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OBSERVATION OF THE Σ_b BARYONS AT CDF

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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 8.3×10^{-8}, corresponding to a significance of greater than 5.2 σ. 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 μb ($|\eta| < 1.0$),[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 Λ_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 Λ_b^0, the two tracks which satisfy the requirements are primarily the pion from the Λ_b^0 decay and the proton from the Λ_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 ± 60 (stat.) $\Lambda_b^0 \to \Lambda_c^+\pi^-$ candidates. The reconstructed Λ_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 Λ_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 Σ_b baryons, the two light quarks are in a flavor symmetric diquark state, leading to a doublet of baryons with $J^P = \frac{1}{2}^+$ (Σ_b) and $J^P = \frac{3}{2}^+$ (Σ_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 Σ_b and Σ_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 Σ_b, where Σ_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 Λ_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 Λ_b^0 candidate is combined with a prompt pion, as the Σ_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 Σ_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 Σ_b Q distribution are tracks from the hadronization of prompt Λ_b^0 baryons and B mesons reconstructed as Λ_b^0 baryons, and combinatorial background. The percentage of each background source in the Σ_b Q distribution is fixed from the Λ_b^0 invariant mass fit shown in Fig. 1, which is 89.4% Λ_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 Λ_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 Λ_b^0 hadronization tracks, is obtained from a Λ_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 Σ_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 Σ_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 Σ_b signal hypothesis and L_{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 8.3×10^{-8}, corresponding to a signal significance of greater than 5.2 σ.

The subsamples are modeled with a simultaneous unbinned maximum likelihood fit comprising a signal for each expected Σ_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 Σ_b signal fit to data, which has a χ^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 Λ_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.) ± 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 Σ_b baryons, and the observed properties are in agreement with theoretical predictions. Using the CDF II measurement[6] of m(Λ_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 Σ_b baryons.

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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 η is defined as $\tanh^{-1}(\cos\theta)$. Transverse momentum, p_{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).

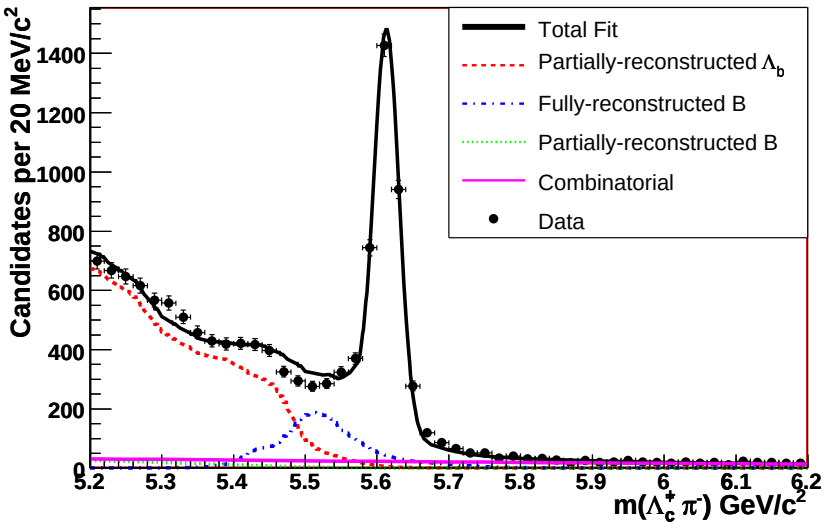

Figure 1: Unbinned maximum likelihood fit to the reconstructed invariant mass of $\Lambda_b^0 \to \Lambda_c^+\pi^-$ candidates. The fully reconstructed Λ_b^0 modes (such as $\Lambda_b^0 \to \Lambda_c^+\pi^-$ and $\Lambda_b^0 \to \Lambda_c^+K^-$) are not shown separately on the figure.

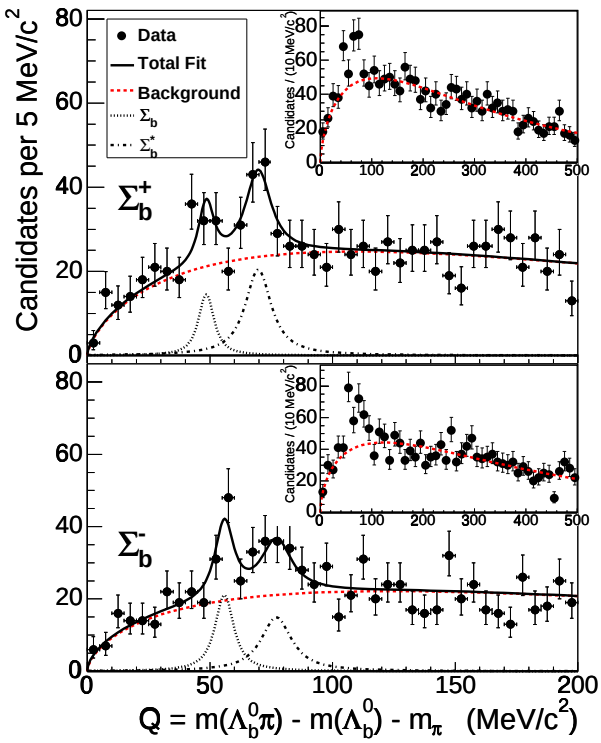

Figure 2: Unbinned maximum likelihood fit to the Σ_b Q distributions. The top plot shows the $\Lambda_b^0\pi^+$ combinations, while the bottom plot shows the $\Lambda_b^0\pi^-$ combinations. The insets show the expected background plotted on the data for $Q \in [0, 500]$ MeV/c^2, while the Σ_b signal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