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Evidence for Exclusive B Decays to Final States Containing a Charmed Baryon

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Abstract

Using data collected in the region of the $\Upsilon(4S)$ resonance with the CLEO II detector, we report on the first observation of exclusive decays of the B meson to final states with a charmed baryon. We have measured the branching fraction $\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-) = (0.187 \pm 0.059 \pm 0.056 \pm 0.045)\%$. In addition, we report upper limits for final states of the form $\overline{B} \to \Lambda_c^+ \overline{p}(n\pi)$ and $\Lambda_c^+ \overline{p}(n\pi)\pi^0$, where $(n\pi)$ denotes up to four charged pions.

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Inclusive production of the charmed baryon Λ_c^+ from the decay of B mesons was first reported by ARGUS [1] and confirmed by CLEO [2]. The branching fraction for $\overline{B} \to \Lambda_c^+ X$ was measured by CLEO to be $\mathcal{B}$=(6.4 ±1.1)%. The fraction of Λ_c^+ from Σ_c^{++} and Σ_c^0 in B decays has been measured by CLEO to be $\approx$ 16 % [3]. B decays to baryons are expected to be dominated by $b \to c\overline{u}d$ transitions which lead to final states of the form $\overline{B} \to \Theta_c \overline{N} X$ where $\Theta_c = \Lambda_c^+,\ \Sigma_c^0,\ \Sigma_c^+$, or Σ_c^{++} and $N = p,\ n$, or Δ. These decays can proceed via external, internal, and exchange diagrams, shown in Figure 1. Two body final states arise from internal and exchange diagrams. Exclusive reconstruction of B mesons to final states with Λ_c^+'s, previously unobserved, are essential in understanding the mechanism for baryon production in B decays. CLEO has studied the Λ_c^+ momentum spectrum in B decays and found that two body final states with Λ_c^+ are suppressed [4]. Theoretical predictions exist for a number of two body B meson decays to charmed baryons [5]. Theoretical calculations of the branching fraction for the process $B \to \Lambda_c^+ \overline{p}$ range from 0.04% to 0.19% while calculations for the branching fraction to the final state $B \to \Sigma_c^+ \overline{p}$ are in the range 0.15-0.30%. For $B \to \Sigma_c^+ \overline{\Delta^+}$, the branching fraction is calculated to be 0.4-2.9%. We present the results of our search for exclusive decays of $\bar{B}^0$ and B^- mesons into final states containing the charmed baryon Λ_c^+. Throughout this study the inclusion of the charge conjugate process is implied.

I. DATA SAMPLE AND SELECTION CRITERIA

This analysis is based on 2.04 fb^{-1} of data taken at the $\Upsilon(4S)$ resonance and 0.97 fb^{-1} at center-of-mass energies just below the threshold for producing B meson pairs, hereafter referred to as continuum. Assuming equal production of charged and neutral B mesons, there are a total of about 2,186,000 ± 39,000 charged and an equal number of neutral B mesons in this data sample. The data were collected with the CLEO II detector at the Cornell Electron Storage Ring (CESR). CLEO II is a general purpose solenoidal-magnet spectrometer and calorimeter with excellent charged particle and electromagnetic shower detection capabilities. A detailed description of the CLEO II detector has been given previously [6].

We reconstruct K_S^0 and Λ candidates from oppositely charged tracks which intersect in the plane transverse to the beam direction. In addition, the combined momentum vector of the two charged tracks is required to point back to the interaction region in three dimensions. A pair of charged tracks are identified as a $K_S^0(\Lambda)$ candidate if the invariant mass of the pair, when interpreted as $\pi^+\pi^-(p\pi^-)$, falls within 3σ of the nominal $K_S^0(\Lambda)$ mass. If the mass of the $K_S^0(\Lambda)$ candidate, when interpreted as $p\pi^-(\pi^+\pi^-)$, falls within the $\Lambda(K_S^0)$ mass region, we reject it. We form π^0 candidates from pairs of showers detected in the calorimeter which yield a $\gamma\gamma$ invariant mass within 2.5σ of the nominal π^0 mass. Photons used to form π^0's are required to have a minimum energy of 100 MeV, are not matched to a charged track from the drift chamber, and have a lateral energy distribution consistent with that expected for photons.

We combine the dE/dx measurements from the central drift chamber with time-of-flight information whenever it is available, to derive probabilities for each charged track to be consistent with either the pion, kaon or proton mass hypothesis. Primary charged tracks are defined as a proton or a kaon if the probability for the specific mass hypothesis is within 2σ of its expected value and it is at least 2σ away from that expected for the pion hypothesis.

TABLE I. Summary of inclusive B decays to Λ_c^+. We report the statistical errors only.

Decay Mode	Fitted Mass MeV/c^2	Fitted σ_m MeV/c^2	Raw Yields $\Upsilon(4S)$	Raw Yields Scaled Cont.	Raw Yields B Decays
$pK^-\pi^+$	2286 $\pm$0.2	5.5 $\pm$0.3	3235 $\pm$111	851 $\pm$98	2384 $\pm$148
pK_S^0	2287 $\pm$0.5	6.1 $\pm$0.5	773 $\pm$47	325 $\pm$49	448 $\pm$68
$\Lambda\pi^+$	2287 $\pm$0.8	6.9 $\pm$0.8	491 $\pm$46	231 $\pm$59	261 $\pm$75
	Total:		4499 $\pm$129	1407 $\pm$124	3093 $\pm$179

For pion and proton candidates from Λ's, we require the probabilities be within 3σ of their expected values. The efficiencies of the particle identification requirements are derived from data using pure samples of protons, kaons, and pions from the decays $\Lambda \to p\pi^-$, $D^{*+} \to D^0\pi^+$ with $D^0 \to K^-\pi^+$, and $K_S^0 \to \pi^+\pi^-$, respectively.

A. Λ_c^+ Selection

We form Λ_c^+ candidates in the decay modes $pK^-\pi^+$, pK_S^0 and $\Lambda\pi^+$ with $K_S^0 \to \pi^+\pi^-$ and $\Lambda \to p\pi^-$. The momentum of the Λ_c^+ candidate is required to be less than 2.3 GeV/c which is the kinematic limit for Λ_c^+'s from B meson decays. To suppress continuum background, the Fox-Wolfram event shape parameter R_2 [7] is required to be less than 0.35. We determine the number of Λ_c^+'s from the $\Upsilon(4S)$ data and the continuum data separately, with the continuum data scaled to account for the difference in luminosity and the $1/s$ dependence of the $e^+e^- \to q\overline{q}$ cross section. We subtract from the number of Λ_c^+ candidates in the $\Upsilon(4S)$ data the Λ_c^+ yield in the scaled continuum data to determine the number of Λ_c^+ candidates from B decays. In Figures 2(a),(b), and (c) we show the invariant mass distributions corresponding to $pK^-\pi^+$, pK_S^0 and $\Lambda\pi^+$combinations from the $\Upsilon(4S)$ and scaled continuum data. The results of the fits to the different decay modes are presented in Table I. We obtain a total of 3093 $\pm$179 Λ_c^+ candidates from B meson decay.

II. EXCLUSIVE B RECONSTRUCTION

We search for exclusive B decays by forming $\Lambda_c^+\overline{p}(n\pi)$ and $\Lambda_c^+\overline{p}(n\pi)\pi^0$ combinations, where $(n\pi)$ denotes up to four charged pions. Instead of the invariant mass distribution of the combinations, we plot the beam constrained mass defined as:

$$M_B^2 = E_{\mathrm{beam}}^2 - (\sum_i \vec{p}_i)^2,$$

where $\vec{p}_i$ is the 3-momentum vector for the i^{th} daughter of the B candidate. We have used E_{beam} instead of $\sum_i E_i$ since the energy of B mesons produced at the $\Upsilon(4S)$ must equal the beam energy. The resolution for the beam constrained mass is about 2.5 MeV/c^2, which is a factor of five better than the resolution of the invariant mass. This width is dominated by the spread of the CESR beam energy. For correctly reconstructed B mesons the measured sum of charged and neutral energies, $E_{\rm meas}$, must equal the beam energy within the experimental resolution. The energy difference, ΔE=$E_{\rm meas}$ - $E_{\rm beam}$, distribution is centered at zero with a Monte Carlo predicted width of 12 to 16 MeV, depending on the different final state being used. Major reduction of background from random combinations is achieved by using only those combinations for which $|\Delta E|$ is within 25 MeV, $\approx 2\sigma$. To study the background in the M_B distribution, we use the ΔE sidebands which we define as the region 4-6σ away from ΔE=0.

To further reduce continuum backgrounds we apply a sphericity angle cut. The sphericity angle Θ_S is defined as the angle between the major momentum axis of the particles which form the B candidate and the major momentum axis of the remaining particles in the event. Because the B's are produced nearly at rest, the two axes are uncorrelated for true $B\overline{B}$ events. For a jet-like continuum event, most events lie near $|\cos\Theta_S|= 1.0$. We require $|\cos\Theta_S| < 0.9$. Another strategy to reduce background is to cut on Θ_B, the polar angle of the B in the laboratory frame with respect to the e^+e^- axis. This distribution is proportional to $\sin^2\Theta_B$ for $e^+e^- \to\Upsilon(4S) \to B\overline{B}$, whereas background events are distributed nearly isotropically. We require $|\cos\Theta_B| < 0.7$.

If there is more than one B candidate in an event, for a given decay channel, we select the entry with the lowest χ^2,

$$\chi^2 = \left(\frac{\Delta E}{\sigma}\right)^2 + \left(\frac{\Delta M(\Lambda_c^+)}{\sigma}\right)^2$$

where ΔE is defined above and $\Delta M(\Lambda_c^+)$ is the Λ_c^+ candidate's mass compared to the known Λ_c^+ mass.

III. RESULTS

In Figure 3, we show the beam constrained mass distributions for $\bar{B}^0 \to \Lambda_c^+\bar{p}$, $B^- \to \Lambda_c^+\bar{p}\pi^-$, $B^- \to \Lambda_c^+\bar{p}\pi^-\pi^+\pi^-$ and $\bar{B}^0 \to \Lambda_c^+\bar{p}\pi^+\pi^-\pi^+\pi^-$ combinations. The corresponding mass distribution for the decay $\bar{B}^0 \to \Lambda_c^+\bar{p}\pi^+\pi^-$ is shown in Figure 4(a). Mass distributions for the $\bar{B}^0 \to \Lambda_c^+\bar{p}\pi^0$, $B^- \to \Lambda_c^+\bar{p}\pi^-\pi^0$, $\bar{B}^0 \to \Lambda_c^+\bar{p}\pi^+\pi^-\pi^0$ and $B^- \to \Lambda_c^+\bar{p}\pi^-\pi^+\pi^-\pi^0$ combinations are shown in Figure 5.

The yields of the signals are determined by fitting the beam constrained mass distributions to the sum of a background shape and a Gaussian with fixed width, σ = 2.5 MeV/c^2, and mean fixed at the nominal B-meson mass of 5.28 GeV/c^2. The background is fit with a functional form consisting of a straight line with parabolic kinematical cutoff [8]. The functional form is chosen to become parabolic 8 MeV/c^2 below the beam energy.

In the beam constrained mass distributions considered above, we see an excess of events in the B mass region for some of the channels. However, there is a statistically significant signal only in the $\bar{B}^0 \to \Lambda_c^+\bar{p}\pi^+\pi^-$ mode. A fit to this distribution yields a signal of 15.0$\pm$4.7 events. We have studied the background under the signal in several ways. The beam constrained mass distribution from combinations in the ΔE sidebands shows no enhancement in the signal region. Similar distributions made for combinations using Λ_c^+ mass sidebands, wrong-sign charge, and continuum data show no enhancement in the signal region. Distributions for

TABLE II. Branching ratio results for $\overline{B} \to \Lambda_c^+ \overline{p}(n\pi)$ and $\Lambda_c^+ \overline{p}(n\pi)\pi^0$

B Mode	Total # of events	$\mathcal{B}(\%)$ Average
$\bar{B}^0 \to \Lambda_c^+ \bar{p}$	< 2.3	$< 4.4 \times 10^{-2}$
$B^- \to \Lambda_c^+ \bar{p}\pi^-$	< 6.4	< 0.084
$\bar{B}^0 \to \Lambda_c^+ \bar{p}\pi^0$	< 2.3	< 0.076
$\bar{B}^0 \to \Lambda_c^+ \bar{p}\pi^+\pi^-$	15.0 ± 4.7	$0.187 \pm 0.059 \pm 0.056 \pm 0.045$
$B^- \to \Lambda_c^+ \bar{p}\pi^-\pi^0$	< 8.7	< 0.36
$B^- \to \Lambda_c^+ \bar{p}\pi^-\pi^+\pi^-$	< 14.7	< 0.55
$\bar{B}^0 \to \Lambda_c^+ \bar{p}\pi^+\pi^-\pi^0$	< 11.6	< 0.76
$\bar{B}^0 \to \Lambda_c^+ \bar{p}\pi^+\pi^-\pi^+\pi^-$	< 6.4	< 0.34
$B^- \to \Lambda_c^+ \bar{p}\pi^-\pi^+\pi^-\pi^0$	< 15.6	< 2.17

combinations from the ΔE sidebands, Λ_c^+ mass sidebands, and continuum data are displayed in Figures 4(b), (c) and (d) respectively. Combining the mass distributions corresponding to all charged pions in the final state gives a statistically significant enhancement in the B mass region, as shown in Figure 6(a). A fit to this distribution yields a combined signal of 25.7 ± 7.5 events. A similar combined distribution for final states containing a π^0 is shown in Figure 6(b). In these latter final states, the background is higher and there is a small enhancement at the B mass of 17 ± 9 events.

We have used the following Λ_c^+ branching fractions from the Review of Particle Properties [9]: $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = 0.032 \pm 0.007$, $\mathcal{B}(\Lambda_c^+ \to p\bar{K}^0) = 0.016 \pm 0.004$, and $\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+) = 0.0058 \pm 0.0016$. We measure the branching fraction to be,

$$\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{p}\pi^+\pi^-) = (0.187 \pm 0.059 \pm 0.056 \pm 0.045)\%,$$

where the first error is statistical, the second is systematic, and the third error is due to uncertainty in the Λ_c^+ branching fractions. Upper limits for the other modes are summarized in Table II.

IV. SYSTEMATIC STUDIES

We estimated the systematic errors in our analysis by studying the stability of our $\bar{B}^0 \to \Lambda_c^+ \bar{p}\pi^+\pi^-$ signal with respect to the applied cuts. The branching fraction dependence on kinematical and topological constraints was investigated by a wide variation of the ΔE, $\cos\Theta_B$ and $\cos\Theta_S$ requirements, and was found to be stable within statistical errors.

The systematic uncertainty associated with the functional form used to fit the B mass sideband was determined by studying its effect on signal yield for the $\bar{B}^0 \to \Lambda_c^+ \bar{p}\pi^+\pi^-$ mode and for the sum of the $B \to \Lambda_c^+ \bar{p}(n\pi)$ modes. Three types of background function were used, one being the background function described in the previous section. We also modeled the background using a phase-space line shape with kinematical cutoff at 5.29 GeV/c^2, as well as a flat distribution. These changes were found to produce an r.m.s. deviation on the number of signal events for $\bar{B}^0 \to \Lambda_c^+ \bar{p}\pi^+\pi^-$ of 0.3 events, or 2%, which we quote as the contribution to the overall uncertainty from background modeling.

TABLE III. Contributions to systematic error

Source	Error(%)
Luminosity	2
Background Shape	2
Uncertainty in # of Background Events	14
Tracking Efficiency	2% per charged track 5% per π^0
Λ_c^+ Branching fractions	22-28
$\cos\Theta_S$ topological requirement	10
$\cos\Theta_B$ topological requirement	3
Σ_c resonance substructure	7
Monte Carlo statistics	3-10
Particle Identification	4% per π 2% per p 5% per K

To estimate the systematic error associated with various backgrounds under the signal peak, we investigated the behavior of the beam constrained mass distribution for the $\bar{B}^0 \to \Lambda_c^+ \bar{p}\pi^+\pi^-$ mode after ΔE sideband subtraction. A fit to the sideband-subtracted B mass distribution results in a 14% change in signal yield. This percentage difference is adopted as the overall systematic uncertainty due to background contributions. The systematic uncertainty associated with the particle identification criteria has been determined to be 4% per π, 2% per proton, and 5% per K [10].

Other contributions to the overall systematic error arise from an uncertainty of 2% in the total number of $B\bar{B}$ pairs in our data sample, uncertainty in the tracking efficiency (2% per charged track and 5% per π^0), and the error on the Λ_c^+ branching ratios ($\approx 25\%$). We have assumed that $\bar{B}^0 \to \Lambda_c^+ \bar{p}\pi^-\pi^+$ proceeds via phase space decay. However, the reconstruction efficiency changes by 7% if we assume that up to 16% of the Λ_c^+'s come from Σ_c^{++} and Σ_c^0 [3]. Additional uncertainties are due to requirements on topological variables (3% for $\cos\Theta_B$, 10% for $\cos\Theta_S$), as well as statistical uncertainty associated with our Monte Carlo samples (3-10%). These contributions are summarized in Table III

V. CONCLUSIONS

We have observed decays of the B meson to final states containing a Λ_c^+. We measure the branching fraction $\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{p}\pi^-\pi^+) = (0.187 \pm 0.059 \pm 0.056 \pm 0.045)\%$, where the first error is statistical, the second systematic, and the third error is due to uncertainty in the Λ_c^+ branching fractions. For all other decay modes we report only upper limits. We see an enhanced signal in the sum of $B \to \Lambda_c^+ \bar{p}(n\pi)$ $(n = 0 - 4)$.

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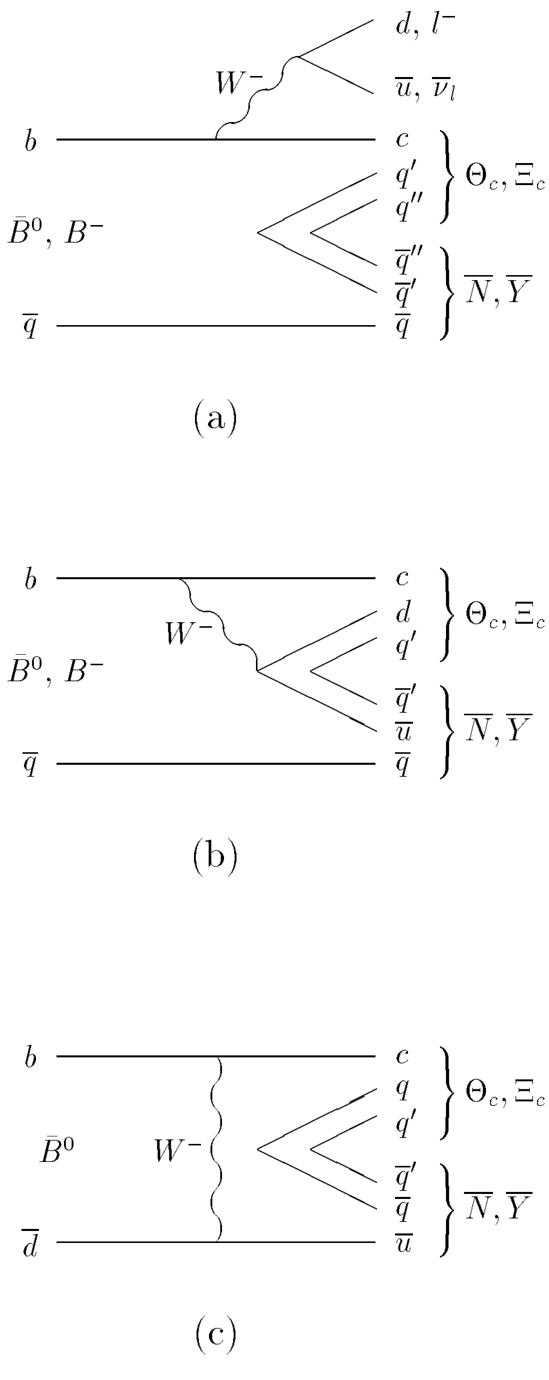

FIG. 1. Spectator decay diagrams for $B \to$ baryon resulting in decays of the form $\overline{B} \to \Theta_c \overline{N} x$ and $\Xi_c \overline{Y} x$, where $N = p,\ n,\ \Delta,\ N^*$, $Y = \Lambda,\ \Sigma^0,\ \Sigma^+,\ \Sigma^-$, $\Theta_c = \Lambda_c^+,\ \Sigma_c^0,\ \Sigma_c^+,\ \Sigma_c^{++}$ and $\Xi_c = \Xi_c^+,\ \Xi_c^0$ In (a) the external W-emission diagram is shown, (b) the internal W-emission and (c) the W-exchange diagram.

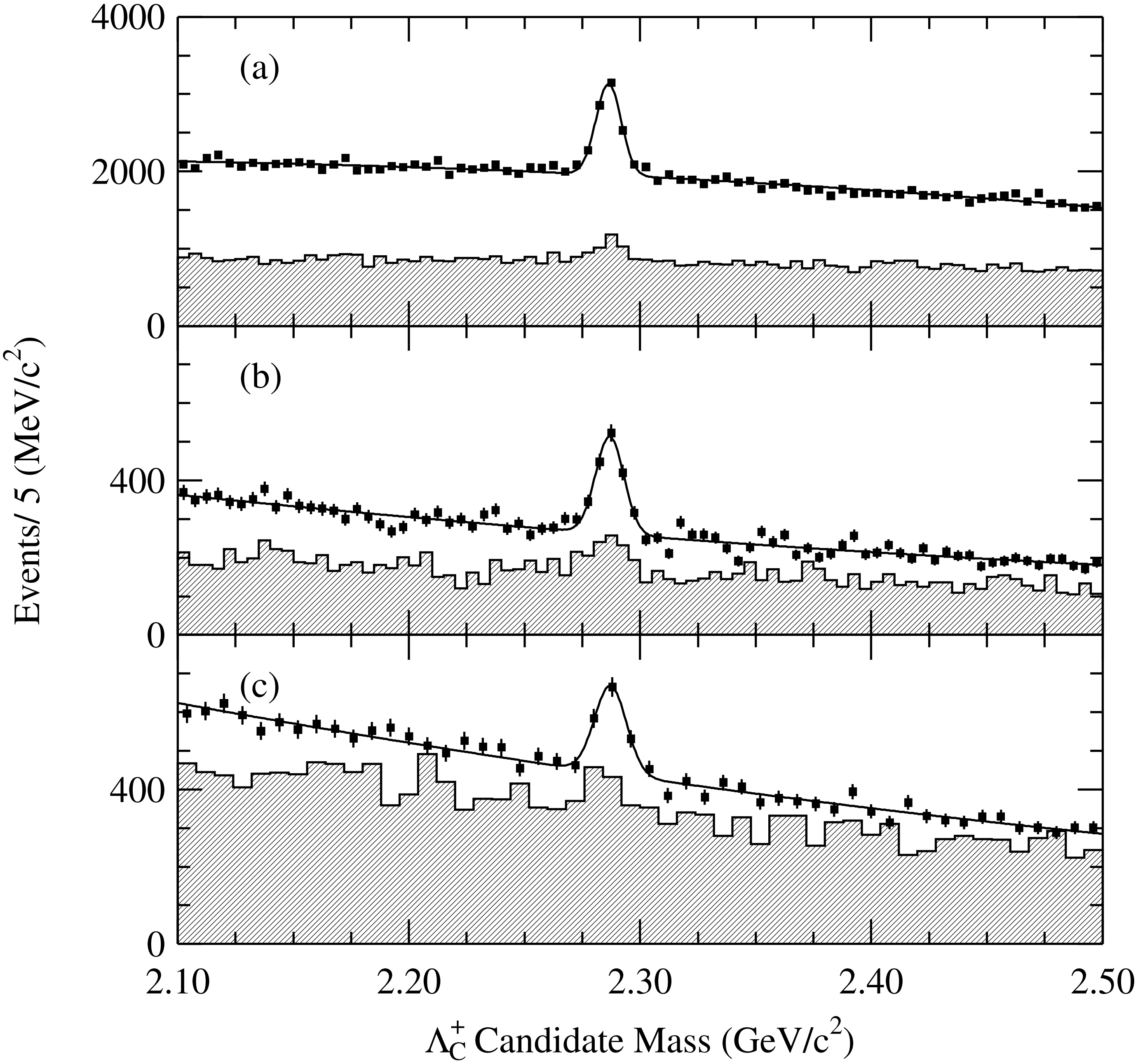

FIG. 2. Λ_c^+ Candidates: (a)$pK^-\pi^+$ invariant mass distribution from the $\Upsilon(4S)$ data (solid points) and the scaled continuum data (shaded histogram). (b) pK_S^0 and (c) $\Lambda\pi^+$

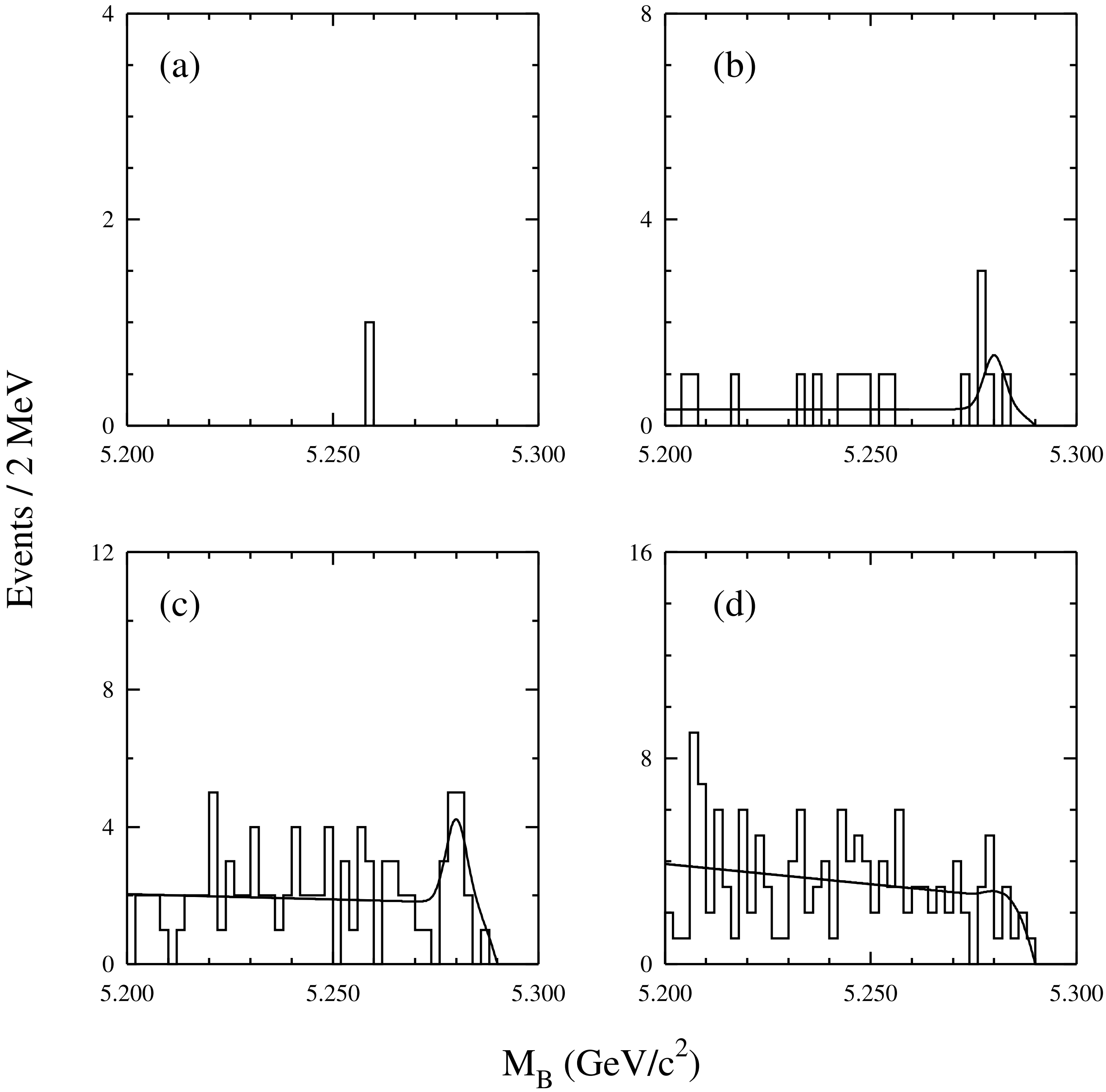

FIG. 3. Beam constrained mass distributions for (a) $\bar{B}^0 \to \Lambda_c^+ \overline{p}$, (b) $B^- \to \Lambda_c^+ \overline{p} \pi^-$, (c) $B^- \to \Lambda_c^+ \overline{p} \pi^- \pi^- \pi^+$, and (d) $\bar{B}^0 \to \Lambda_c^+ \overline{p} \pi^- \pi^- \pi^+ \pi^+$.

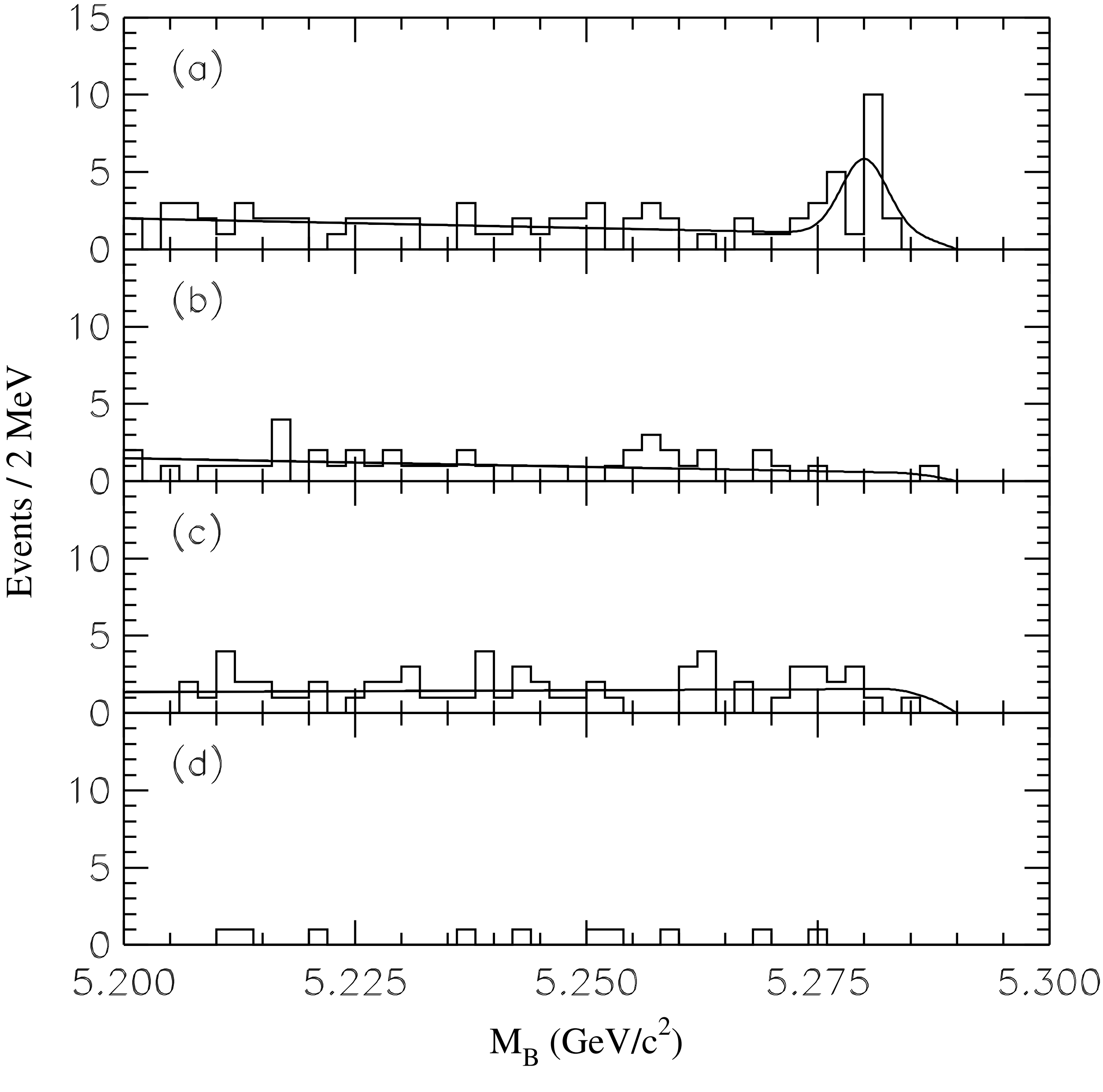

FIG. 4. Beam constrained mass distributions for $\bar{B}^0 \to \Lambda_c^+ \overline{p} \pi^- \pi^+$: (a) M_B Signal distribution, (b) M_B distribution for ΔE sidebands with a fit to the background shape superimposed, (c) M_B distribution for Λ_c^+ sidebands with a fit to the background shape superimposed and (d) M_B distribution from the continuum data sample .

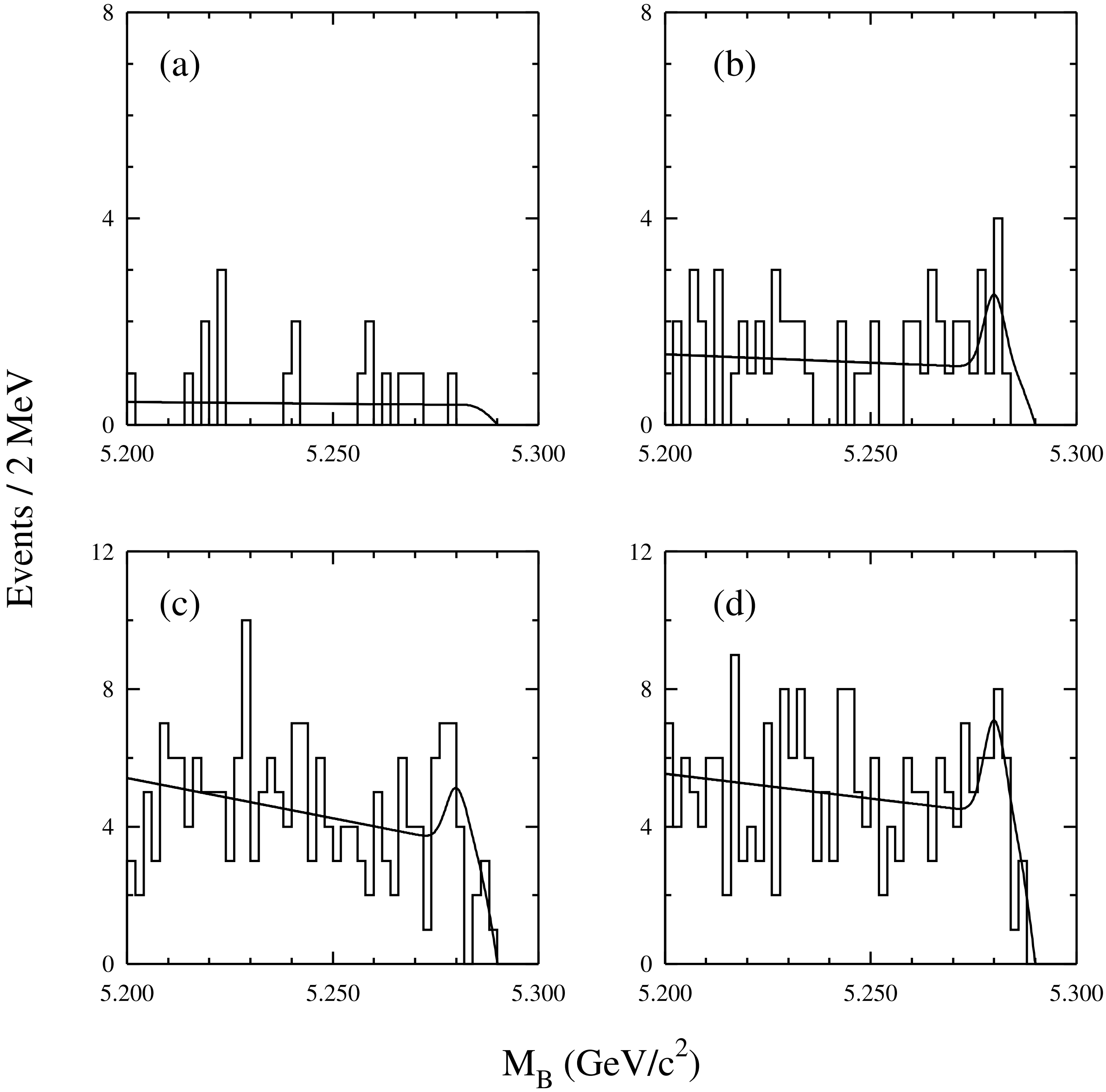

FIG. 5. Beam constrained mass distributions for (a) $\bar{B}^0 \to \Lambda_c^+ \overline{p} \pi^0$, (b) $B^- \to \Lambda_c^+ \overline{p} \pi^- \pi^0$, (c) $\bar{B}^0 \to \Lambda_c^+ \overline{p} \pi^- \pi^+ \pi^0$ and (d) $B^- \to \Lambda_c^+ \overline{p} \pi^- \pi^- \pi^+ \pi^0$.

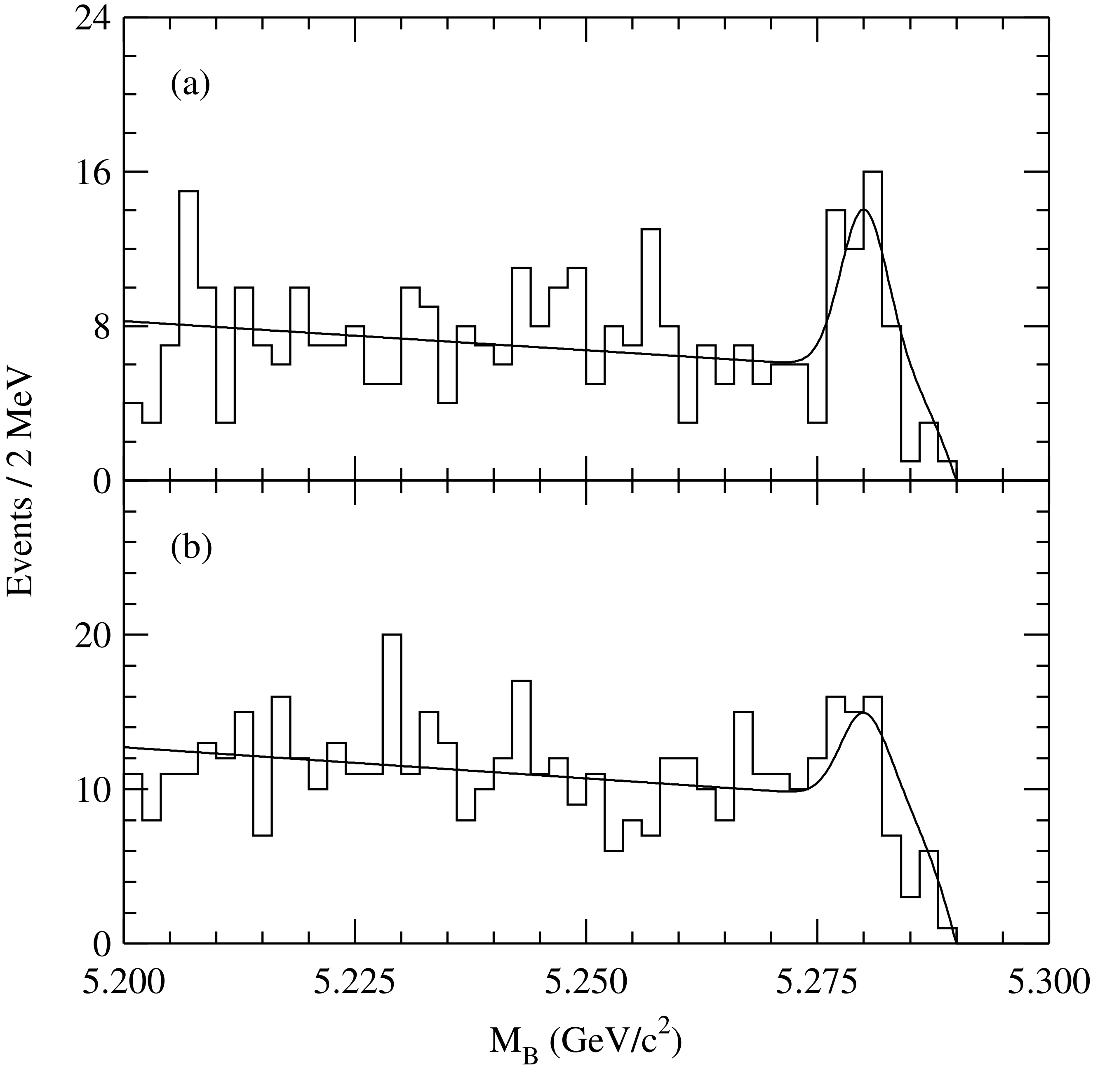

FIG. 6. Beam constrained mass distributions for (a) $\overline{B}\to\Lambda_c^+\overline{p}(n\pi)$ (n=0-4) and (b) $\overline{B}\to\Lambda_c^+\overline{p}(n\pi)\pi^0$ (n=0-3).