lambda_c^+$  and  $\Lambda_b^0$  must have  $p_T$  greater than 4.5 and 6.0  $\text{GeV}/c$ , respectively. To suppress prompt backgrounds from the primary interaction, we make the following decay time requirements:  $ct(\Lambda_b^0) > 250 \mu\text{m}$  and its significance  $ct(\Lambda_b^0)/\sigma_{ct} > 10$ . We define  $ct(\Lambda_b^0) \equiv$

$L_{xy}(\Lambda_b^0)m_{\Lambda_b^0}c/p_T(\Lambda_b^0)$  as the  $\Lambda_b^0$  proper time, where  $L_{xy}(\Lambda_b^0)$  is defined as the projection, onto  $p_T(\Lambda_b^0)$ , of the vector connecting the primary vertex to the  $\Lambda_b^0$  vertex in the transverse plane. We use a primary vertex determined event-by-event when computing this vertex displacement. To reduce combinatorial backgrounds and partially reconstructed decays, we also require  $|d_0(\Lambda_b^0)| < 80 \mu\text{m}$ , where  $d_0(\Lambda_b^0)$  is the impact parameter of the momentum vector of the  $\Lambda_b^0$  candidate with respect to the primary vertex. To suppress the contributions from  $\bar{B}^0 \rightarrow D^+ \pi^-$  decays, where  $D^+ \rightarrow K^- \pi^+ \pi^+$ , we require  $m(pK^- \pi^+)$  to be within  $16 \text{ MeV}/c^2$  of the known  $\Lambda_c^+$  mass [13], and  $ct(\Lambda_c^+) \in [-70, 200] \mu\text{m}$ . We define  $ct(\Lambda_c^+) \equiv L_{xy}(\Lambda_c^+)m_{\Lambda_c^+}c/p_T(\Lambda_c^+)$  as the  $\Lambda_c^+$  proper time, where  $L_{xy}(\Lambda_c^+)$  is defined analogously to  $L_{xy}(\Lambda_b^0)$  but computed with respect to the  $\Lambda_b^0$  vertex.

The invariant mass distribution of  $\Lambda_c^+ \pi^-$  candidates is shown in Fig. 1 overlaid with a binned maximum likelihood fit. A clear  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$  signal is observed at the expected  $\Lambda_b^0$  mass. The invariant mass distribution is described by several components: the  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$  signal, a combinatorial background, partially and fully reconstructed  $B$  mesons which pass the  $\Lambda_c^+ \pi^-$  selection criteria, partially reconstructed  $\Lambda_b^0$  decays, and fully reconstructed  $\Lambda_b^0$  decays other than  $\Lambda_c^+ \pi^-$  (e.g.,  $\Lambda_b^0 \rightarrow \Lambda_c^+ K^-$ ). The combinatorial background is modeled with an exponentially decreasing function. All other components are represented in the fit by fixed shapes derived from Monte Carlo (MC) simulations [14,15]. The normalizations are constrained by Gaussian terms to branching ratios that are either measured (for  $B$  meson decays) or theoretical predictions (for  $\Lambda_b^0$  decays). In the fit, the  $\Lambda_b^0$  components are normalized relative to the  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$  signal. To normalize the  $B$  meson components, we explicitly reconstruct a  $\bar{B}^0 \rightarrow (K^- \pi^+ \pi^+) \pi^-$  signal in the  $\Lambda_c^+ \pi^-$

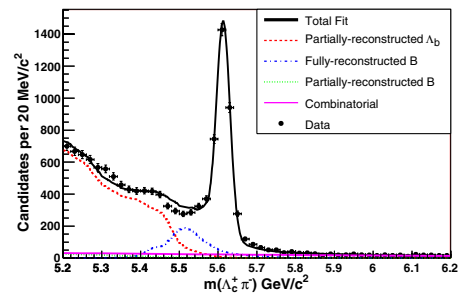


FIG. 1 (color online). Fit to the invariant mass of  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$  candidates. Curves for fully reconstructed  $\Lambda_b^0$  decays such as  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$  and  $\Lambda_b^0 \rightarrow \Lambda_c^+ K^-$  are not indicated on the figure. The  $\Lambda_b^0$  signal region,  $m(\Lambda_c^+ \pi^-) \in [5.565, 5.670] \text{ GeV}/c^2$ , consists primarily of  $\Lambda_b^0$  baryons, with some contamination from  $B$  mesons and combinatorial events. The discrepancies between the fit and data below the  $\Lambda_b^0$  signal region are due to incomplete knowledge of the branching ratios of the decays in this region and are included in the  $\Sigma_b^{(*)}$  background model systematics.

sample by replacing the proton mass hypothesis with the pion mass hypothesis. The fit to the invariant  $\Lambda_c^+ \pi^-$  mass distribution results in  $3180 \pm 60$  (stat.)  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$  candidates.

The reconstruction of  $\Sigma_b^{(*)}$  proceeds by combining  $\Lambda_b^0$  candidates in the  $\Lambda_b^0$  signal region,  $m(\Lambda_c^+ \pi^-) \in [5.565, 5.670]$  GeV/ $c^2$ , with all remaining high quality tracks. A pion mass hypothesis is used when computing the invariant mass of the  $\Sigma_b^{(*)}$  candidate. We search for narrow resonances in the mass difference distribution of  $Q = m(\Lambda_b^0 \pi) - m(\Lambda_b^0) - m_\pi$ , where  $m(\Lambda_b^0)$  is the reconstructed  $\Lambda_c^+ \pi^-$  mass. The  $\Sigma_b^{(*)}$  candidates are divided into two subsamples using the charge of the pion from  $\Sigma_b^{(*)}$  decay, denoted by  $\pi_{\Sigma_b}$ : in the  $\Lambda_b^0 \pi^-$  subsample, the  $\pi_{\Sigma_b}$  has the same charge as the pion from  $\Lambda_b^0$  while in the  $\Lambda_b^0 \pi^+$  subsample, the  $\pi_{\Sigma_b}$  has the opposite charge as the pion from  $\Lambda_b^0$ .

The  $\Sigma_b^{(*)}$  signal region, defined as  $Q \in [30, 100]$  MeV/ $c^2$ , is motivated by the predictions in [2–6]. The signal is modeled by the PYTHIA [16] event generator where only the decays  $\Sigma_b^{(*)} \rightarrow \Lambda_b^0 \pi$ ,  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ , and  $\Lambda_c^+ \rightarrow p K^- \pi^+$  are allowed. We optimize the  $\Sigma_b^{(*)}$  selection criteria by maximizing  $\epsilon(S_{MC})/\sqrt{B}$ , where  $\epsilon(S_{MC})$  is the efficiency of the  $\Sigma_b^{(*)}$  signal measured in the MC simulation and  $B$  is the number of background events in the signal region estimated from the upper and lower sideband regions of  $Q \in [0, 30]$  MeV/ $c^2$  and  $Q \in [100, 500]$  MeV/ $c^2$ . These sideband regions are parameterized by a power law multiplied by an exponential. We combine the  $\Lambda_b^0 \pi^-$  and  $\Lambda_b^0 \pi^+$  subsamples to optimize cuts on the  $p_T$  of the  $\Sigma_b^{(*)}$  candidate, the impact parameter significance  $|d_0/\sigma_{d_0}|$  of the  $\pi_{\Sigma_b}$  track, and the  $\cos\theta^*$  of the  $\pi_{\Sigma_b}$  track, where  $\theta^*$  is defined as the angle between the momentum of the  $\pi_{\Sigma_b}$  in the  $\Sigma_b^{(*)}$  rest frame and the direction of the total  $\Sigma_b^{(*)}$  momentum in the lab frame. The maximum of  $\epsilon(S_{MC})/\sqrt{B}$  is realized for  $p_T(\Sigma_b) > 9.5$  GeV/ $c$ ,  $|d_0/\sigma_{d_0}| < 3.0$ , and  $\cos\theta^* > -0.35$ .

In the  $\Sigma_b^{(*)}$  search, the dominant background is from the combination of prompt  $\Lambda_b^0$  baryons with extra tracks produced in the hadronization of the  $b$  quark. The remaining backgrounds are from the combination of hadronization tracks with  $B$  mesons reconstructed as  $\Lambda_b^0$  baryons, and from combinatorial background events. The percentage of each background component in the  $\Lambda_b^0$  signal region, computed from the  $\Lambda_b^0$  mass fit, is  $(89.5 \pm 1.7)\%$   $\Lambda_b^0$  baryons,  $(7.2 \pm 0.6)\%$   $B$  mesons, and  $(3.3 \pm 0.1)\%$  combinatorial events. Other backgrounds such as 5-track decays of  $B^+$  mesons are negligible, as confirmed in inclusive single  $b$  hadron simulations [14,15]. The high mass region above the  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$  signal in Fig. 1 determines the combinatorial background shape. Reconstructing  $\bar{B}^0 \rightarrow D^+ \pi^-$  data as  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$  gives the  $B$  hadronization background

shape. The  $\Lambda_b^0$  hadronization background shape is obtained from a  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$  PYTHIA simulation. The events in this simulation are reweighted so that the  $p_T(\Lambda_b^0)$  distribution agrees with data. As the simulation has fewer low momentum tracks around the  $\Lambda_b^0$  than found in data, the simulated events are further reweighted until the  $p_T$  spectrum of tracks around the  $\Lambda_b^0$  is consistent with data. The background shapes are parameterized by a power law multiplied by an exponential, and the normalizations are fixed from the percentage of that background component in the  $\Lambda_b^0$  signal region. The total background shown in Fig. 2 (inset) is compatible with the  $Q$  sidebands, and the background shape and normalization are fixed components of the  $\Sigma_b^{(*)}$  fit.

In the  $Q$  signal region, we observe an excess of events over the total background as shown in Fig. 2. The excess in the  $\Lambda_b^0 \pi^-$  subsample is 118 over 288 expected background candidates. In the  $\Lambda_b^0 \pi^+$  subsample, the excess is 91 over 313 expected background candidates.

We perform a simultaneous unbinned maximum likelihood fit to the  $\Lambda_b^0 \pi^-$  and  $\Lambda_b^0 \pi^+$  subsamples for a signal from each expected  $\Sigma_b^{(*)}$  state plus the background, referred to as the “four signal hypothesis.” Each signal consists of a nonrelativistic Breit-Wigner distribution convoluted with two Gaussian distributions describing the detector resolution, with a dominant narrow core of an 1.2 MeV/ $c^2$  width and a small broad component of a 3 MeV/ $c^2$  width for the tails. The natural width of each Breit-Wigner distribution is computed from the central  $Q$  value [8]. The expected difference of the isospin mass splittings within the  $\Sigma_b^{(*)}$

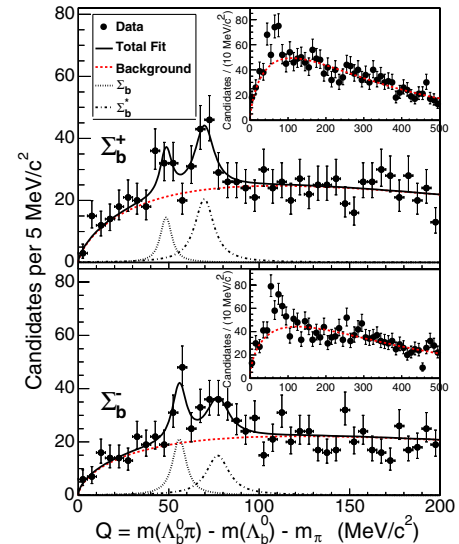


FIG. 2 (color online). The  $\Sigma_b^{(*)}$  fit to the  $\Lambda_b^0 \pi^+$  and  $\Lambda_b^0 \pi^-$  subsamples. The top plot shows the  $\Lambda_b^0 \pi^+$  subsample, which contains  $\Sigma_b^{(*)+}$ , while the bottom plot shows the  $\Lambda_b^0 \pi^-$  subsample, which contains  $\Sigma_b^{(*)-}$ . The insets show the expected background plotted on the data for  $Q \in [0, 500]$  MeV/ $c^2$ , while the signal fit is shown on a reduced range of  $Q \in [0, 200]$  MeV/ $c^2$ .

TABLE I. Likelihood ratios ( $LR$ ) in favor of the four signal hypothesis over alternative hypotheses. Also shown is the probability for each hypothesis to produce the observed data ( $p$ -value), calculated using the  $LR$  as a test statistic on randomly generated samples. The final column gives the equivalent standard deviations from the normal distribution.

Hypothesis	$LR$	$p$ -value	Significance ( $\sigma$ )
No Signal	$2.6 \times 10^{18}$	$< 8.3 \times 10^{-8}$	$> 5.2$
Two $\Sigma_b$ States	$4.4 \times 10^6$	$9.2 \times 10^{-5}$	3.7
No $\Sigma_b^-$ Signal	$1.2 \times 10^5$	$3.2 \times 10^{-4}$	3.4
No $\Sigma_b^+$ Signal	49	$9.0 \times 10^{-3}$	2.4
No $\Sigma_b^{*-}$ Signal	$4.9 \times 10^4$	$6.4 \times 10^{-4}$	3.2
No $\Sigma_b^{*+}$ Signal	$8.1 \times 10^4$	$6.0 \times 10^{-4}$	3.2

and  $\Sigma_b$  multiplets is below our sensitivity with this sample of data. Consequently, we constrain  $m(\Sigma_b^{*+}) - m(\Sigma_b^+) = m(\Sigma_b^{*-}) - m(\Sigma_b^-) \equiv \Delta_{\Sigma_b^*}$ . The four  $\Sigma_b$  signal fit to data, which has a fit probability of 76% in the range  $Q \in [0, 200]$  MeV/ $c^2$ , is shown in Fig. 2.

Systematic uncertainties on the mass difference and yield measurements fall into three categories: mass scale,  $\Sigma_b^{(*)}$  background model, and  $\Sigma_b^{(*)}$  signal parameterization. The systematic uncertainty on the mass scale is determined by the discrepancies of the CDF II measured  $Q$  values of the  $D^*$ ,  $\Sigma_c$ , and  $\Lambda_c^*$  hadrons from the world average  $Q$  values [13]. The  $Q$  value dependence of this systematic uncertainty is modeled with a linear function, which is used to extrapolate the mass scale uncertainty for each  $\Sigma_b^{(*)}$   $Q$  value. This is the largest systematic uncertainty for the mass difference measurements, ranging from 0.1 to 0.3 MeV/ $c^2$ . The systematic effects related to assumptions made on the  $\Sigma_b^{(*)}$  background model are: the sample composition of the  $\Lambda_b^0$  signal region, the normalization and functional form of the  $\Lambda_b^0$  hadronization background taken from a PYTHIA simulation, and our limited knowledge of the shape of the  $\Lambda_b^0$  hadronization background (the largest systematic uncertainty on the yield measurements, ranging from 2 to 15 events). The systematic effects related to assumptions made on the  $\Sigma_b^{(*)}$  signal parameterization are: underestimation of the detector resolution, the uncertainty in the natural width prediction from [8], and the constraint that  $m(\Sigma_b^{*+}) - m(\Sigma_b^+) = m(\Sigma_b^{*-}) - m(\Sigma_b^-)$ .

The significance of the signal is evaluated using the likelihood ratio,  $LR \equiv L/L_{\text{alt}}$ , where  $L$  is the likelihood of the four signal hypothesis and  $L_{\text{alt}}$  is the likelihood of an alternative hypothesis [17]. We study the alternate hypotheses of no signal, two  $\Sigma_b$  states (one per  $\Lambda_b^0 \pi$  charge combination), and three  $\Sigma_b^{(*)}$  states, performed by eliminating one of the states in the four signal hypothesis. Systematic variations are included in the fit as nuisance parameters over which the likelihood is integrated. The resulting likelihood ratios are given in Table I. To assess the significance of the signal, we repeat the four signal

TABLE II. Final results for the  $\Sigma_b$  measurement. The first uncertainty is statistical, and the second is systematic. The absolute  $\Sigma_b$  mass values are calculated using a CDF II measurement of the  $\Lambda_b^0$  mass [18], which contributes to the systematic uncertainty.

State	Yield	$Q$ or $\Delta_{\Sigma_b^*}$ (MeV/ $c^2$ )	Mass (MeV/ $c^2$ )
$\Sigma_b^+$	$32^{+13+5}_{-12-3}$	$Q_{\Sigma_b^+} = 48.5^{+2.0+0.2}_{-2.2-0.3}$	$5807.8^{+2.0}_{-2.2} \pm 1.7$
$\Sigma_b^-$	$59^{+15+9}_{-14-4}$	$Q_{\Sigma_b^-} = 55.9 \pm 1.0 \pm 0.2$	$5815.2 \pm 1.0 \pm 1.7$
$\Sigma_b^{*+}$	$77^{+17+10}_{-16-6}$	$\Delta_{\Sigma_b^*} = 21.2^{+2.0+0.4}_{-1.9-0.3}$	$5829.0^{+1.6+1.7}_{-1.8-1.8}$
$\Sigma_b^{*-}$	$69^{+18+16}_{-17-5}$		$5836.4 \pm 2.0^{+1.8}_{-1.7}$

hypothesis fit on samples randomly generated from alternate signal hypotheses. In  $12 \times 10^6$  background samples, none had a  $LR$  equivalent or greater than the one found in data. We evaluate the probability for background only to produce four signals of this or greater significance to be less than  $8.3 \times 10^{-8}$ , corresponding to a significance of greater than  $5.2\sigma$ . The probabilities for each of the alternate hypotheses to produce the observed signal structure is also given in Table I. The final results for the  $\Sigma_b$  measurement are quoted in Table II. Using the CDF II measurement of  $m_{\Lambda_b^0} = 5619.7 \pm 1.2(\text{stat.}) \pm 1.2(\text{syst.})$  MeV/ $c^2$  [18], we find the absolute masses of the  $\Sigma_b$  states given in Table II. The systematic uncertainties on the absolute  $\Sigma_b$  mass values are dominated by the total  $\Lambda_b^0$  mass uncertainty.

In summary, using a sample of  $3180 \pm 60$  (stat.)  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$  candidates reconstructed in  $1.1 \text{ fb}^{-1}$  of CDF II data, we search for resonant  $\Lambda_b^0 \pi^\pm$  states. We observe a signal of four states whose masses and widths are consistent with those expected for the lowest-lying charged  $\Sigma_b^{(*)}$  baryons. This result represents the first observation of the  $\Sigma_b^{(*)}$  baryons.

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- [1] For a review see A.V. Manohar and M.B. Wise, Cambridge Monogr. Part. Phys., Nucl. Phys., Cosmol. **10**, 1 (2000), and references therein.
- [2] D.P. Stanley and D. Robson, Phys. Rev. Lett. **45**, 235 (1980); and Phys. Rev. D **21**, 3180 (1980); D. Izatt, C. DeTar, and M. Stephenson, Nucl. Phys. B **199**, 269 (1982); J.M. Richard and P. Taxil, Phys. Lett. B **128**, 453 (1983); J.L. Basdevant and S. Boukraa, Z. Phys. C **30**, 103 (1986); W.Y.P. Hwang and D.B. Lichtenberg, Phys. Rev. D **35**, 3526 (1987); A. Martin and J.M. Richard, Phys. Lett. B **185**, 426 (1987); D.B. Lichtenberg, R. Roncaglia, J.G. Wills, and E. Predazzi, Z. Phys. C **47**, 83 (1990).
- [3] E. Jenkins, Phys. Rev. D **54**, 4515 (1996); **55**, R10 (1997).

- [4] C. Albertus, J.E. Amaro, E. Hernandez, and J. Nieves, Nucl. Phys. A **740**, 333 (2004); D. Ebert, R.N. Faustov, and V.O. Galkin, Phys. Rev. D **72**, 034026 (2005); S. Capstick, *ibid.* **36**, 2800 (1987).
- [5] R. Roncaglia, D.B. Lichtenberg, and E. Predazzi, Phys. Rev. D **52**, 1722 (1995); M. Karliner and H.J. Lipkin, arXiv:hep-ph/0307243; condensed version in Phys. Lett. B **575**, 249 (2003).
- [6] K.C. Bowler *et al.* (UKQCD Collaboration), Phys. Rev. D **54**, 3619 (1996); N. Mathur, R. Lewis, and R.M. Woloshyn, *ibid.* **66**, 014502 (2002).
- [7] J.L. Rosner, Phys. Rev. D **57**, 4310 (1998); J.L. Rosner, Phys. Rev. D **75**, 013009 (2007).
- [8] J.G. Körner, M. Krämer, and D. Pirjol, Prog. Part. Nucl. Phys. **33**, 787 (1994).
- [9] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **71**, 032001 (2005).
- [10] A. Sill *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **447**, 1 (2000); A. Affolder *et al.* (CDF Collaboration), *ibid.* **526**, 249 (2004).
- [11] A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. Lett. **98**, 122002 (2007).
- [12] The transverse plane ( $x, y$ ) is perpendicular to the direction of the proton beam. The azimuthal angle  $\phi$  is measured from the  $x$ -axis. The transverse momentum  $p_T$  is the magnitude of the projection of the momentum in the transverse plane.
- [13] W.M. Yao *et al.* (Particle Data Group), J. Phys. G **33**, 1 (2006).
- [14] We use a variety of single  $b$  hadron simulations, all using the  $p_T(B)$  and  $y(B)$  distributions obtained from  $B$  decays in data [D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **71**, 032001 (2005)]. The simulated  $p_T(\Lambda_b^0)$  distribution is reweighted to match the sideband-subtracted data.
- [15] The  $b$  hadrons are decayed using the EVTGEN package [D.J. Lange, Nucl. Instrum. Methods Phys. Res., Sect. A **462**, 152 (2001)].
- [16] T. Sjöstrand, P. Eden, C. Friberg, L. Lonnblad, G. Miu, S. Mrenna, and E. Norrbin, Comput. Phys. Commun. **135**, 238 (2001).
- [17] R. Royall, J. Am. Stat. Assoc. **95**, 760 (2000).
- [18] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. Lett. **96**, 202001 (2006).