

First Observation of Bottom Baryon Σ_b States at CDF

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Abstract. We present the latest results on the search for bottom baryon states Σ_b using $\sim 1 \text{ fb}^{-1}$ of CDF data. The study is performed with the world's largest sample of fully reconstructed Λ_b^0 decays collected by CDF II detector at $\sqrt{s} = 1.96 \text{ TeV}$ in the hadronic trigger path. We observe 4 new states consistent with $\Sigma_b^{(*)\pm}$ bottom baryons.

1. Introduction

High energy particle colliders provide a wealth of experimental data on bottom mesons. However, only one bottom baryon, the Λ_b^0 , has been directly observed [1, 2, 3, 4].

Heavy baryons containing one heavy quark and a light diquark became a nice 3-body laboratory to test QCD models. In the limit of heavy quark mass $m_Q \rightarrow \infty$, heavy baryons' properties are governed by the dynamics of the light diquark in a gluon field created by the heavy quark acting as a static source. The heavy baryon like Λ_b^0 can be considered as a "helium atom" of QCD. In this Heavy Quark Symmetry (HQS) approach [5] at the heavy quark limit a heavy quark spin does not interact with the gluon field, the spin decouples from the degrees of freedom of the light quark and the quantum numbers of the heavy quark and the light diquark are separately conserved by the strong interaction. Consequently the light diquark momentum $\mathbf{j}_{\text{qq}} = \mathbf{s}_{\text{qq}} + \mathbf{L}_{\text{qq}}$, the heavy quark spin \mathbf{s}_Q and total momentum $\mathbf{J}_{\text{Qqq}} = \mathbf{s}_Q + \mathbf{j}_{\text{qq}}$ are considered as good quantum numbers. Based on the HQS principles an effective field theory was constructed where $\frac{1}{m_Q}$ corrections can be systematically included in the perturbative expansions. The theory was named as Heavy Quark Effective Theory (HQET) (see [6] and references therein).

For the bottom $Q \equiv b$ baryons with a single heavy quark and two light ones (see Table 1) the bottom quark spin, $\mathbf{s}_Q = \frac{1}{2}^+$, is combined with the light diquark momentum \mathbf{j}_{qq} comprised

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of spin $\mathbf{s}_{\mathbf{q}\mathbf{q}} = \mathbf{0}^+ \oplus \mathbf{1}^+$ and its angular momentum $\mathbf{L}_{\mathbf{q}\mathbf{q}}$. The baryons with a diquark having $\mathbf{s}_{\mathbf{q}\mathbf{q}} = \mathbf{0}^+$ and isospin $\mathbf{I} = \mathbf{0}$ are called Λ - type, while the states with $\mathbf{s}_{\mathbf{q}\mathbf{q}} = \mathbf{1}^+$ and isospin $\mathbf{I} = \mathbf{1}$ are called Σ - type. The ground state Λ_b^0 baryon has $\mathbf{I} = \mathbf{0}$, $\mathbf{J}^{\mathbf{P}} = \frac{1}{2}^+$. A doublet of ground Σ -like bottom baryons comprises Σ_b with $\mathbf{I} = \mathbf{1}$, $\mathbf{J}^{\mathbf{P}} = \frac{1}{2}^+$ and Σ_b^* with $\mathbf{I} = \mathbf{1}$, $\mathbf{J}^{\mathbf{P}} = \frac{3}{2}^+$.

The combination of an orbital momentum $\mathbf{L}_{\mathbf{q}\mathbf{q}} = \mathbf{1}^-$ of a diquark with its spin of $\mathbf{s}_{\mathbf{q}\mathbf{q}} = \mathbf{0}^+$ adds to the spectroscopy a number of excited P - wave bottom Λ -states. The lowest lying orbital excitations are Λ_b^{*0} with $\mathbf{J}^{\mathbf{P}} = \frac{1}{2}^-$, $\frac{3}{2}^-$ [7, 8, 9].

Table 1. Bottom baryon Λ - and Σ - states and their quantum numbers. The $[q_1q_2]$ denotes a pair *antisymmetric* in flavor and spin. The $\{q_1q_2\}$ denotes a pair *symmetric* in flavor and spin.

| State | Quarks | $\mathbf{J}^{\mathbf{P}}$ | $(\mathbf{I}, \mathbf{I}_3)$ |
|------------------|-----------|---------------------------|------------------------------|
| Λ_b^0 | $b[ud]$ | $(1/2)^+$ | $(0, 0)$ |
| Σ_b^+ | buu | $(1/2)^+$ | $(1, +1)$ |
| Σ_b^0 | $b\{ud\}$ | $(1/2)^+$ | $(1, 0)$ |
| Σ_b^- | bdd | $(1/2)^+$ | $(1, -1)$ |
| Σ_b^{*+} | buu | $(3/2)^+$ | $(1, +1)$ |
| Σ_b^{*0} | $b\{ud\}$ | $(3/2)^+$ | $(1, 0)$ |
| Σ_b^{*-} | bdd | $(3/2)^+$ | $(1, -1)$ |
| Λ_b^{*0} | $b[ud]$ | $(1/2)^-$ | $(0, 0)$ |
| Λ_b^{*0} | $b[ud]$ | $(3/2)^-$ | $(0, 0)$ |

Theoretical expectations for ground bottom baryon states are summarized in Table 2. The calculations have been done with non-relativistic and relativistic potential quark models, $1/N_c$ expansion, quark models in the HQET approximation, sum rules, and finally with lattice QCD models [10].

In a physics reality $\mathbf{m}_{\mathbf{Q}}$ is finite and a degeneration of a $\{\Sigma_b, \Sigma_b^*\}$ doublet is resolved by a hyperfine mass splitting between its states. There is also an isospin mass splitting (see Table 2) between members of Σ_b and Σ_b^* isotriplets [11, 12, 13, 14]. As it was pointed out [14] the value of the isospin splitting within Σ_b triplet does differ from Σ_b^* triplet, namely $(\Sigma_b^{*+} - \Sigma_b^{*-}) - (\Sigma_b^+ - \Sigma_b^-) = 0.40 \pm 0.07 \text{ MeV}/c^2$. This number contributes to systematic uncertainty of our experimental results (see Section 5).

Table 2. Mass and width predictions for $\Sigma_b^{(*)\pm}$.

| Σ_b property | MeV/ c^2 |
|--|-------------------|
| $m(\Sigma_b) - m(\Lambda_b^0)$ | 180 – 210 |
| $m(\Sigma_b^*) - m(\Sigma_b)$ | 10 – 40 |
| $m(\Sigma_b^-) - m(\Sigma_b^+)$ | 5 – 7 |
| $m(\Lambda_b^0)$, fixed | 5619.7 |
| from CDF II | $\pm 1.2 \pm 1.2$ |
| $\Gamma(\Sigma_b), \Gamma(\Sigma_b^*)$ | $\sim 8, \sim 15$ |
| see below | |

According to HQS the physics of pion transitions between heavy baryons is governed by the light diquark. The one or two pions are emitted from the light diquark while the heavy quark propagates unaffected by the pion emission process. Various pion transitions of bottom baryons

into the lower ground states are summarized at the Figure 1. The mass predictions for the S -wave (i.e. ground state) Σ -like baryons show that there is enough phase space for the both Σ_b and Σ_b^* to decay into Λ_b^0 via single-pion emission. The two excited (P -wave) Λ_b^{*0} states might decay into Λ_b^0 via two-pion transitions provided a sufficient phase space.

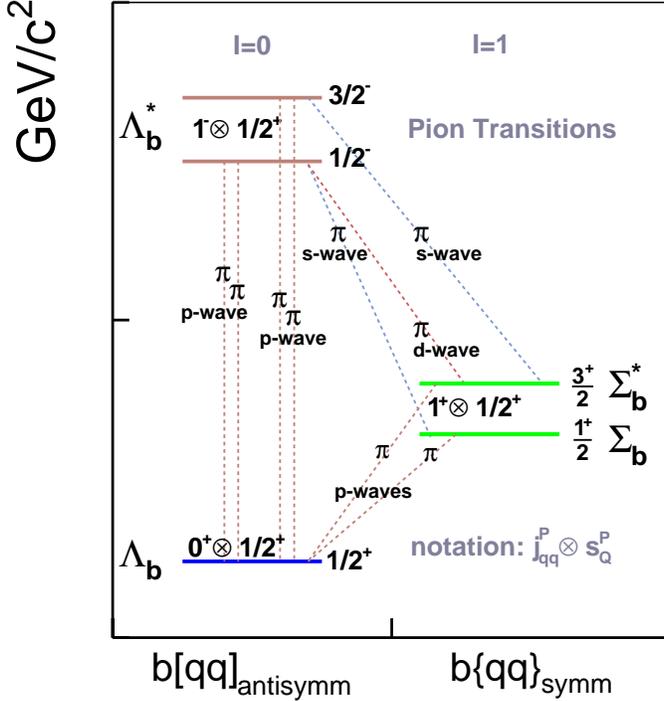


Figure 1. Transitions of ground states Σ_b , Σ_b^* into a low lying ground state Λ_b^0 via a single-pion emission in a P -wave as the diquark with $j_{qq} = 1^+$ is converted to one with $j_{qq} = 0^+$. If Λ_b^{*0} states have masses sufficiently higher than the decay thresholds, the two-pion transitions into Λ_b^0 or a single-pion decays into Σ_b or Σ_b^* states are possible (see also a discussion [7, 8, 9]). Λ_b^{*0} single-pion transitions to Λ_b^0 are forbidden due to isospin conservation and also by parity (for the higher $J^P = \frac{3}{2}^-$ state).

It is important for our experimental expectations to understand the natural width of $\Sigma_b^{(*)}$ baryons. As we expect that $\Sigma_b^{(*)}$ masses lie within $(180 - 210)$ MeV/ c^2 above Λ_b^0 and well above a threshold for a single-pion mode, we would expect that the single-pion P -wave transition will dominate the total width [15, 16]. The authors [16] find

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

where \vec{p}_π is the three-momentum of soft π_{Σ_Q} , $f_p \equiv g_A/f_\pi$, $f_\pi = 92$ MeV and g_A is the axial vector coupling of the constituent quark for the nucleon. A fit of this formula to the known PDG width measurements [17] of charm states Σ_c and Σ_c^* yields $g_A = 0.75 \pm 0.05$ which is in excellent agreement with $g_A = 0.75$ numerical theoretical value for the nucleon. Using the fit results we have estimated $\Gamma(\Sigma_b^{(*)})$, see the Table 2. The error of the fitted g_A contributes as a systematic uncertainty to our experimental measurements (see Section 5).

2. Principle of the Analysis

The topology of the event with $\Sigma_b^{(*)}$ state produced in Tevatron collisions is demonstrated in Figure 2. The $\Sigma_b^{(*)}$ candidates are searched in the decay chain²:

² Unless otherwise stated all references to the specific charge combination imply the charge conjugate combination as well.

- Strong decay $\Sigma_b^{(*)\pm} \rightarrow \Lambda_b^0 \pi_{\Sigma_b}^{\pm}$ with both $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ and its daughter $\Lambda_c^+ \rightarrow p K^- \pi^+$ in weak decay modes.

To remove a contribution due to a mass resolution of each Λ_b^0 candidate and to avoid absolute mass scale systematic uncertainties, the $\Sigma_b^{(*)\pm}$ candidates are reconstructed in the mass difference Q -value spectra defined as

$$Q = M(\Lambda_b^0 \pi_{\Sigma_b}^{\pm}) - M(\Lambda_b^0) - M_{\text{PDG}}(\pi^{\pm}).$$

The narrow signatures are searched for in the Q -spectrum constructed separately for every charge state of $\Sigma_b^{(*)\pm}$ candidates. The subsample of $\Sigma_b^{(*)-}$ contains $\Lambda_b^0 \pi^-$ and $\overline{\Lambda_b^0} \pi^+$ combinations from the decays of the particles $\Sigma_b^{(*)-}$ and the antiparticles $\overline{\Sigma_b^{(*)+}}$, respectively. The subsample of $\Sigma_b^{(*)+}$ contains $\Lambda_b^0 \pi^+$ and $\overline{\Lambda_b^0} \pi^-$ combinations from the decays of the particles $\Sigma_b^{(*)+}$ and the antiparticles $\overline{\Sigma_b^{(*)-}}$, respectively.

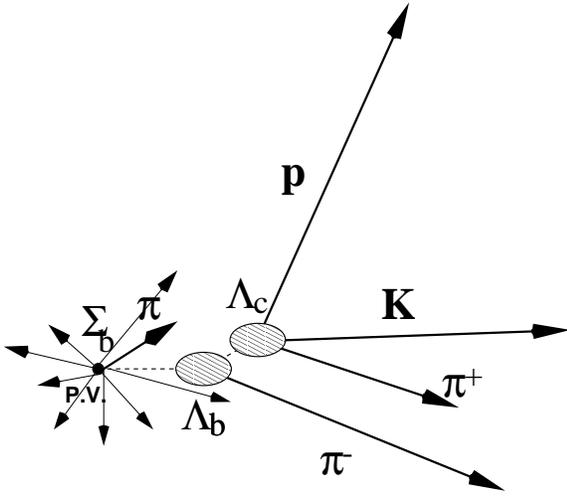


Figure 2. Sketch of the event topology of a Σ_b produced in the CDF detector [18]. The bottom baryon Σ_b is produced at the collision origin, i.e. primary vertex of the event. The Σ_b decays strongly into Λ_b^0 with soft $\pi_{\Sigma_b}^{\pm}$ emitted. Due to a fast nature of the strong decay the soft pion originates from the primary vertex. The Λ_b^0 and its daughter Λ_c^+ decay weakly with a secondary decay vertex measured in SVX II[19]. The tracks with a common secondary vertex are displaced relative to a primary vertex and the proton from Λ_c^+ decay and π^- from Λ_b^0 decay most likely contribute to the CDF hadron Two Track Trigger (see Section 3 and [20]).

The $\Sigma_b^{(*)\pm}$ signal region at Q -value spectrum is defined as $30 \text{ MeV}/c^2 \lesssim Q \lesssim 100 \text{ MeV}/c^2$, based on the theoretical expectation (see Table 2). We pursued a *blind analysis* and developed the $\Sigma_b^{(*)\pm}$ selection criteria using *only* the pure background sample in the upper and lower sideband regions of $0 \text{ MeV}/c^2 \lesssim Q \lesssim 30 \text{ MeV}/c^2$ and $100 \text{ MeV}/c^2 \lesssim Q \lesssim 500 \text{ MeV}/c^2$. The signal was modeled by a PYTHIA [21] Monte Carlo.

3. Triggers and Datasets

Our results are based on data collected with the CDF II detector [18] and corresponding to an integrated luminosity of $\sim 1.1 \text{ fb}^{-1}$. As $p\bar{p}$ collisions at 1.96 TeV have an enormous inelastic total cross-section of $\sim 60 \text{ mb}$, while b -hadron events comprise only $\approx 20 \text{ } \mu\text{b}$ ($|\eta| < 1.0$), triggers selecting b -hadron events are of vital importance. Our analysis is based on a data sample collected by a three-level Two displaced Track Trigger. It reconstructs a pair of high $p_T > 2.0 \text{ GeV}/c$ tracks at Level 1 with the CDF central tracker and enables secondary vertex selection at Level 2. This requires each of the tracks to have an impact parameter measured by the CDF silicon detector SVX II [19, 20] to be larger than $120 \text{ } \mu\text{m}$. The excellent impact parameter resolution of SVX II makes this challenging task possible. The trigger proceeds with a full event reconstruction at Level 3. The Two displaced Track Trigger is efficient for heavy quark hadron decay modes (see Figure 2 and its caption).

4. Event Selection

The candidates of the basic state in our analysis, Λ_b^0 , have been reconstructed in the mode $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ with $\Lambda_c^+ \rightarrow pK^- \pi^+$. The Two displaced Track Trigger requirements (see Section 3) are confirmed offline for each Λ_b^0 candidate. The Charm Λ_c^+ and bottom Λ_b^0 candidates have both been subjected to 3-dimensional vertex fits. The collection of the fitted Λ_c^+ candidates has been confined to a mass range of $m_{\Lambda_c^+}^{PDG} \pm 16 \text{ MeV}/c^2$ [17]. To suppress a prompt background we apply a cut on the proper decay time $c\tau(\Lambda_b^0) > 250 \mu\text{m}$ with its significance $c\tau(\Lambda_b^0)/\sigma_{c\tau} > 10$. The proper decay time of Λ_c^+ with respect to the Λ_b^0 vertex is required to be $-70 \mu\text{m} < c\tau(\Lambda_c^+ \leftarrow \Lambda_b^0) < 200 \mu\text{m}$. We define the topological quantities as $c\tau \equiv L_{xy} \cdot m_{\Lambda_Q}/p_T$ and $L_{xy} = \vec{D}_{xy} \cdot \vec{p}_T/p_T$ where \vec{D}_{xy}, \vec{p}_T are the vectors of corresponding distance or momentum in a transverse plane. To reduce combinatorial background and contribution from partially reconstructed modes the impact parameter $d_0(\Lambda_b^0)$ is also restricted to be below of $80 \mu\text{m}$, where $d_0 = |\vec{D}_{xy} \times \vec{p}_T/p_T|$. The kinematic cuts for Λ_b^0 and Λ_c^+ candidates, $p_T(\Lambda_b^0) > 6.0 \text{ GeV}/c$ and $p_T(\Lambda_c^+) > 4.5 \text{ GeV}/c$ are applied as well.

The powerful $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ signal is shown in Figure 3 with a binned maximum likelihood fit superimposed. The background from physical states contributing to the left side of the signal is analyzed with Monte Carlo simulations. The fit to the invariant $\Lambda_c^+ \pi^-$ mass distribution yields $3125 \pm 62(\text{stat})$ of $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ candidates. We possess the world's largest Λ_b^0 sample.

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

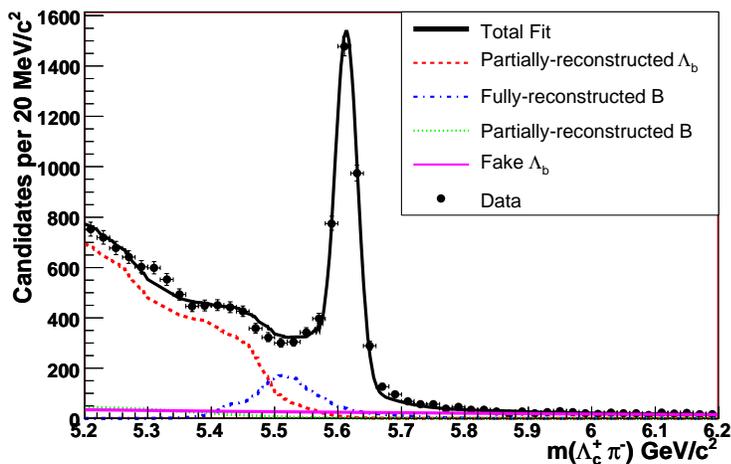


Figure 3. Fit to the invariant mass of $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ candidates. Fully reconstructed Λ_b^0 decays such as $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ and $\Lambda_b^0 \rightarrow \Lambda_c^+ K^-$ are not indicated on the figure. The Λ_b^0 signal region, $5.565 \text{ GeV}/c^2 < m(\Lambda_c^+ \pi^-) < 5.670 \text{ GeV}/c^2$, consists primarily of Λ_b^0 baryons, with some contamination from B mesons and combinatorial events. The left side band is enriched by partially reconstructed Λ_b^0 decays like $\Lambda_b^0 \rightarrow \Lambda_c^{*+} \pi^-$ and by fully reconstructed 4-prong B -meson decays like $B^0 \rightarrow D^+ \pi^-, D^+ \rightarrow K^- \pi^+ \pi^+$. The right side band consists from a combinatorial background.

5. Σ_b Candidates and Signals

Following a method outlined in a Section 2 the Λ_b^0 candidates (see a Section 4) from a signal region of $[5.565, 5.670] \text{ GeV}/c^2$ have been coupled with the pion tracks $\pi_{\Sigma_b}^\pm$ to create $\Sigma_b^{(*)\pm}$ candidates and the pairs $\Lambda_b^0 \pi_{\Sigma_b}^\pm$ have been subjected to a common vertex fit.

The $\Sigma_b^{(*)}$ analysis cuts are optimized according to a *blind analysis* technique using the upper and lower sideband regions (see a Section 4) of experimental Q -value spectrum while the signal is modeled by a PYTHIA [21]. The following kinematic and topological variables are used: $p_T(\Sigma_b)$, the soft pion track impact parameter significance $|d_0/\sigma_{d_0}|(\pi_{\Sigma_b})$, and the polar angle of the soft pion in a Σ_b -rest frame, $\cos \theta^*(\pi_{\Sigma_b}) = \vec{p}_{\Sigma_b} \cdot \vec{p}_\pi^*/(|\vec{p}_{\Sigma_b}| \cdot |\vec{p}_\pi^*|)$. A figure of merit is defined as $\epsilon(S_{MC})/\sqrt{B}$, where $\epsilon(S_{MC})$ is the signal efficiency measured in the Monte Carlo sample and

B is the background in the signal region estimated from the upper and lower sidebands. The maximum of the figure of merit is reached for $p_T(\Sigma_b) > 9.5 \text{ GeV}/c$, $|d_0/\sigma_{d_0}|(\pi_{\Sigma_b}) < 3.0$, and $\cos \theta^* > -0.35$.

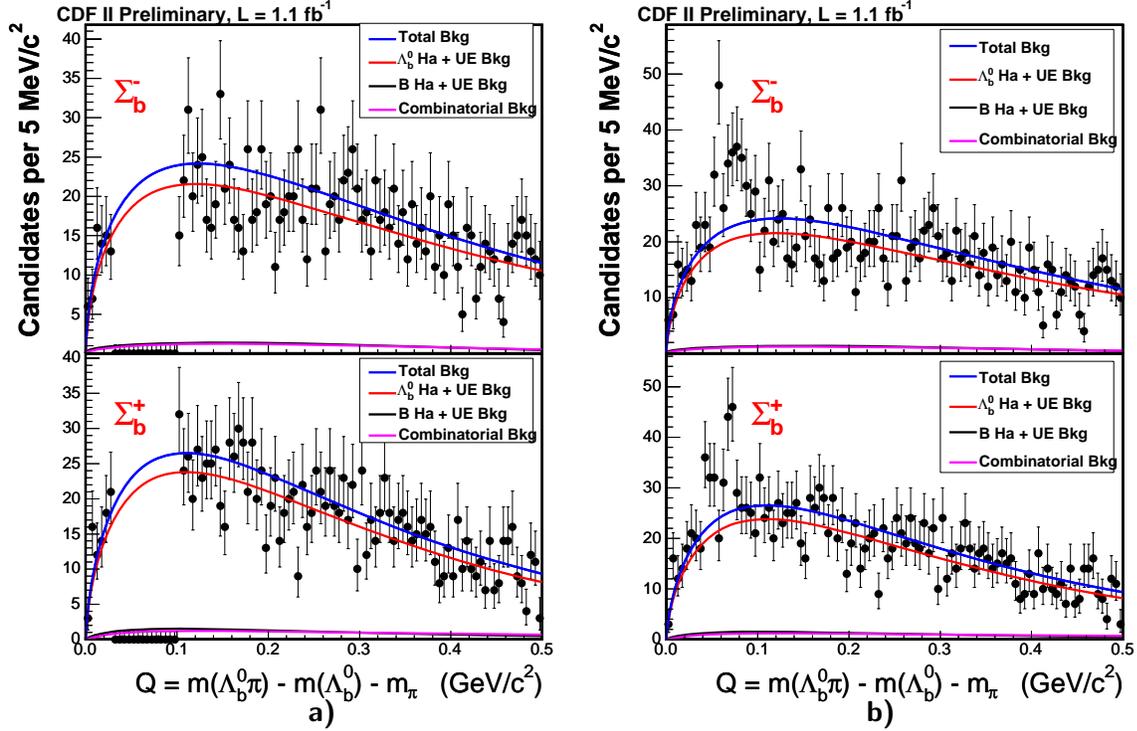


Figure 4. a) The three background sources described in the text and their sum are shown superimposed on the Q distributions, with the signal region blinded. The top plot shows the $\Lambda_b^0 \pi_{\Sigma_b^-}$ distribution, which contains all Σ_b^- . The bottom plot shows the $\Lambda_b^0 \pi_{\Sigma_b^+}$ distribution, with all Σ_b^+ . The sideband regions are parameterized with a power law multiplied by an exponential. The percentage of each background component in the Λ_b^0 signal region is computed from the Λ_b^0 mass fit (see Figure 3), and is: $N(\Lambda_b^0) \approx 90.1\%$, $N(B) \approx 6.3\%$ and $N(\text{combinatorial}) \approx 3.6\%$; b) The excess in the $\Lambda_b^0 \pi_{\Sigma_b^-}$ (top plot) subsample is 148 candidates over 268 expected background candidates, whereas in the $\Lambda_b^0 \pi_{\Sigma_b^+}$ (bottom plot) subsample the excess is 108 over 298 expected background candidates.

The Q -value spectra with blinded signal region are shown in Figure 4a with its detailed caption. In the $\Sigma_b^{(*)}$ search, the dominant background is from the combination of prompt Λ_b^0 baryons with extra tracks produced in the hadronization process. The remaining backgrounds are from the combination of hadronization tracks with B mesons reconstructed as Λ_b^0 baryons, and from combinatorial background events.

Upon unblinding the Q signal region in both spectra we observe an excess of events over the background as shown in Figure 4b with the details explained in the caption.

Next we perform a simultaneous unbinned maximum likelihood fit to the $\Lambda_b^0 \pi_{\Sigma_b^-}$ and $\Lambda_b^0 \pi_{\Sigma_b^+}$ subsamples for a signal from each expected $\Sigma_b^{(*)\pm}$ state plus the background, referred to as the “four signal hypothesis.” Each signal consists of a Breit-Wigner distribution convoluted with two Gaussian distributions describing the detector resolution, with a dominant narrow core and a small broad component for the tails. The natural width of each Breit-Wigner distribution is computed from the central Q -value (see a Section 1 and [16]). The fit shown in Figure 5 results in the yields $N_{\Sigma_b^+} = 33_{-12}^{+13}$, $N_{\Sigma_b^-} = 62_{-14}^{+15}$, $N_{\Sigma_b^{*+}} = 82 \pm 17$,

and $N_{\Sigma_b^{*-}} = 79 \pm 18$ candidates, with the signals located at $Q_{\Sigma_b^+} = 48.2^{+1.9}_{-2.2}$ MeV/ c^2 , $Q_{\Sigma_b^-} = 55.9^{+1.0}_{-0.9}$ MeV/ c^2 , and $\Delta_{\Sigma_b^*} = 21.5^{+2.0}_{-1.8}$ MeV/ c^2 , where $\Delta_{\Sigma_b^*} \equiv (Q_{\Sigma_b^*} - Q_{\Sigma_b})$.

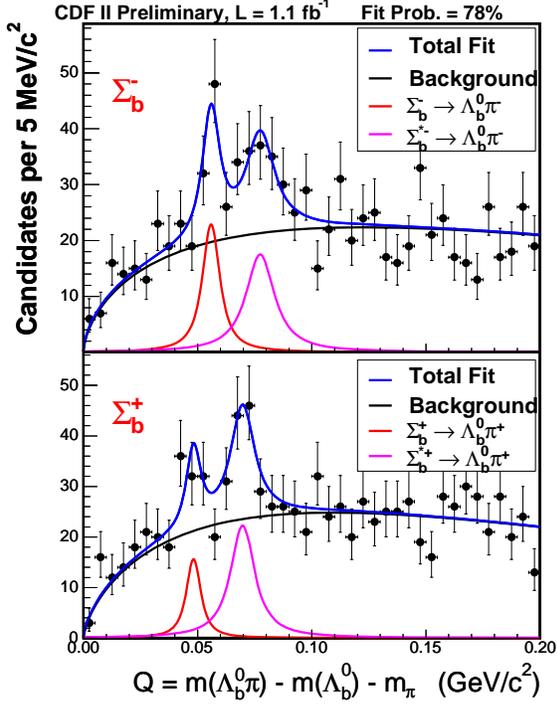


Figure 5. Simultaneous fit to the $\Lambda_b^0 \pi_{\Sigma_b^-}$ (top) and $\Lambda_b^0 \pi_{\Sigma_b^+}$ (bottom) spectra for $\Sigma_b^{(*)\mp}$ candidates shown on a range of $Q \in [0, 200]$ MeV/ c^2 .

Systematic uncertainties on the mass difference and yield measurements fall into three categories: mass scale, $\Sigma_b^{(*)\pm}$ background model, and $\Sigma_b^{(*)\pm}$ signal parameterization. The mass scale is determined from the difference in the mean of the narrow resonances $m(D^{*+}) - m(D^0)$, $m(\Sigma_c^{0,++}) - m(\Lambda_c^+)$, $m(\Lambda_c(2625)^+) - m(\Lambda_c^+)$ between data and PDG[17]. The uncertainties on the background come from the assumption on the sample composition of the Λ_b^0 signal region, the normalization and functional form of the Λ_b^0 hadronization background. The systematic effects related to assumptions made on the $\Sigma_b^{(*)\pm}$ signal parameterization are: underestimation of the detector resolution in Monte Carlo, the accuracy of the natural width prediction from [16], and the fit constraint that $(Q_{\Sigma_b^{*+}} - Q_{\Sigma_b^+}) = (Q_{\Sigma_b^{*-}} - Q_{\Sigma_b^-})$ [14]. All systematic uncertainties on the $Q_{\Sigma_b^{(*)\pm}}$ mass difference measurements are small compared to the statistical uncertainties. The final results [22] for the signal yields, including systematic errors, are $N_{\Sigma_b^+} = 33^{+13}_{-12}$ (stat.) $^{+5}_{-3}$ (syst.), $N_{\Sigma_b^-} = 62^{+15}_{-14}$ (stat.) $^{+9}_{-4}$ (syst.), $N_{\Sigma_b^{*+}} = 82^{+17}_{-17}$ (stat.) $^{+10}_{-6}$ (syst.), and $N_{\Sigma_b^{*-}} = 79^{+18}_{-18}$ (stat.) $^{+16}_{-5}$ (syst.). The final results [22] for the masses are $Q_{\Sigma_b^+} = 48.2^{+1.9}_{-2.2}$ (stat.) $^{+0.1}_{-0.2}$ (syst.) MeV/ c^2 , $Q_{\Sigma_b^-} = 55.9^{+1.0}_{-0.9}$ (stat.) $^{+0.1}_{-0.1}$ (syst.) MeV/ c^2 , and $\Delta_{\Sigma_b^*} = 21.5^{+2.0}_{-1.9}$ (stat.) $^{+0.4}_{-0.3}$ (syst.) MeV/ c^2 . Using the CDF II measurement of $m_{\Lambda_b^0} = 5619.7 \pm 1.2$ (stat.) ± 1.2 (syst.) MeV/ c^2 [23], the masses of the four states are [22]:

$m_{\Sigma_b^+} = 5807.5^{+1.9}_{-2.2}$ (stat.) ± 1.7 (syst.) MeV/ c^2 , $m_{\Sigma_b^-} = 5815.2^{+1.0}_{-0.9}$ (stat.) ± 1.7 (syst.) MeV/ c^2 , $m_{\Sigma_b^{*+}} = 5829.0^{+1.6}_{-1.7}$ (stat.) ± 1.7 (syst.) MeV/ c^2 , $m_{\Sigma_b^{*-}} = 5836.7^{+2.0}_{-1.8}$ (stat.) ± 1.7 (syst.) MeV/ c^2 , where the systematic uncertainties are now dominated by the total Λ_b^0 mass uncertainty.

Table 3. Likelihood ratios calculated for the alternative signal hypothesis with respect to the one of four $\Sigma_b^{(*)\pm}$ states. The strength of the signal hypothesis is further given by the likelihood ratio, $LR \equiv L/L_{\text{alt}}$, where L is the likelihood of the four signal hypothesis and L_{alt} is the likelihood of an alternate hypothesis.

| Hypothesis | LR |
|---------------------------|----------------------|
| Null | 2.6×10^{19} |
| Two Σ_b States | 1.6×10^6 |
| No Σ_b^- Signal | 3.3×10^4 |
| No Σ_b^+ Signal | 3 |
| No Σ_b^{*-} Signal | 2.4×10^4 |
| No Σ_b^{*+} Signal | 1.8×10^4 |

The alternative hypothesis is estimated using all systematic variations of the background and signal functions. The variation with the largest value of L_{alt} corresponding to the least favorable hypothesis is taken.

The significance of the signal is evaluated with two methods: using statistical Monte-Carlo pseudo-experiments and comparing the likelihoods of the default four signal hypothesis with pessimistic alternate ones. The randomly generated background samples are fit with the four signal hypothesis. The probability for background to produce the observed experimental number of signal events or more is found to be less than 8.5×10^{-8} , corresponding to a significance of greater than 5.2σ . The results on study of likelihood ratios are summarized in a Table 3 and its detailed caption.

6. Conclusions

In summary, using a sample of $\sim 3100 \Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ candidates reconstructed in 1.1 fb $^{-1}$ of CDF II data, we search for resonant $\Lambda_b^0 \pi^\pm$ states. We observe a significant signal of four states whose masses and widths are consistent with those expected for the lowest-lying charged $\Sigma_b^{(*)}$ baryons: Σ_b^+ , Σ_b^- , Σ_b^{*+} and Σ_b^{*-} . This result represents the first observation of the $\Sigma_b^{(*)}$ baryons.

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