Fermi National Accelerator Laboratory

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Observation of $\Sigma_c^0 \to \Lambda_c^+ \pi^-$ Decays*

The Tagged Photon Spectrometer Collaboration

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ABSTRACT

Using a sample of approximately 120 $\Lambda_c^+ \to pK^-\pi^+$ decays reconstructed in photoproduction experiment E691 at Fermilab, we have searched for Σ_c production and decay into $\Lambda_c\pi$. A signal of 14 ± 4 Σ_c^0 decays is observed. The $\Sigma_c^0 - \Lambda_c^+$ mass difference is measured to be $168.4 \pm 1.0 \pm .3$ MeV/c^2. We also report on the relative fraction of Σ_c production as compared to inclusive Λ_c production at an average photon energy of 145 GeV.

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We have used the Tagged Photon Spectrometer (TPS) at Fermilab to perform a high statistics study of charmed particles. With the addition of a silicon microstrip vertex detector to detect secondary decays of charmed particles with low backgrounds, we have been able to reconstruct over 100 decays of $\Lambda_c^+ \to pK^-\pi^+$ and its charge conjugate. (Throughout this paper the charge conjugate state is implicitly included.) In an earlier letter we presented a measurement of the Λ_c lifetime.[1] Here we investigate the photoproduction of the charmed baryon multiplet Σ_c and its decay into $\Lambda_c^+\pi^\pm$.

The TPS is a large acceptance two-magnet spectrometer equipped with silicon microstrip detectors (SMDs), drift chambers, two Cherenkov counters, and electromagnetic and hadronic calorimetry. This spectrometer has been extensively described elsewhere.[2] A $90 - 260$ GeV bremsstrahlung photon beam (the average photon energy,145 GeV) was directed into a 5 cm long beryllium target. Events which had a minimum transverse energy of 2.2 GeV deposited in the calorimeters were recorded. This trigger was highly efficient for photoproduced charm ($\sim 80\%$) while suppressing background by about a factor of three. The present results are based on an analysis of our total data sample of 100 million events.

Charmed particle candidates were identified by selecting high mass track combinations that were reconstructed in the SMDs and tracking chambers. They must have satisfied a joint Cherenkov particle identification probability ($\geq .25$) and have formed a good secondary vertex. Charged particles were identified by two threshold Cherenkov counters. Protons and kaons were separated from pions with good efficiency from 6-71 GeV and 6-37 GeV respectively, and protons were separated from kaons in the range 21-71 GeV. In this analysis proton candidates were required to be positively identified, and kaon candidates were required to be not identified as pions. Due to the low Cherenkov misidentification probability and the good mass resolution of the spectrometer, the contamination to the Λ_c^+ sample from misidentified D^+ and D_s^+ decays was negligible.[1]

The excellent impact parameter resolution of the vertex detector (typically $15\mu m$ at the target center) allowed the secondary charmed vertices to be distinguished from the primary interaction point. The secondary decay vertex position was determined from the charmed track candidates using a constrained vertex-fitting algorithm. This vertex was required to have a not too large value of χ^2 per degree of freedom ($\chi^2/\mathrm{DOF} \leq 3.5$). Primary vertex candidates were then reconstructed from the remaining spectrometer tracks. The charmed particle momentum vector was required to point back to within 80 microns of the primary vertex candidate. In case of primary vertex ambiguity, the upstream vertex associated with the smallest impact parameter was selected. The longitudinal distance (along the beam axis) between the primary and secondary vertex positions, ΔZ, divided by the errors on these longitudinal positions taken in quadrature, σ_z, formed a good test for isolating charmed decays. We required a separation $\Delta Z/\sigma_z \geq 8$ in the present analysis. In addition, we rejected $pK\pi$ candidates if any of the tracks in the charmed particle decay vertex were consistent with having originated from another vertex in the event. Since this last requirement is biased against events with short decay times, it was not used in the lifetime analysis.[1]

The $pK\pi$ invariant mass distribution is shown in Figure 1. A signal for the $\Lambda_c^+ \to pK^-\pi^+$ is observed at an approximate mass of $\mathrm{M}(\Lambda_c^+) = 2.286$ GeV/c^2. (A detailed discussion of the mass determination is given in reference 1.) Using a Gaussian shape to fit the signal and linear form for the background yields $119 \pm 15 \pm 8$ signal events. The first error is the statistical error. The second error is the systematic error and reflects uncertainties in fitting the signal and background shape. The number of particles compared to the number of antiparticles given by the fit is nearly equal. A signal width of 8.4 MeV/c^2 determined with the final version of the E691 Monte Carlo is used in the fit and agrees well with the data. The fitted curve is displayed in Figure 1.

To search for the decay $\Sigma_c \rightarrow \Lambda_c \pi$ we add a pion (bachelor pion) to the $pK\pi$ state, and form the $pK^-\pi^+\pi^\pm$ invariant mass, which is denoted $M(\Lambda_c^+\pi^\pm)$. The bachelor pion is required to be a member of the main vertex and not to be identified as a kaon or proton. The mass differences between Σ_c and Λ_c candidates, $\Delta M = M(\Lambda_c^+\pi^\pm) - M(\Lambda_c^+)$, are displayed in Figures 2(a) and 3(a) for those events in the Λ_c mass range 2.270-2.300 GeV/c^2. A statistically significant signal in the Σ_c^0 mass difference spectrum is observed in Figure 2(a). A strong correlation is observed between Λ_c^+ and Σ_c^0 events when the $pK^-\pi^+$ mass spectrum is displayed for those events with mass difference in the range $165 \leq \Delta M \leq 173$ MeV/c^2, Figure 2(b). The mass difference spectrum of Σ_c^{++} candidates is displayed in Figure 3(a). It shows only a slight enhancement. The corresponding $pK^-\pi^+$ mass plot, requiring the same ΔM cut on the Σ_c^{++}-Λ_c^+ mass difference, is shown in figure 3(b).

A maximum likelihood fit is used to extract the number of $\Sigma_c^0, \Sigma_c^{++}$ events above background and the average masses. A relativistic phase space approximation of the form $(1. + a\Delta M) \times \Delta M^b$ is used to fit the background. The signal events are fit to a Gaussian form. The constants a and b which give the shape of the background are determined from Σ_c background events. These are events found in $pK^-\pi^+$ invariant mass plot excluding those events in the Λ_c signal region. The width of the Gaussian signal term is determined from a

Monte Carlo evaluation of experimental resolution. The resolutions determined for both the Σ_c^0 and the Σ_c^{++} are found to be similar and fixed to the value $\sigma = (2.4 \pm .3)$ MeV/c^2. The natural line widths of the resonances (Γ) are predicted to be small[3] and are not included in the fits. Adding a width, Γ, of 1-2 MeV/c^2 has negligible effect on the measured mass and is consistent with the uncertainty in the experimental resolution. The fit to the Σ_c^0 mass difference spectrum gives 14 ± 4 events, with $M(\Sigma_c^0) - M(\Lambda_c^+) = 168.4 \pm 1.0 \pm .3$ MeV/c^2. When fit to a background term only, an increase in χ^2 corresponding to a change of about 4.5 standard deviations is observed. A fit to the Σ_c^{++} mass difference plot yields 5 ± 3 events, which is not significant. Changing background parameterization to a quadratic polynomial or letting the shape parameters float produces negligible shifts in the fitted masses or yields. We estimate a systematic error of ± 2 events in each case and attribute it to our choice of fitting procedure.

The cross section for directly producing Σ_c's relative to that for inclusive Λ_c production is calculated by using the appropriate reconstruction efficiencies. The Cherenkov identification cuts used in this analysis restrict Λ_c^+ candidates to the kinematic region $x_F \geq .2$. Monte Carlo studies indicate that the efficiency for reconstructing $\Sigma_c^{0,++} \rightarrow \Lambda_c^+ \pi^{-,+}$, $\Lambda_c^+ \rightarrow pK^-\pi^+$, ($x_F \geq .2$) is $(1.47 \pm .14 \pm .04)\%$ and is independent of bachelor pion charge. We use the same efficiency for both states and include a systematic error of $\pm .04\%$. The reconstruction efficiency for inclusive $\Lambda_c \rightarrow pK^-\pi^+$ decays ($x_F \geq .2$) is $(1.62 \pm .06 \pm .08)\%$. We also assume $BR(\Sigma_c \rightarrow \Lambda_c \pi) = 1$. All other factors cancel in the ratio. The final efficiency corrected yields including systematic effects are $\sigma_{\Sigma_c^0}/\sigma_{\Lambda_c^+} = .13 \pm .04 \pm .02$ and $\sigma_{\Sigma_c^{++}}/\sigma_{\Lambda_c^+} = .05 \pm .03 \pm .02$ or $\leq$ .11(90%confidence level).

If one assumes symmetric photoproduction of states within the Σ_c isotriplet and averages over the observed Σ_c^{++} and Σ_c^0 corrected yields, then $\sigma_{\Sigma_c}/\sigma_{\Lambda_c} = .09 \pm .03 \pm .02$ for each mode or about $(27 \pm 9 \pm 6)\%$ for all Σ_c production relative to Λ_c production at these photon energies.

In conclusion, we observe $\Sigma_c^0 \to \Lambda_c^+ \pi^-$ decays and measure the Σ_c^0-Λ_c^+ mass difference to be $168.4 \pm 1.0 \pm .3$ MeV/c^2. Recent measurements from the ARGUS[4] collaboration indicate the mass differences for both Σ_c^{++} and Σ_c^0 to be nearly the same, the mean mass reported as $167.6 \pm 0.3 \pm 1.6$ MeV/c^2. The E-400[5] collaboration has also recently published a Σ_c^0-Λ_c^+ mass difference of $178.2 \pm 0.4 \pm 2.0$ MeV/c^2. Our measurement is in good agreement with the ARGUS result, but disagrees with the E400 measurement.

In addition, we measure the ratio of Σ_c's produced with respect to inclusive Λ_c production at a mean photon energy of 145 GeV and $x_F \geq .2$ as, $\sigma_{\Sigma_c^0}/\sigma_{\Lambda_c^+} = .13 \pm .04 \pm .02$ and $\sigma_{\Sigma_c^{++}}/\sigma_{\Lambda_c^+} \leq .11$ at the 90% confidence level. Although there is no significant Σ_c^{++} signal, our results are also consistent with equal cross sections for Σ_c^0 and Σ_c^{++}.

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REFERENCES

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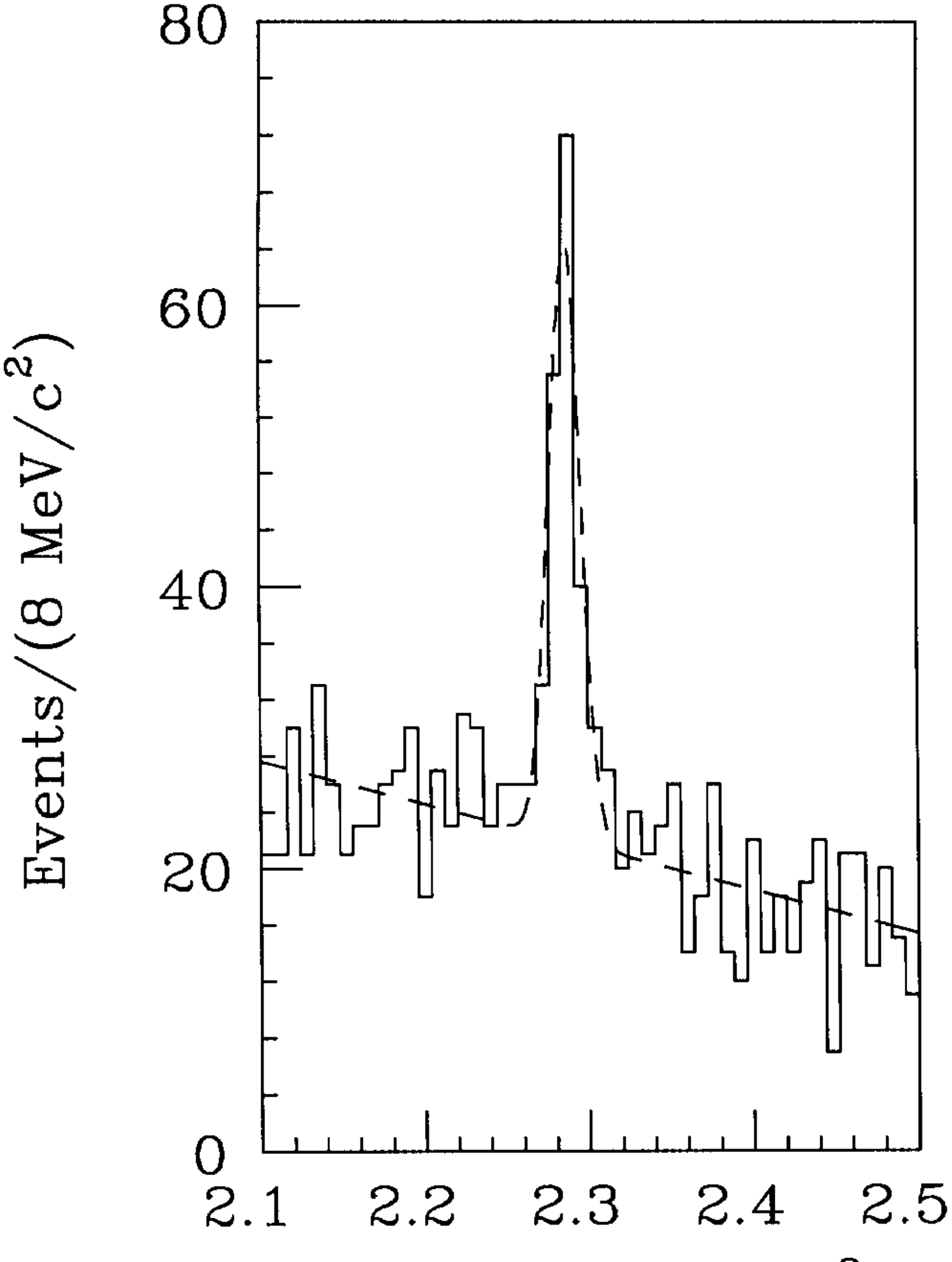
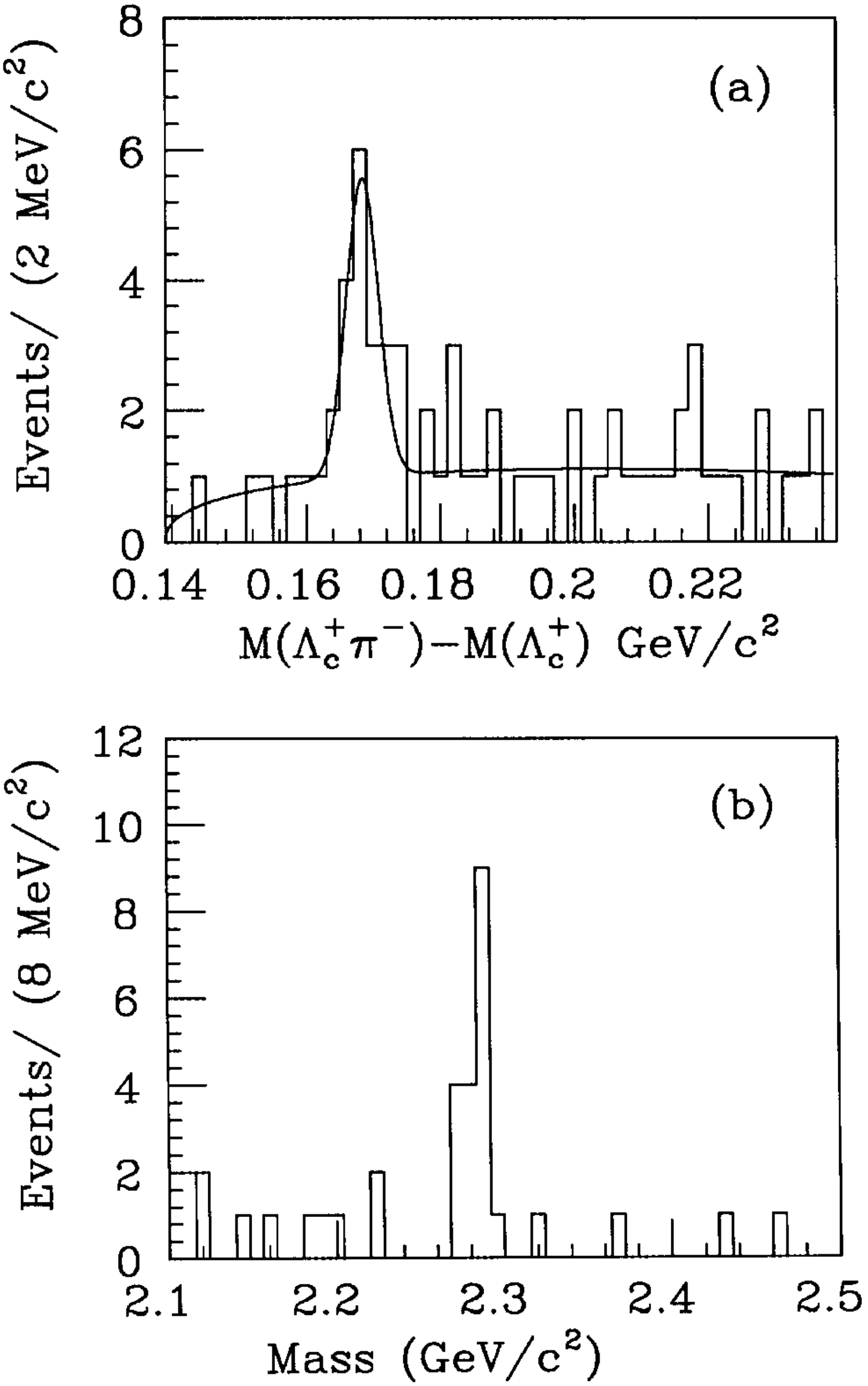
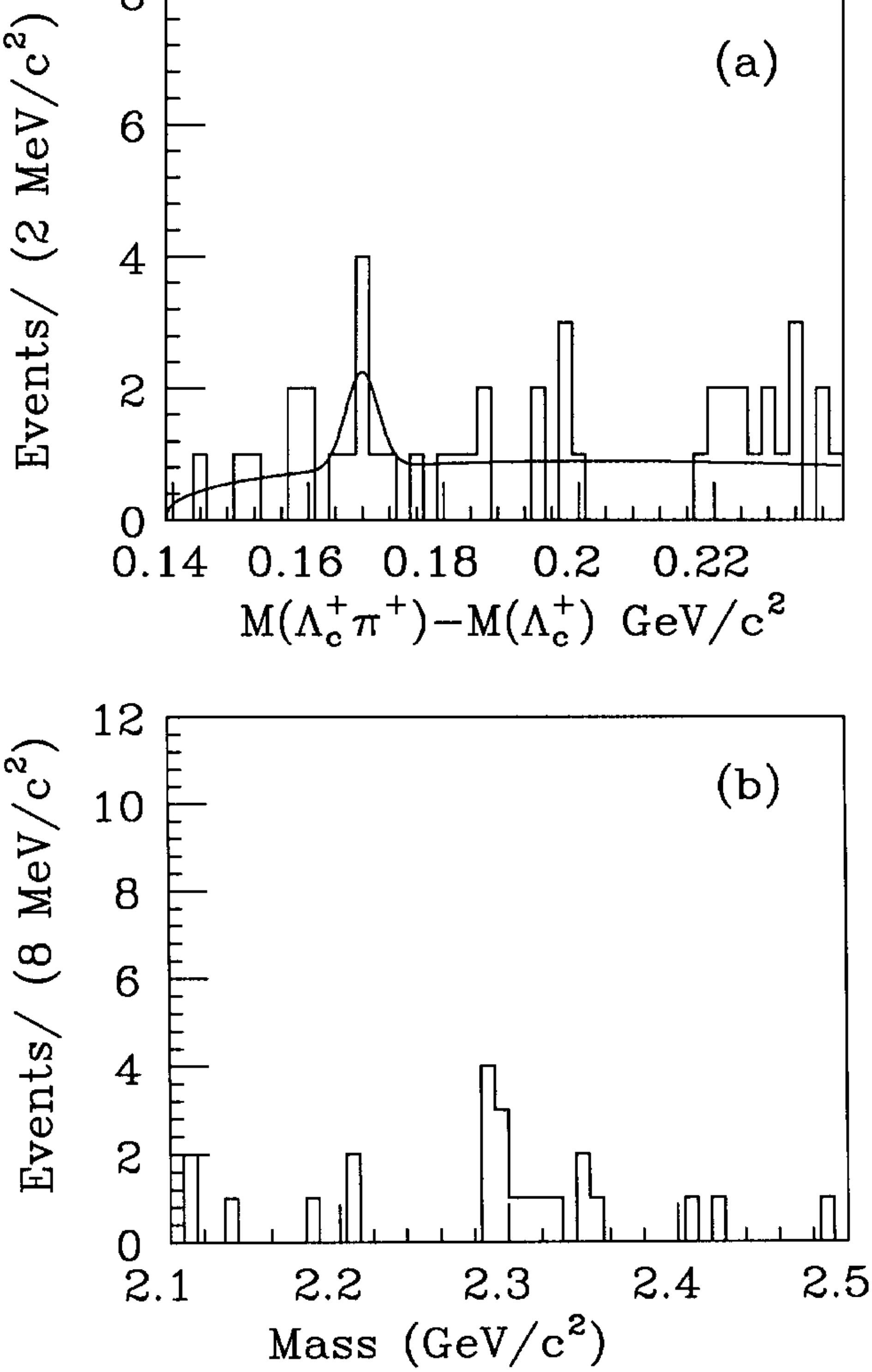
FIGURE CAPTIONS

1. $\Lambda_c \rightarrow pK^-\pi^+$ mass spectrum.
2. (a)$\Sigma_c^0 \rightarrow \Lambda_c^+\pi^-$ mass difference spectrum for $2.270 \leq \mathrm{M}(\Lambda_c^+) \leq 2.300$ GeV/c^2, (b) $pK^-\pi^+$ mass spectrum for Σ_c^0 candidates, $165 \leq \Delta\mathrm{M} \leq 173$ Mev/c^2.
3. (a)$\Sigma_c^{++} \rightarrow \Lambda_c^+\pi^+$ mass difference spectrum for $2.270 \leq \mathrm{M}(\Lambda_c^+) \leq 2.300$ GeV/c^2, (b) $pK^-\pi^+$ mass spectrum for Σ_c^{++} candidates, $165 \leq \Delta\mathrm{M} \leq 173$ Mev/c^2.



80
60
40
20
0
Events/(8 MeV/c²)
2.1
2.2
2.3
2.4
2.5
Mass pKπ (GeV/c²)


(a)
Events/ (2 MeV/c^2)
0
2
4
6
8
0.14
0.16
0.18
0.2
0.22
M($\Lambda_c^+\pi^-$)−M(Λ_c^+) GeV/c^2
(b)
Events/ (8 MeV/c^2)
0
2
4
6
8
10
12
2.1
2.2
2.3
2.4
2.5
Mass (GeV/c^2)


(a)
Events/ (2 MeV/c^2)
0
2
4
6
8
0.14
0.16
0.18
0.2
0.22
M(Λc+π+)−M(Λc+) GeV/c^2
(b)
Events/ (8 MeV/c^2)
0
2
4
6
8
10
12
2.1
2.2
2.3
2.4
2.5
Mass (GeV/c^2)