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Search for $\Lambda_b \rightarrow J/\psi\,\Lambda^0$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV

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Abstract

We have searched for the beauty baryon decay $\Lambda_b \to J/\psi\Lambda^0$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV with the Collider Detector at Fermilab (CDF). In the $J/\psi\Lambda^0$ invariant mass distribution we observe a flat distribution and a small number of events, consistent with no signal. Using the b quark cross section measured by CDF we put an upper limit on the $b \to \Lambda_b$ production fraction times the branching ratio $F(\Lambda_b)Br(\Lambda_b \to J/\psi\Lambda^0)$ of 0.50×10^{-3} at 90% confidence level.

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The technique of tagging b hadrons through their decay into J/ψ has been shown to be successful by the CDF collaboration with the first full reconstruction of beauty mesons in a $p\bar{p}$ collider [1]. Recently, the UA1 collaboration has reported [2] the observation of the $\Lambda_b \to J/\psi\Lambda^0$ decay at the CERN $p\bar{p}$ collider. In this process, the decay $J/\psi \to \mu^+\mu^-$ provides a relatively clean trigger signature and the secondary decay $\Lambda^0 \to p\pi^-$, with a branching ratio of 64.1%, is easily identified due to the typical V^0 decay associated with the long Λ^0 lifetime. We report on the equivalent search for the Λ_b in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV using CDF. To relate the expected number of $\Lambda_b \to J/\psi\Lambda^0$ events to the decay branching ratio $Br(\Lambda_b \to J/\psi\Lambda^0)$ we use the b quark cross section derived from the observation of the $B^\pm \to J/\psi K^\pm$ decay in the same dimuon sample [1]. Throughout this analysis whenever a particle is mentioned the charge conjugate state has been treated accordingly.

A detailed description of CDF can be found elsewhere [3]. The events used for this analysis, corresponding to an integrated luminosity of 2.6 ± 0.2 pb^{-1}, were collected by CDF in the $p\bar{p}$ collider run of 1988-1989 using a multilevel dimuon trigger. The first level of this trigger required the presence of a track in the muon chambers with p_T greater than a nominal threshold set at 3 GeV/c. The second level trigger required two muon chamber tracks that: satisfied the level 1 trigger, were separated from each other by at least one full muon module (15^o wide in ϕ) and both matched, within a muon module, tracks reconstructed in the central tracking chamber (CTC) hardware track processor. The muon chambers cover the pseudorapidity region $\mid \eta \mid < 0.63$ and the CTC provides three dimensional track reconstruction in the range $\mid \eta \mid < 1.2$.

The search for the $\Lambda_b \rightarrow J/\psi\Lambda^0$ begins with the reconstruction of the J/ψ . Muon candidates are selected requiring that the difference between the track coordinates in the muon chamber and the extrapolation of the associated track in the CTC be less than three times the expected deviation due to multiple scattering, energy loss and measurement error. The tracks associated with the two muons are required to have opposite sign and originate from the same event vertex along the beam axis. Since the trigger efficiency falls steeply below 3 GeV/c, the muon candidates, in the offline reconstruction, are required to have $p_T > 3$ GeV/c. The invariant mass distribution from this selection of dimuon combinations is shown in Figure 1. When fitted with a Gaussian line shape plus linear background the reconstructed J/ψ mass is 3096 ± 1(stat) MeV/c^2, in good agreement with the world average mass of 3096.93 ± 0.09 MeV/c^2 [4]. The width is measured to be $\sigma = 27 \pm 1$ MeV/c^2. We define the J/ψ signal region by a 2σ cut around 3097 MeV/c^2 *i.e.*: 3043 MeV/c^2 $< m_{\mu\mu} <$ 3151 MeV/c^2. There are 1124 events in this mass interval, of which 1050 ± 40 are estimated to be real J/ψ events.

For the events in the J/ψ signal region we search for the $\Lambda^0 \rightarrow p\pi^-$ decay as follows. Every pair of opposite sign tracks is fit with the constraint that the two tracks meet at a common point in three dimensions. To reduce the background from random combinations we require the χ^2 confidence level from this fit to be less than 0.999. For the remaining combinations we calculate the decay distance in the transverse plane, $L_{R\phi}$, between the fitted decay vertex and the primary interaction point. The resolution in this variable is 1 cm and is dominated by multiple scattering in the material between the interaction point and the CTC active volume. Most of the random track combinations have small decay lengths while a real Λ^0 with $p_T = 2.5$ GeV/c (typical of the Λ^0 momenta seen in these events) has an average decay distance of 18 cm. We require $L_{R\phi} > 2$ cm. Because the ratio of the proton mass to the pion mass is large and because of the relatively high p_T of the Λ^0 compared to the Q value for its decay, the proton from a $\Lambda^0 \rightarrow p\pi^-$ decay is always the highest momentum particle and takes most of the Λ^0 momentum. We therefore assign the proton mass to the highest momentum track. The resulting $p\pi^-$ invariant mass distribution is shown in Figure 2. We fit the Λ^0 signal with the sum of a Gaussian distribution plus a linear background and obtain a mass of 1116 ± 1 MeV/c^2 and a resolution of $\sigma = 1.0 \pm 0.2$ MeV/c^2. In the Λ^0 signal region, defined by 1113 MeV/$c^2 < m_{p\pi} < 1119$ MeV/c^2, there are 126 combinations of which we estimate 55 ± 12 real Λ^0 .

To search for $\Lambda_b \rightarrow J/\psi\Lambda^0$ we combine the reconstructed J/ψ and Λ^0 with the further requirement that the Λ^0 lie in the same hemisphere as the J/ψ . The muon p_T cut implemented in the trigger limits the $J/\psi \rightarrow \mu^+\mu^-$ acceptance to $p_T(J/\psi) > 6$ GeV/c . Because tracks are only reconstructed in the CTC for $p_T > 250$ MeV/c, the Λ^0 acceptance is limited to $p_T(\Lambda^0) > 1.5$ GeV/c. Thus our sensitivity to the $\Lambda_b \rightarrow J/\psi\Lambda^0$ is limited approximately to $p_T(\Lambda_b) > 8$ GeV/c.

In this kinematical region the decay products of the Λ_b are always boosted in its direction of flight and the requirement that the Λ^0 be in the same hemisphere as the J/ψ has an efficiency of 99.6 ± 0.4 %.

The dimuon combinations in the J/ψ signal region are fit with the constraint that they meet at a common point and that their invariant mass be 3097 MeV/c^2. The resulting $J/\psi\Lambda^0$ invariant mass spectrum is shown in Figure 3. No significant peak is observed in the region between 5300 MeV/c^2 and 6000 MeV/c^2.

The Monte Carlo simulation indicates that constraining the dimuon mass to the J/ψ mass improves the accuracy of the Λ_b mass measurement by a factor of 0.67. The predicted Λ_b mass resolution is 20 MeV/c^2.

The expected number of $\Lambda_b \rightarrow J/\psi\Lambda^0$ reconstructed decays is related to the branching ratio by:

$$N(\Lambda_b) = 2L\sigma(b)F(\Lambda_b)Br(\Lambda_b \rightarrow J/\psi\ \Lambda^0)\epsilon(J/\psi, \Lambda_b \rightarrow J/\psi\ \Lambda^0)\epsilon(\Lambda^0) \tag{1}$$

where:

- L is the integrated luminosity,
- $\sigma(b)$ is the b quark production cross section for $p_T^b > p_T^{min}$ and $|y^b| < 1$ where y^b is the rapidity of the b quark,
- $F(\Lambda_b)$ is the fraction of b quarks fragmenting into Λ_b, or heavier beauty baryons that decay into the Λ_b,
- $Br(\Lambda_b \rightarrow J/\psi\ \Lambda^0)$ is the decay branching fraction,
- $\epsilon(J/\psi, \Lambda_b \rightarrow J/\psi\ \Lambda^0)$ is the reconstruction efficiency for the J/ψ from a $\Lambda_b \rightarrow J/\psi\Lambda^0$ decay originating from a b quark with $p_T^b > p_T^{min}$ and $|y^b| < 1$ that has hadronized into a Λ_b ,

- $\epsilon(\Lambda^0)$ is the $\Lambda^0 \to p\pi^-$ reconstruction efficiency once the J/ψ is found.

The leading factor of 2 in equation (1) arises since we search for both Λ_b and $\overline{\Lambda_b}$ and the cross section includes only b quark production. The b quark cross section derived from the observation of the $B^\pm \to J/\psi K^\pm$ decay is [1]:

$$\sigma(p\bar{p} \to bX, p_T^b > 11.5 \text{ GeV}/c, |y^b| < 1) = 6.1 \pm 1.9(\text{stat}) \pm 2.4(\text{sys})\ \mu\text{b}$$

Since the kinematical region where we are sensitive to the $B^\pm \to J/\psi K^\pm$ and $\Lambda_b \to J/\psi\Lambda^0$ decays is the same we can directly use this b quark cross section without extrapolation thus reducing the systematic uncertanties associated with the assumed b quark production p_T spectrum. The expected number of $\Lambda_b \to J/\psi\Lambda^0$ events calculated using this cross section is also insensitive to the systematic biases associated with the integrated luminosity and the dimuon triggering efficiency. In fact the Λ_b search is based on the same J/ψ sample used to reconstruct the $B^\pm \to J/\psi K^\pm$ decay. Implicit in this technique is the assumption that the fragmentation mechanism of the b quark into baryons and mesons is the same and therefore that the Λ_b and the $B^\pm$ are produced with similar spectra in p_T and η.

To determine the reconstruction efficiencies we use the following Monte Carlo method. We generate b quarks according to the p_T and rapidity spectrum predicted by the $O(\alpha_s^3)$ calculation of Nason, Dawson & Ellis (NDE) [5] and share the energy between the b quark and the b hadron using the Peterson model [6] with $\epsilon = 0.006$ [7]. The efficiency for detecting the $\Lambda_b \to J/\psi\Lambda^0$ depends on the unknown polarization of the parent particle and its decay products. To calculate the efficiencies we assume that all particles are unpolarized and thus generate the $\Lambda_b \to J/\psi\Lambda^0$, $J/\psi \to \mu^+\mu^-$ and $\Lambda^0 \to p\pi^-$ uniformly in their respective rest frames. Potential polarization effects from all decays are assigned to the systematic error as discussed below.

The efficiency for triggering on a J/ψ is determined using parameterizations of the level 1 and level 2 trigger efficiency as function of the muon p_T and a simulation of the geometric acceptance of the muon chamber system. Combining the triggering efficiency with the efficiency for reconstructing and selecting the muons [1] we obtain a reconstruction efficiency of 4.5% (without branching ratio) for the J/ψ from a $\Lambda_b \rightarrow J/\psi\Lambda^0$ decay originating from a b quark with $p_T^b > 11.5$ GeV/c and $|y^b| < 1$.

Since the pion from the $\Lambda^0 \rightarrow p\pi^-$ has low p_T , the Λ^0 finding efficiency is sensitive to the track reconstruction efficiency at very low p_T . This efficiency is determined merging Monte Carlo generated $\Lambda_b \rightarrow J/\psi\Lambda^0$ events into real J/ψ events and searching for $\Lambda^0 \rightarrow p\pi^-$ using the same procedure used for the data. The efficiency to find the $\Lambda^0 \rightarrow p\pi^-$ decay once the J/ψ is reconstructed is 31%, not including the branching ratio. Figure 4 shows this efficiency as a function of the pion p_T . Most of the inefficiency is due to the steeply falling track reconstruction efficiency for particles with p_T below 400 MeV/c.

Systematic errors on the calculated reconstruction efficiencies are associated with the model used to produce and decay the Λ_b and with uncertainties in the simulation of the detector. We studied the effect of variations of the b quark p_T spectrum. Since the b quark cross section is derived from the $B^\pm \rightarrow J/\psi K^\pm$ decay using the spectrum predicted by NDE we studied the variations of the relative detection efficiency between $B^\pm \rightarrow J/\psi K^\pm$ and $\Lambda_b \rightarrow J/\psi\Lambda^0$. Variations in the shape of the b quark p_T spectrum can change this relative detection efficiency by ±10%. To evaluate the sensitivity to the polarization effects in the model used to decay the Λ_b , we varied the decay angular distributions associated with the $\Lambda_b \rightarrow J/\psi\Lambda^0$ decay chain. The $J/\psi \rightarrow \mu^+\mu^-$ decay was generated according to longitudinal and transverse J/ψ polarizations. For the

$\Lambda^0 \rightarrow p\pi^-$ we generated the decay according to longitudinally polarized Λ^0 . The maximum variation of the efficiency with respect to the uniform angular distributions was found to be 15%. We estimate a 16% systematic error on the Λ^0 reconstruction efficiency due to the uncertainties in the simulation of the detector response. Combining these contributions in quadrature, the overall systematic uncertanty obtained is 24%. The global Λ_b reconstruction efficiency is $(0.53 \pm 0.13) \times 10^{-3}$ where we have used the values of $(5.97 \pm 0.25)\%$ and $(64.1 \pm 0.5)\%$ for the $J/\psi \rightarrow \mu^+\mu^-$ and $\Lambda^0 \rightarrow p\pi^-$ branching ratios [4] respectively.

From the mass distribution of Figure 3 and equation (1) we obtain the 90% confidence level upper limit on $F(\Lambda_b)Br(\Lambda_b \rightarrow J/\psi\Lambda^0)$ in the following way. For a given mass the upper limit is calculated [4] from a probability distribution function obtained by convoluting a Poission distribution corresponding to the number of $J/\psi\Lambda^0$ mass combinations observed in a ± 40 MeV/c^2 wide region with a Gaussian distribution. The width of the Gaussian distribution is the systematic uncertainty on the scale factor that relates $N(\Lambda_b)$ with its branching ratio. The bin of ± 40 MeV/c^2 is equal to $\pm 2\sigma$ where σ is the expected Λ_b mass resolution. The maximum number of events found in any ± 40 MeV/c^2 wide region between 5300 MeV/c^2 and 6000 MeV/c^2 is 2 events. With the conservative assumption that these are 2 signal events we obtain the 90% confidence level upper limit of $F(\Lambda_b)Br(\Lambda_b \rightarrow J/\psi\Lambda^0) < 0.50 \times 10^{-3}$. The value reported by UA1 is $F(\Lambda_b)Br(\Lambda_b \rightarrow J/\psi\Lambda^0) = (1.8 \pm 0.6(\text{stat}) \pm 0.9(\text{sys})) \times 10^{-3}$ [2]; using this value and the b quark cross section measured at CDF we should have reconstructed 30 ± 23 $\Lambda_b \rightarrow J/\psi\Lambda^0$ events in our dimuon sample.

In summary, we have searched for the $\Lambda_b \rightarrow J/\psi\Lambda^0$ decay in 2.6 ± 0.2 pb^{-1} of dimuon events collected by CDF in the 1988-1989 $p\bar{p}$ collider run. We do not see any evidence for this decay. The detection efficiency for this channel depends on the assumed production and decay mechanism. We have assumed that b baryons and mesons are produced in the fragmentation process in similar ways. From the b quark cross section measured by CDF using the $B^{\pm} \rightarrow J/\psi K^{\pm}$ decays observed in the same data sample we conclude that $F(\Lambda_b)Br(\Lambda_b \rightarrow J/\psi\ \Lambda^0) < 0.50 \times\ 10^{-3}$ at 90% confidence level.

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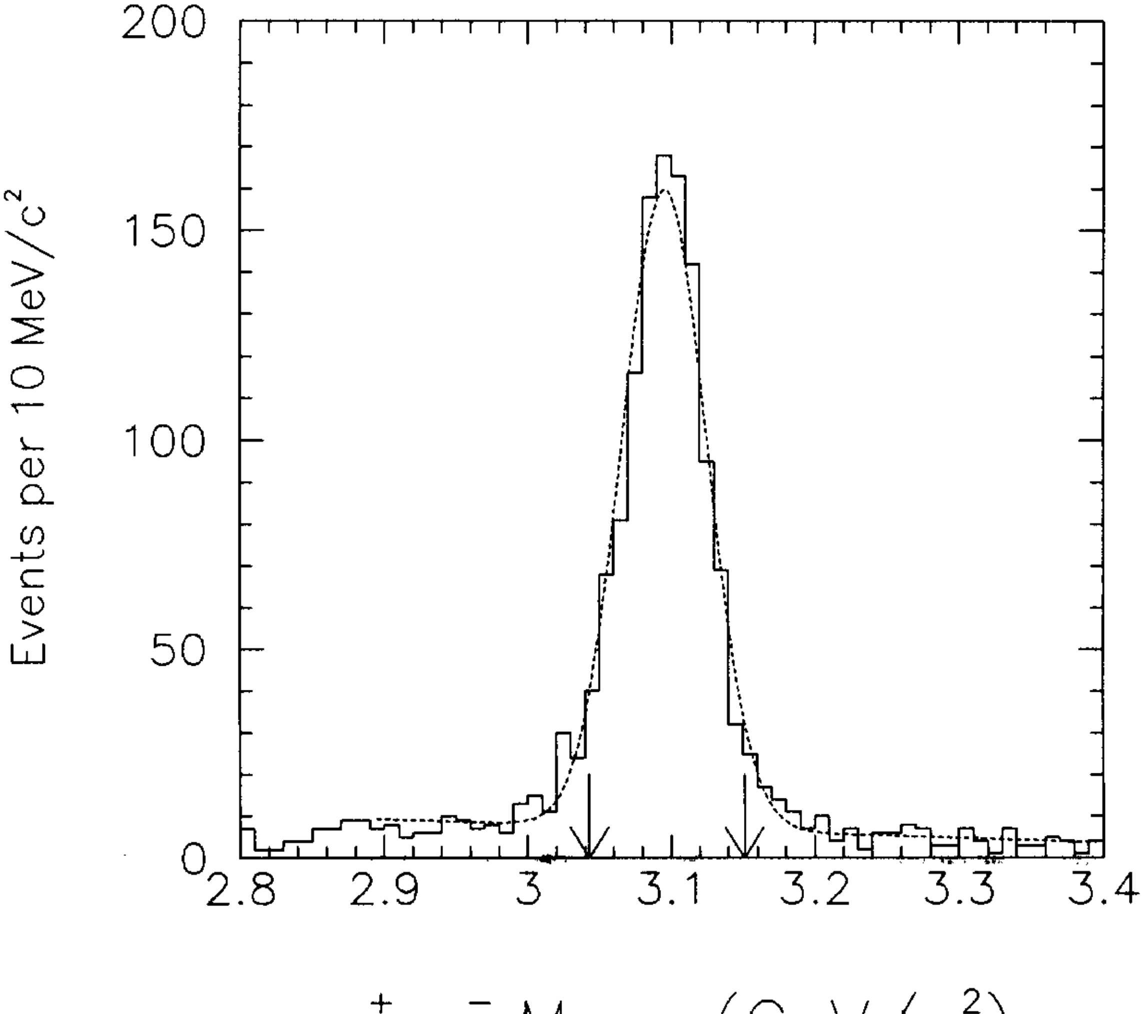
Figure Captions

Figure 1: The $\mu^+\mu^-$ invariant mass distribution in the vicinity of the J/ψ . The fit is a Gaussian plus a linear background.

Figure 2: The $p\pi^-$ (and charge conjugate) invariant mass distribution in the vicinity of the Λ^0 after the χ^2 and the decay length cuts. The fit is a Gaussian plus a linear background.

Figure 3: The $J/\psi\Lambda^0$ (and charge conjugate) invariant mass distributions after the selection criteria described in the text. (a) In 40 MeV/c^2 bins. (b) The region between 5240 MeV/c^2 and 6040 MeV/c^2 in 20 MeV/c^2 bins.

Figure 4: The Λ^0 reconstruction efficiency (without branching ratio) as a function of the pion p_T for Λ^0 from $\Lambda_b \rightarrow J/\psi\Lambda^0$ after the trigger requirement on the J/ψ .



200
150
100
50
0
2.8
2.9
3
3.1
3.2
3.3
3.4
Events per 10 MeV/c^2
$\mu^+ \mu^-$ Mass (GeV/c^2)

Figure 1

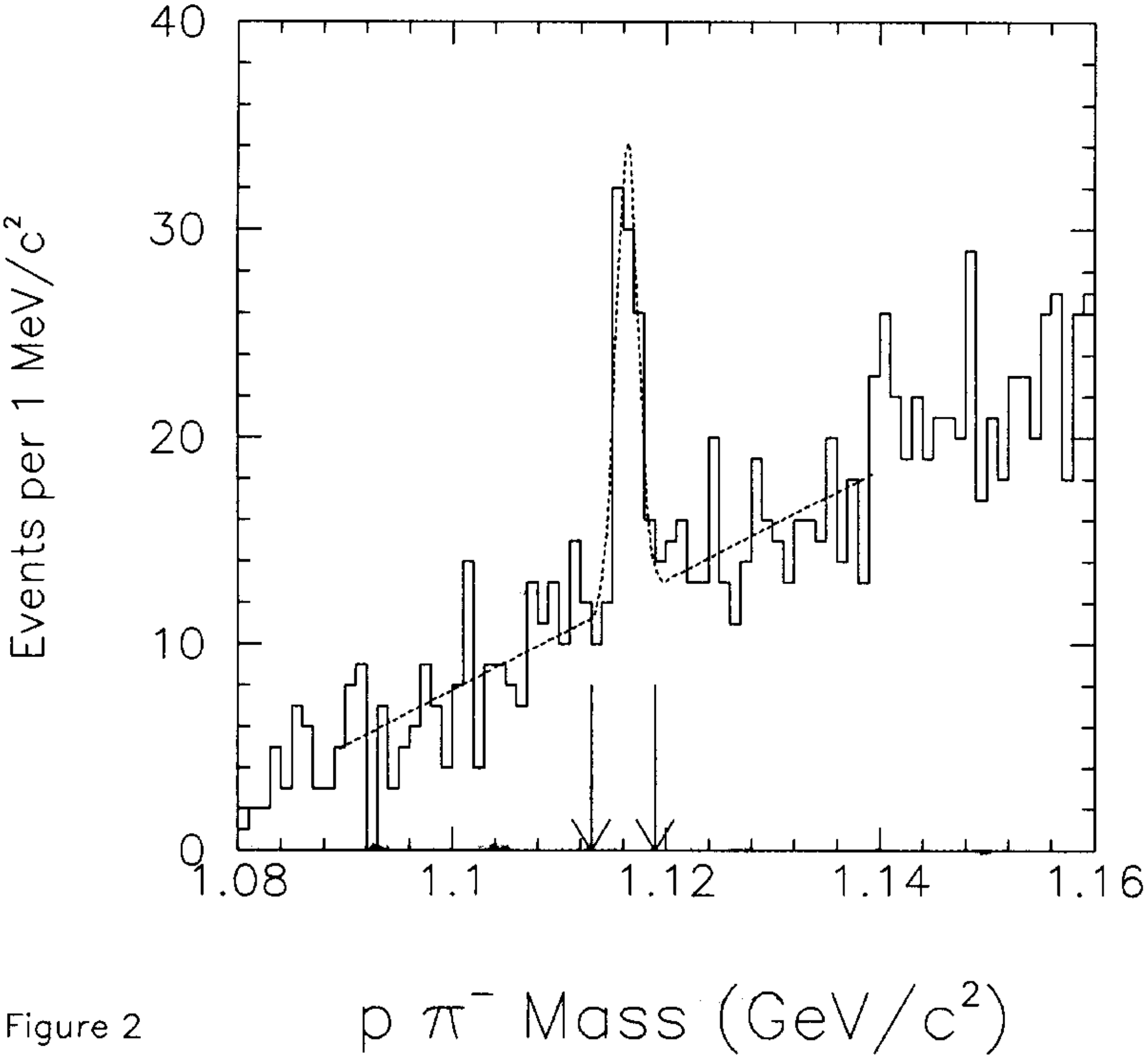


Figure 2

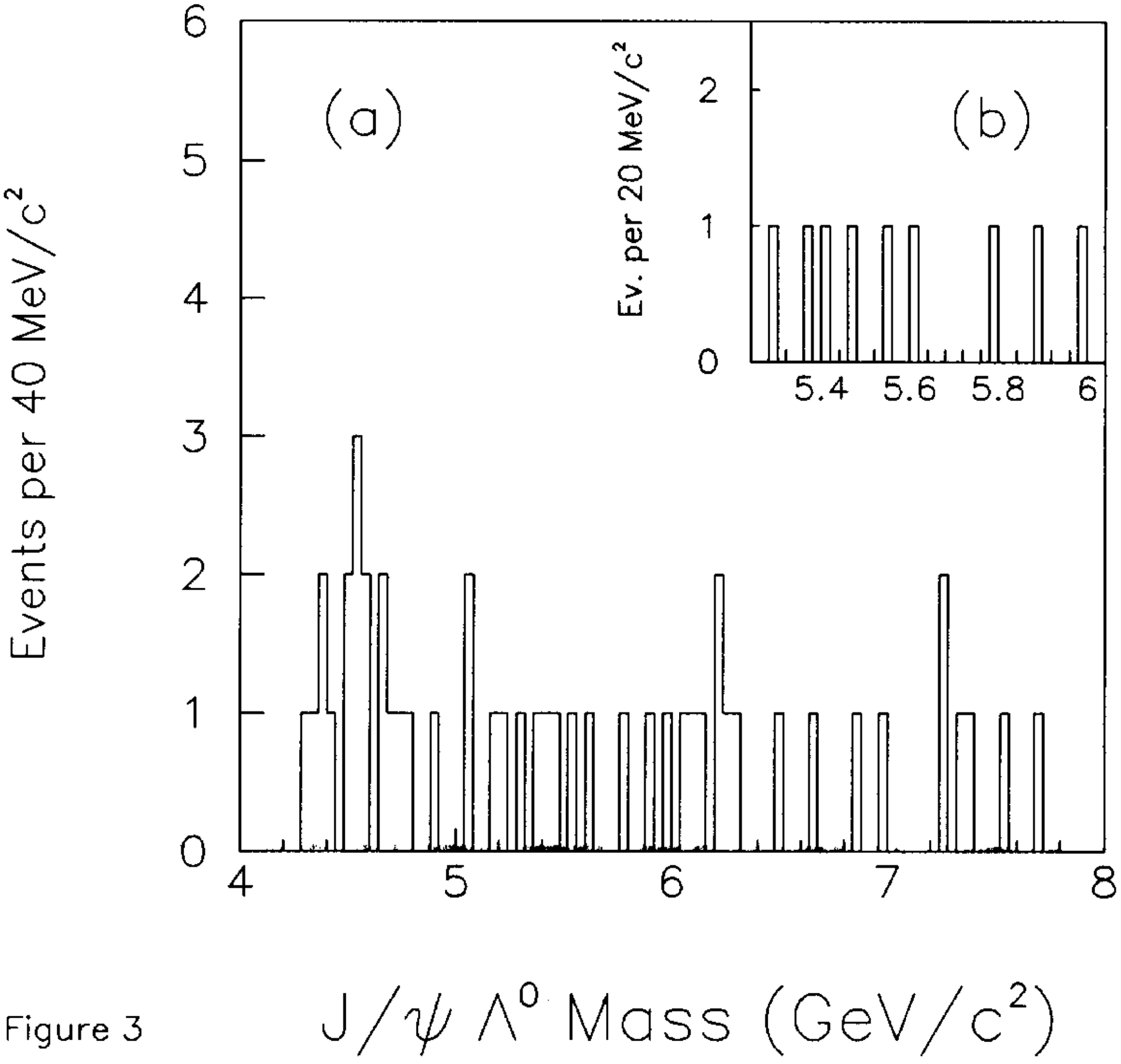

(a)
(b)
Events per 40 MeV/c²
Ev. per 20 MeV/c²
0
1
2
3
4
5
6
4
5
6
7
8
5.4
5.6
5.8
6
J/ψ Λ⁰ Mass (GeV/c²)

Figure 3

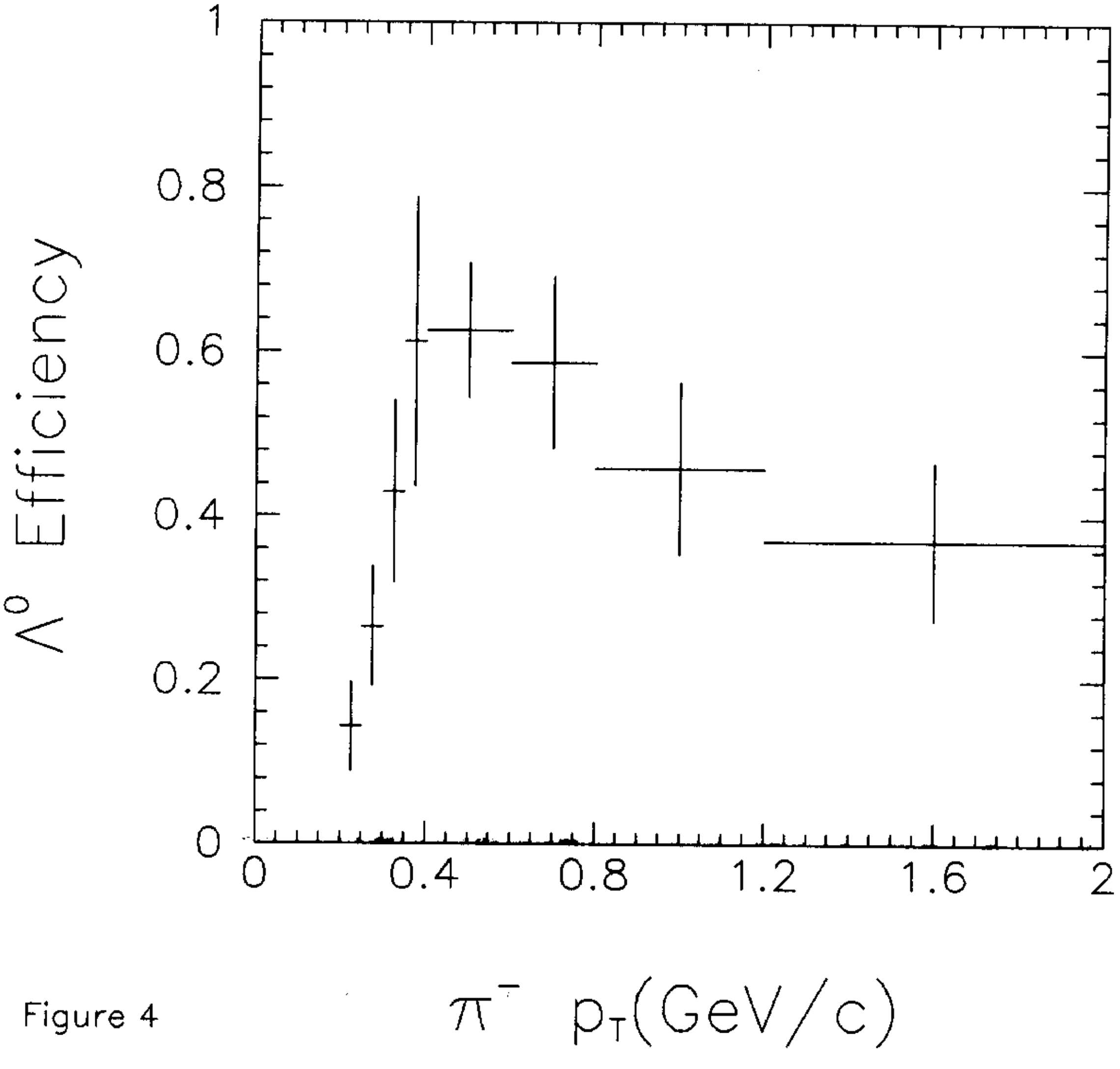


Figure 4