First Observation of 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 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 $\Lambda_c^+ \to pK^-\pi^+$. We interpret these states as the $(\Sigma_b^{(*)}\pm)$ baryons and measure their masses to be:

$m_{\Sigma_b^{(*)}} = 5807.8^{+2.0}_{-2.2}$ (stat.) $\pm 1.7$ (syst.) MeV/$c^2$  
$m_{\Sigma_c^+} = 5829.0^{+1.6}_{-1.8}$ (stat.) $^{+1.7}_{-1.8}$ (syst.) MeV/$c^2$  
$m_{\Sigma_c^-} = 5815.2 \pm 1.0$ (stat.) $\pm 1.7$ (syst.) MeV/$c^2$  
$m_{\Sigma_c^0} = 5836.4 \pm 2.0$ (stat.) $^{+1.7}_{-1.8}$ (syst.) 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 $Λ^0_b$ baryons, which consist of the $u$, $d$, and $b$ quarks, with $3180 \pm 60$ (stat.) $Λ^0_b \to Λ^+_c π^−$ candidates. This is made possible by the large $b\bar{b}$ production cross-section in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ 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 $Λ^0_b π^\pm$ resonances, where $Λ^0_b \to Λ^+_c π^−$ and $Λ^+_c \to pK^− π^+$, using 1.1 fb$^{-1}$ of data. The $Λ^0_b π$ states are interpreted as the lowest-lying charged $Σ_b$ baryons and will be labeled $Σ_b^{(*)}$. The symbol $Σ_b$ refers to $Σ_b^−$, while $Σ_b^+$ refers to $Σ_b^{+*}$. Unless otherwise noted, any reference to a specific charge state implies the antiparticle state as well.

The $Σ_b^{(+)}$ baryons contain one $b$ and two $u$ quarks, while the $Σ_b^{(-)}$ baryons contain one $b$ and two $d$ quarks; these states are expected to exist but have not been observed. 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 $Σ_b^{(*)}$ states, the diquark system has strong isospin $I = 1$ and $J^P = 1^+$, which couples to the heavy quark spin and results in a doublet of baryons with $J^P = \frac{3}{2}^+$ (Σ$b^+$) and $J^P = \frac{1}{2}^+$ (Σ$b^0$). 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 $Σ_b^{(-)}$ and $Σ_b^{(+)}$ states.

Single gluon exchanges between the heavy quark and the light diquark system determine the spectroscopic properties of baryons [2]. There exists a variety of predictions for the $Σ_b^{(*)}$ masses from non-relativistic and relativistic potential quark models [3], 1/$N_c$ expansion [4], quark models in the HQET approximation [5], sum rules [6], and lattice quantum chromodynamics calculations [7]. On the basis of [3–7], we expect $m(Σ_b^0) - m(Λ^0_b) \sim 180 - 210$ MeV/c$^2$, $m(Σ_b^+) - m(Σ_b^0) \sim 10 - 40$ MeV/c$^2$, and $m(Σ_b^{(*)}) - m(Σ_b^{(*)}) \sim 5 - 7$ MeV/c$^2$. The difference between the isospin mass splittings of the $Σ_b^0$ and $Σ_b^+$ multiplets is predicted to be $|m(Σ_b^{(*)}) - m(Σ_b^{(*)})| = 0.40 \pm 0.07$ MeV/c$^2$ [8].

The natural width of $Σ_b^{(*)}$ baryons is expected to be dominated by the P-wave one pion transition $Σ_b^{(*)} \to Λ^0_b π$, whose partial width depends on the available phase space and the pion coupling to a constituent quark. For the range of predicted $Σ_b^{(*)}$ masses, the natural widths $Γ(Σ_b^{(*)})$ calculated from an HQET prediction vary between 2 and 20 MeV/c$^2$ [9].

The CDF II detector is described in detail elsewhere [10]. Its components and capabilities most relevant to this analysis are the tracking system and the ability to select displaced tracks from heavy flavor decays. The tracking system lies within a uniform axial magnetic field of 1.4 T. The inner tracking volume, with radii between 2.5 and 28 cm from the beam line, is occupied by a system of double-sided silicon microstrip detectors [11]. An additional layer of single-sided silicon microstrip detectors is mounted directly on the beampipe at an average radius of 1.5 cm. The remainder of the tracking volume is occupied by a cylindrical drift chamber [12], with a radial extent of 40 to 137 cm.

A displaced track trigger is employed to select bottom and charmed hadrons [13]. This trigger requires a pair of tracks with opposite charge, identified in the transverse view [14]. The tracks must have impact parameters $d_0$ which fall within the range $|d_0| \in [0.12, 1.00]$ mm, where $d_0$ is defined as the distance of closest approach of the track to the primary vertex in the transverse plane [15]. Each track is required to have transverse momentum $p_T > 2.0$ GeV/c. The scalar sum of the tracks’ transverse momenta must exceed 5.5 GeV/c and the azimuthal angle between the tracks is required to be within the range $2^\circ - 90^\circ$. In addition, the intersection point of the triggered tracks is required to have a transverse displacement of at least 200 μm with respect to the beam line.

In reconstructing the decays $Λ^0_b \to Λ^+_c π^−$ and $Λ^+_c \to pK^− π^+$, the proton from the $Λ^+_c$ decay and the $π^−$ from the $Λ^0_b$ decay are most likely to satisfy the displaced track trigger requirements. Therefore, we require that both must have $p_T > 2$ GeV/c, while the $K^−$ and $π^+$ candidates have $p_T > 0.5$ GeV/c to ensure well-understood tracking efficiency. We also require $p_T(p) > p_T(π^+) \times 10^{-5}$ to suppress $Λ^+_c$ 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 $Λ^+_c$ daughter tracks are constrained to originate from a single point. The $Λ^+_c$ candidate is constrained to the known $Λ^+_c$ mass, and the $Λ^+_c$ momentum vector is extrapolated to intersect the $π^−$ momentum vector to form the $Λ^0_b$ vertex. The probability of the 3-D $Λ^0_b$ kinematic vertex fit must exceed 0.1%, and the $Λ^+_c$ and $Λ^0_b$ must have $p_T$ greater than 4.5 and 6.0 GeV/c, respectively. To suppress prompt backgrounds from the primary interaction, we make the following decay time requirements: $ct(Λ^0_b) > 250$ μm and its significance $ct(Λ^0_b)/σ_{ct} > 10$. 

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We define \( ct(L_0^0) = L_0^0 \times 2c/p_T(L_0^0) \) as the \( L_0^0 \) proper time, where \( L_0^0 \) is defined as the length of the projection, onto the two-track momentum vector, of the transverse plane vector from the primary vertex to the \( L_0^0 \) vertex. 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 \( |d_0(L_0^0)| < 80 \mu m \), where \( d_0(L_0^0) \) is the impact parameter of the \( L_0^0 \) candidate. To suppress the contributions from \( B^0 \to \pi^+ \pi^- \) decays, we require \( m(pK^-\pi^+) \) to be within 16 MeV/c\(^2\) of the known \( \Lambda_c^+ \) mass [16], and \( ct(\Lambda_c^+) \in [-70,200] \mu m \). We define \( ct(\Lambda_c^+) = L_0^0 \times 2c/p_T(\Lambda_c^+) \) as the \( \Lambda_c^+ \) proper time, where \( L_0^0 \) is defined as the length of the projection, onto the three-track momentum vector, of the transverse plane vector from the \( L_0^0 \) vertex to the \( \Lambda_c^+ \) vertex.

The invariant mass distribution of \( \Lambda_c^+ \pi^- \) candidates is shown in Fig. 1 overlaid with a binned maximum likelihood fit. A clear \( L_0^0 \to \Lambda_c^+ \pi^- \) signal is observed at the expected \( L_0^0 \) mass. The invariant mass distribution is described by several components: the \( L_0^0 \to \Lambda_c^+ \pi^- \) signal, a combinatorial background, partially and fully reconstructed \( B \) mesons which pass the \( \Lambda_c^+ \pi^- \) selection criteria, partially reconstructed \( L_0^0 \) decays, and fully reconstructed \( L_0^0 \) decays other than \( \Lambda_c^+ \pi^- \) (e.g. \( L_0^0 \to K^-\pi^+ \)). 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 [17, 18]. Within the \( L_0^0 \) baryon and \( B \) meson groups of shapes, the normalizations are constrained by Gaussian terms to branching ratios that are either measured (for \( B \) meson decays) or theoretical predictions (for \( L_0^0 \) decays). The branching ratios of many yet-unobserved \( L_0^0 \) decay modes are extrapolated from \( B(\Lambda_0 \to \Lambda_c^+ \pi^-) \) [19] and \( B(\Lambda_0 \to \Lambda_c^+ \pi^-) \) [20] using the ratios of branching ratios in analogous \( B \) decays [16]; factorization is assumed in two-body \( b \to c \) decays of \( L_0^0 \). In the fit, the \( L_0^0 \) components are normalized relative to the \( L_0^0 \to \Lambda_c^+ \pi^- \) signal. To normalize the \( B \) meson components, we explicitly reconstruct a \( B^0 \to (K^-\pi^+\pi^-)\pi^- \) signal in the \( \Lambda_c^+ \pi^- \) sample by replacing the proton mass hypothesis with the pion mass hypothesis. The yield is \( N_{B^{0}} = 774 \pm 72 \) (stat.) events. We scale this number by the ratio of all \( B \) decays into four tracks observed in the MC simulation to the subset which results in a \( (K^-\pi^+\pi^-)\pi^- \) signature; this ratio is found to be 1.75 [16]. The fit to the invariant \( \Lambda_c^+ \pi^- \) mass distribution results in \( 3180 \pm 60 \) (stat.) \( L_0^0 \to \Lambda_c^+ \pi^- \) candidates.

The reconstruction of \( \Sigma_c^{(*)} \) proceeds by combining \( L_0^0 \) candidates in the \( \Lambda_0^0 \) signal region with all remaining high quality tracks. A pion mass hypothesis is used when computing the invariant mass of the \( \Sigma_c^{(*)} \) candidate. To minimize the contribution of the mass resolution of each \( L_0^0 \) candidate, we search for narrow resonances in the mass difference distribution of \( Q = m(\Lambda_0^0 \pi^-) - m(\Lambda_0^0) - m_{\pi} \). The \( \Sigma_c^{(*)} \) candidates are divided into two subsamples using the charge of the pion from \( \Sigma_b^{(*)} \) decay, denoted by \( \pi_{\Sigma_b} \); in the \( \Lambda_0^0 \) signal region, \( L_0^0 \) has the same charge as the pion from \( \Lambda_0^0 \), while in the \( L_0^0 \) sample the \( \pi_{\Sigma_b} \) has the opposite charge as the pion from \( \Lambda_0^0 \).

On the basis of the theoretical predictions in [3-7], the \( \Sigma_c^{(*)} \) signal region is defined as \( Q \in [30,100] \) MeV/c\(^2\). We optimize the \( \Sigma_c^{(*)} \) selection criteria using the pure background sample in 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. The signal is modeled by the Pythia [21] event generator where only the decays \( \Sigma_c^{(*)} \to \Lambda_0^0 \pi^- \pi^- \), \( \Lambda_0^0 \to \Lambda_c^+ \pi^- \), and \( \Lambda_c^+ \to pK^-\pi^+ \) are allowed. For the optimization, we combine the \( \Lambda_c^+ \pi^- \) and \( \Lambda_0^0 \pi^- \) subsamples. We 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 \( \Sigma_c^{(*)} \) momentum in the lab frame. In this optimization, we maximize \( \epsilon(S_{MC})/\sqrt{B} \), 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 sidebands. 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 \( \Lambda_0^0 \) 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 $\Lambda^0_b$ baryons, and from combinatorial background events. The percentage of each background component in the $\Lambda^0_b$ signal region, computed from the $\Lambda^0_b$ mass fit, is (89.5 ± 1.7)% $\Lambda^0_b$ baryons, (7.2 ± 0.6)% $B$ mesons, and (3.3 ± 0.1)% combinatorial events. Other backgrounds such as 5-track decays of $B^+$ mesons are negligible, as confirmed in inclusive single $b$ hadron simulations [17, 18].

The high mass region above the $\Lambda^0_b \rightarrow \Lambda^+_c \pi^-$ signal in Fig. 1 determines the combinatorial background. Reconstructing $B^0 \rightarrow D^+ \pi^-$ data as $\Lambda^0_b \rightarrow \Lambda^+_c \pi^-$ gives the $B$ hadronization background. The $\Lambda^0_b$ hadronization background is obtained from a $\Lambda^0_b \rightarrow \Lambda^+_c \pi^-$ PYTHIA simulation.

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The events in this simulation are reweighted so that the $p_T(\Lambda^0_b)$ distribution agrees with data. As the simulation has fewer low momentum tracks around the $\Lambda^0_b$ than found in data, the simulated events are further reweighted until the $p_T$ spectrum of tracks around the $\Lambda^0_b$ is consistent with data. After establishing the shape and normalization of each background $Q$ distribution, the background shapes are parameterized by a power law multiplied by an exponential. The total background shape shown in Fig. 2 (inset) is compatible with the $Q$ sidebands and is a fixed component in the $\Sigma^b_0$ 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 $\Lambda^0_b \pi^-$ subsample is $118$ over $288$ expected background candidates. In the $\Lambda^0_b \pi^+$ subsample the excess is $91$ over $313$ expected background candidates.

We perform a simultaneous unbinned maximum likelihood fit to the $\Lambda^0_b \pi^-$ and $\Lambda^0_b \pi^+$ subsamples for a signal from each expected $\Sigma^b_0$ 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 [9].

The expected difference of the isospin mass splittings within the $\Sigma^b_0$ and $\Sigma_b$ multiplets is below our sensitivity with this sample of data. Consequently, we constrain $m(\Sigma^b_0^+)=m(\Sigma^b_0^-)=m(\Sigma^b_0^*)\equiv\Delta\Sigma_b$. 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 masses of the $D^*$, $\Sigma_c$, and $\Lambda^*_c$ hadrons from the world average mass values [16].

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 $\Lambda^0_b$ signal region, the normalization and functional form of the $\Lambda^0_b$ hadronization background taken from a PYTHIA simulation, and our limited knowledge of the shape of the $\Lambda^0_b$ 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 [9], and the constraint that $m(\Sigma_b^{(*)})-m(\Sigma_b^0)=m(\Sigma_b^{(*)})-m(\Sigma_b^-)$.

The significance of the signal is evaluated using the likelihood ratio, $LR \equiv L/L_{alt}$, where $L$ is the likelihood of the four signal hypothesis and $L_{alt}$ is the likelihood of an alternative hypothesis [22]. We study the alternate hypotheses of no signal, two $\Sigma_b$ states (one per $\Lambda^0_b \pi$ 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 Tab. I. To assess the significance of the signal, we repeat the four signal hypothesis fit on samples randomly generated from alternate signal hypotheses. In 12 million 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 Tab. I. The final results for the $\Sigma_b$ measurement are quoted in Tab. II. Using the CDF II measurement of $m_{\Lambda_b^0} = 5619.7 \pm 1.2$ (stat.) $\pm 1.2$ (syst.) MeV/c$^2$ [23], we find the absolute masses of the $\Lambda_b^0$ states given in Tab. II. The systematic uncertainties on the absolute $\Sigma_b$ mass values are dominated by the total $\Lambda_b^0$ mass uncertainty.

<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>$2.6 \times 10^{18} &lt; 8.3 \times 10^{-8}$</td>
<td>&gt; 5.2</td>
<td></td>
</tr>
<tr>
<td>Two $\Sigma_b$ States</td>
<td>$4.4 \times 10^{3}$</td>
<td>$9.2 \times 10^{-5}$</td>
<td>3.7</td>
</tr>
<tr>
<td>No $\Sigma_b^-$ Signal</td>
<td>$1.2 \times 10^{5}$</td>
<td>$3.2 \times 10^{-4}$</td>
<td>3.4</td>
</tr>
<tr>
<td>No $\Sigma_b^+$ Signal</td>
<td>$49$</td>
<td>$9.0 \times 10^{-3}$</td>
<td>2.4</td>
</tr>
<tr>
<td>No $\Sigma_b^{++}$ Signal</td>
<td>$4.9 \times 10^{4}$</td>
<td>$6.4 \times 10^{-4}$</td>
<td>3.2</td>
</tr>
<tr>
<td>No $\Sigma_b^{--}$ Signal</td>
<td>$8.1 \times 10^{4}$</td>
<td>$6.0 \times 10^{-4}$</td>
<td>3.2</td>
</tr>
</tbody>
</table>

**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.

<table>
<thead>
<tr>
<th>State</th>
<th>Yield</th>
<th>$Q$ or $\Delta m_\chi$ (MeV/c$^2$)</th>
<th>Mass (MeV/c$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Sigma_b^+$</td>
<td>39$\pm^{+13+9}_{-12-3}$</td>
<td>$Q_{\Sigma_b^+}$ = 48.5$^{+2.0+0.2}_{-2.2-0.3}$</td>
<td>5807.8$^{+2.0}_{-2.2} \pm 1.7$</td>
</tr>
<tr>
<td>$\Sigma_b^-$</td>
<td>59$\pm^{+15+9}_{-14-4}$</td>
<td>$Q_{\Sigma_b^-}$ = 55.9$\pm 1.0 \pm 0.2$</td>
<td>5815.2$\pm 1.0 \pm 1.7$</td>
</tr>
<tr>
<td>$\Sigma_b^+$</td>
<td>77$\pm^{+17+10}_{-16-6}$</td>
<td>$\Delta m_{\chi_b^+}$ = 21.2$\pm 2.0_{+0.4}$</td>
<td>5829.0$^{+1.8}_{-1.6} \pm 1.7$</td>
</tr>
<tr>
<td>$\Sigma_b^{--}$</td>
<td>69$\pm^{+18+16}_{-17-5}$</td>
<td>$\Delta m_{\chi_b^{--}}$ = 1.9$\pm 0.3$</td>
<td>5836.4$^{+2.0}_{-1.8} \pm 1.7$</td>
</tr>
</tbody>
</table>

**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 [23], which contributes to the systematic uncertainty.

In summary, using a sample of 3180 $\pm$ 60 (stat.) $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ candidates reconstructed in 1.1 fb$^{-1}$ of CDF II data, we search for resonant $\Lambda_b^0 \pi^\pm$ states. We observe a 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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[15] 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.


[17] 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 $p_T(A_{B}^{0})$ distribution is reweighted to match the sideband-subtracted data.


