Fermi National Accelerator Laboratory

FERMILAB-Pub-92/265-E

E705

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April 1993

Submitted to *Physical Review D*

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

Search for Hidden Charm Resonance States Decaying into J/Ψ or Ψ' Plus Pions *

The E705 Collaboration

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A search has been made in 300 GeV/c $\pi^{\pm}$ and proton Li interactions to detect previously unobserved $c\overline{c}$ or $q\overline{q}\,c\overline{c}$ states by looking for production of states which decay into J/Ψ or Ψ' plus one or two pions. A 2.5σ enhancement is observed at a mass of 3.527 GeV/c^2 in the J/Ψ π^0 spectrum which is interpreted as the recently reported $^1P_1$ state of charmonium. In the J/Ψ plus two pion mass spectrum, we report, together with the expected Ψ'->J/Ψ$\pi^+\pi^-$, the tentative observation of a structure at a mass of 3.836 GeV/c^2. No enhancements are seen in the J/Ψ $\pi^{\pm}\pi^{\pm}$, J/Ψ $\pi^{\pm}\pi^0$, J/Ψ $\pi^{\pm}$ or Ψ'$\pi^{\pm}$ mass spectra.

PACS number: 13.40.H

* Submitted to Physical Review D

Introduction

Since nearly all observations of hidden charm states have been made at e^+e^- colliders, existing results consist mainly of states which have the quantum numbers of the photon or states produced via the decay of these directly produced vector states. Examples include the χ meson states which are produced via the radiative decay of the Ψ'(3685). However, because of small branching ratios or unfavorable quantum numbers, many states are difficult to produce by vector meson decay. And, above $D\overline{D}$ threshold, vector mesons tend to have vanishingly small branching fractions into lower mass hidden charm states. These restrictions of e^+e^- production of heavy flavor states make it interesting to examine hadroproduction processes, where the requirement of producing charmonium states through a vector state is not present. In addition, it is theoretically conceivable that states of four or more quarks can be produced in hadronic interactions. Experimentally, there may be evidence for such four quark states. Examples are the a_0(980) and the f_0(975) which may have an $s\overline{s}q\overline{q}$ composition.

We have performed an experiment, Fermilab experiment E705, in which we have measured the production of various charmonium states[1,2] including the J/Ψ, Ψ' and various χ states in 300 GeV/c interactions of $\pi^{\pm}$, protons and antiprotons with a natural Li target. We have examined the J/Ψ and Ψ' data to search for evidence of either heretofore undetected charmonium states or states of four quarks which decay into either a J/Ψ or Ψ' plus pions. We report in this paper the results of this search in both our pion and proton induced data samples.

The J/Ψ and Ψ' are detected in E705 via their $\mu^+\mu^-$ decay modes. The E705 spectrometer[3] contained a muon detector in which muons were identified as particles which penetrated a thickness (adequate to range out particles of up to 6 GeV/c) of copper and steel and which generated a triple coincidence of planes of scintillation counters embedded in the absorber material. When two or more such triple coincidences were present in a given event, an on-line trigger processor[4] determined if there was a pair of muons with an invariant mass greater than 2.4 GeV/c^2. If this was found to be the case, the event was written to tape.

The dimuon mass spectra accumulated in such a manner using the different beams contain J/Ψ and Ψ' signals as shown in Fig. 1. For events which fall within the mass region of the J/Ψ and Ψ', we have formed the various mass combinations of the dimuons with one or two charged or neutral pions.

Charged pions are defined as tracks that do not satisfy the criteria for either an electron or a muon. The identification of a track as an electron is made if it has E/p close to unity, where E is the energy deposited by the track in the E705 electromagnetic detector[5] and p is its momentum as determined from the bending of the particle in the analysis magnet (p_T kick of 0.766 GeV/c). In Fig. 2 we show a scatter plot of E/p vs. the energy in the active converter region (the first four radiation lengths of the EM calorimeter) divided by $\sqrt{E}$. The tracks in close proximity to showers in the EM detector (i.e. within 3 cm in both the x and y projections) with $1.2 \geq E/p \geq 0.8$ and with significant energy (>200 MeV and $>0.15\sqrt{E}$ GeV) deposited in the active converter region were designated as electrons, whereas all other tracks, except for identified muons, were taken to be pion candidates. A further criterion was applied to the pion candidates by requiring the transverse shower distribution not to fit the shape expected for an electron shower. The momenta of the pion candidates have a lower limit of 2 GeV/c since the E705 analysis magnet swept charged particles with momenta below 2 GeV/c out of the spectrometer acceptance.

Neutral pions are constructed by forming di-photon combinations, where individual photons are identified as energy deposits in the EM calorimeter above 2 GeV which had a reasonable fit to the appropriate single photon shape as predicted by the EGS electromagnetic shower program. In addition, it was required that the energy deposit in the active converter portion of the EM calorimeter be ≥ 200 MeV and $\geq 0.15\sqrt{E}$ GeV and that no charged track point to the shower (to within 5 cm). The di-photon mass combinations formed using photons meeting these criteria show a clean π^0 signal as shown in Fig. 3a. Fig. 3b shows the comparison of the expected π^0 resolution, as predicted by a detailed Monte Carlo, to the background-subtracted di-photon mass spectrum. The observed π^0 mass varies between 137.6 to 142.5 MeV/c^2 depending on the region of the detector, and the width of the peak from $\sigma \approx 10.3$ to 14.3 MeV/c^2, leading to a systematic error assigned to the absolute energy scale for the photons of 3%. Based on this spectrum, π^0's are taken to be any di-photon mass combination in the mass range 110 MeV/$c^2 \leq M_{\gamma\gamma} \leq 170$ MeV/c^2.

<u>Hidden Charm States Decaying to J/Ψ Plus One Pion</u>

We have investigated the $J/\Psi\pi^0$ spectrum in a search for neutral resonance states decaying into J/Ψ plus a single pion. As shown in Fig. 4a, which combines both our proton and pion data, we observe a 2.5σ effect (42±17 events over background with a width of 0.014±0.005 GeV/c^2) at 3.527±0.008 GeV/c^2 in our $J/\Psi\pi^0$ mass spectrum. The background has been determined from combinations of J/Ψ's with π^0's from other events containing a J/Ψ. The enhancement remains visible even if we plot separately the pion and proton data (Fig. 4b and c) and the number of events in the peak is determined from the fit to be 26±12 and 16±10 for the pion and proton data respectively. The cross section times branching ratio ($x_f > 0$) for this state which we extract from our pion data is 5.3 ± 2.5 nb/nucleon.

We have tentatively identified this enhancement as the $^1P_1$ state of charmonium which has been previously reported[6] at a mass of 3526.2±0.15±0.2 Mev/c^2 by Fermilab Experiment E760. The identification of this state as the isospin-violating decay of the charmonium $^1P_1$ into $J/\Psi\pi^0$ is supported by its mass, which is near the center of mass of the χ states.

We have also searched for evidence of a signal in our $J/\Psi\pi^{\pm}$ mass spectrum. As shown in Fig. 5a, the $M(\mu\mu\pi^{\pm})$- $M(\mu\mu)$ mass difference spectrum obtained from the composite negative and positive beam data shows no evidence for structure. Detailed examination of the threshold region (0.140 - 0.164 GeV/c^2), shown in close-up in Fig. 5b where a 3.5 GeV/c^2 signal would appear, also reveals no evidence for any excess of events over the various background shapes that have been tried. The background curves shown superimposed on the data in Fig 5a and b were formed by pairing a J/Ψ with a charged pion from another J/Ψ event. As can be seen, this background shape fits the data very well, and there is no evidence for any enhancement in these mass difference spectra.

Finally, we have examined the $\Psi'\pi^{\pm}$ mass spectrum for evidences of resonance structure. Fig. 6a shows the mass difference spectrum, $M(\mu\mu\pi^{\pm})$- $M(\mu\mu)$, for the $\Psi'\rightarrow\mu\mu$ events from the composite negative and positive beam data. The close-up of the threshold region of this difference mass plot is shown in Fig. 6b. The background shapes shown superimposed on the data are generated by pairing a Ψ' from one event with a charged pion from another event containing a Ψ'. The background shape is normalized to the total number of Ψ' events. Once again, there is no evidence for any significant enhancement over background in this spectrum. A slight excess of 20$\pm$12 events is observed between 0.136 and 0.164 GeV/c^2. This represents a 1.6σ effect. However, a requirement of low dimuon momentum on the data eliminates the excess, suggesting that measurement errors on high momentum muons may generate this slight threshold effect.

Hidden Charm States Decaying to J/Ψ Plus Two Pions

For the J/Ψ events used in the study of $J/\Psi\pi^+\pi^-$ final states, two additional criteria were imposed on the charged pions to increase signal to background for resonance states. The first requirement was for the J/Ψ events to have low multiplicity ($\leq$ 5 charged pions per event in the spectrometer acceptance). Only 8.7% of the J/Ψ events failed to meet this requirement. Second, the mass of the di-pion combination was required to be greater than 80% of its maximum kinematically possible value. This requirement was imposed since, according to Brown and Cahn[7], the phase space for a decay such as $\Psi'\rightarrow J/\Psi\pi\pi$ is modified by chiral symmetry so that the di-pion mass is skewed toward high values. While chiral symmetry breaking and final state pion scattering would tend to diminish this effect, Mark III data[8] show that it still persists. Imposing the 80% di-pion mass cut is expected to retain 38% of the background $J/\Psi\pi^+\pi^-$ states (assuming the di-pion mass distribution to be just phase space), while 69% of the $\Psi'\rightarrow J/\Psi\pi^+\pi^-$ signal is expected to pass the cut. Overall, imposing this requirement eliminated 73% of the $J/\Psi\pi^+\pi^-$ events, consistent with the amount of background expected to be removed by the cut.

In view of the fact that our target (^{7}Li) is almost isoscalar, and for the purpose of maximizing statistics, in the following analysis we present the combined data from the negative and positive pion beams. The lower-statistics proton beam data are reported separately, since in general charmonium production is expected to differ for pions and protons.

The $J/\Psi\pi^+\pi^-$ mass spectra obtained from our πLi data, using the cuts discussed above, are shown in Figs. 7a. The $J/\Psi\pi^+\pi^-$ backgrounds were generated in two ways: by pairing di-pions from one event with J/Ψ's from another event (which preserves pion correlations) or by using same sign di-pions. Both methods gave very similar backgrounds. In general the spectra obtained by pairing J/Ψ and di-pions from different events are used, since these background spectra can be produced with greater statistics. A clear $\Psi' \to J/\Psi\pi^+\pi^-$ signal at 3.683±.005 GeV/c^2 can be seen in the opposite sign di-pion mass spectrum. In addition to the Ψ' signal, an enhancement is observed at 3.836±0.013 GeV/c^2. No such peaks are observed in the same sign di-pion mass spectra obtained using the same cuts.

A fit to a single peak plus background does not fit the $J/\Psi\pi^+\pi^-$ data well. An addition of a second peak, as shown superimposed on the data in Fig.7a, significantly improves the fit. The numbers of events above background in the Ψ' and in the second peak are determined to be 77±21 and 58±21, respectively. The widths of the Ψ' peak and the enhancement at 3.836 GeV/c^2 are 0.017±0.004 GeV/c^2 and 0.024±0.005 GeV/c^2 respectively (using the constraint of 3.097 GeV/c^2 on the mass of the dimuon), in good agreement with Monte Carlo estimates of the spectrometer resolution for the $J/\Psi\pi^+\pi^-$ mass combinations of 0.022 and 0.029 GeV/c^2 respectively. Under the assumption that the enhancement is a definite resonance state, we have determined its cross section times branching ratio relative to the simultaneously observed Ψ' signal, and from this, an absolute value for $BR(X \to J/\Psi\pi^+\pi^-)\cdot\sigma(\pi^- N \to X + x')$ of 5.3±1.9±1.3 nb per nucleon for $x_F>0$. In determining this cross section, we have used acceptances based on Monte Carlo studies which assume that the x_F distribution for the 3.836 GeV/c^2 enhancement is the same as the one observed for the J/Ψ production. The A dependence of the cross section is assumed to be $A^{0.92}$, the same as that observed in J/Ψ production.

We have searched for this enhancement in our 300 GeV/c proton beam data. The proton data have considerably lower statistics than our combined π^+ and π^- data. Because of the lower statistics, clear peaks are not observed in $J/\Psi\pi^+\pi^-$ mass spectrum at the Ψ' and the 3.836 GeV/c^2 mass in the proton data. However, there is an excess of $J/\Psi\pi^+\pi^-$ events in the proton data above background in the region ranging from the Ψ' to 3.836 GeV/c^2 that cannot be fit by the expected background shape (Fig. 7b). If, motivated by the observations of the pion data, we attempt to fit the proton beam spectrum with two Gaussians plus the background, we estimate that the excesses in the region of the two peaks are 27±23 and 45±24 events respectively: clearly the statistics of the proton data are not sufficient to validate or invalidate the pion beam results.

While the statistics are low for the Ψ' and the enhancement at 3.836 GeV/c^2, they are still adequate to study the di-pion mass distributions in the mass region of the two peaks. Fig. 8a and b show the di-pion mass distributions obtained after a subtraction of the backgrounds to the Ψ' and the 3.836 GeV/c^2 in the $J/\Psi\pi^+\pi^-$ mass spectrum in each bin of di-pion mass and before making the cut rejecting events with low di-pion mass. Both di-pion mass spectra are peaked toward the high end of the mass distribution as suggested by the Brown and Cahn theory.

Possible kinematic explanations of the 3.836 GeV/c^2 enhancement have been investigated. Improper reconstruction of real Ψ' decays at the wrong mass due to idiosyncrasies of track reconstruction have been excluded, since no spurious peaking has been produced in Ψ' Monte Carlo events subjected to the complete reconstruction process applied to the data. More to the point, we have calculated the cross-section for Ψ' production, relative to the J/Ψ again, by using the events in the Ψ' peak only. Using a branching ratio for $\Psi' \to J/\Psi\pi^+\pi^-$ of 0.324±0.026[9] and a relative efficiency of 9% for accepting and reconstructing the di-pion given that the dimuon is accepted and reconstructed, we obtain for the Ψ' cross section relative to the J/Ψ a value of 15±4±3 %, in good agreement with the value of 14±2±2 % measured in our experiment[1] from the observation of the $\Psi' \to \mu\mu$ decay mode. If all of the events in the second peak were to be interpreted as mis-measured Ψ', then the corresponding value of relative cross section would increase by a factor of 1.75, in clear disagreement with our independent measurement of Ψ' production. Also considered were Dalitz decays, $\chi \to J/\Psi e^+e^-$, or conversions of the photons from $\chi \to \gamma\Psi$ resulting in $J/\Psi e^+e^-$ final states in which the e^+e^- were misidentified as $\pi^+\pi^-$. Neither the opening angles of the charged pions nor the size of the observed enhancement are consistent with these hypotheses.

If the enhancement at 3.836 GeV/c^2 is confirmed by future experiments, then the most likely interpretation is that it is due to a $c\bar{c}$ charmonium state. A more speculative interpretation would be that it is due to a $c\bar{c}\ q\bar{q}$ state. The lack of a signal in the $J/\Psi\pi^\pm\pi^0$ mass spectrum shown in Fig. 9 and in the $J/\Psi\pi^\pm\pi^\pm$ spectra supports the interpretation of the enhancement seen in the $J/\Psi\pi^+\pi^-$ spectrum as an isospin singlet . The observation of a $J/\Psi\pi^+\pi^-$ mode for the 3.836 GeV/c^2 state which is above threshold for decays into $D\bar{D}$ (note that decays into DD^* are not allowed since the 3.836 GeV/c^2 is below DD^* threshold) implies that the 0^{++}, 1^{--}, 2^{++}, and 3^{--} quantum number assignments for this enhancement, which would permit the otherwise kinematically allowed S, P, D and F wave decays into $D\bar{D}$, are not favored. The remaining charmonium candidates for such a state are the $^1P_1(1^{+-})$,$^3D_2(2^{--})$, or the $^1F_3(3^{+-})$ states. All other charmonium states are excluded by G parity or by allowed open charm channels in $D\bar{D}$ which would dominate the decay width. Of the three states of charmonium which may provide the explanation of the enhancement at 3.836 GeV/c^2, the $^1P_1$ state is predicted to lie at or near the center of mass of the χ states at approximately 3.525 GeV/c^2. While the 3.836 GeV/c^2 enhancement could still be the first radial excitation of the $^1P_1$, the fact that we do not observe the lower mass $^1P_1$ state in the $J/\Psi\pi^+\pi^-$ mass spectrum makes this explanation unlikely. On the other hand, the $^1F_3$ state is expected to be heavier than 3.836 GeV/c^2. For an inverse square law potential the F states have the same energy as the charmonium 4S state which is identified with the observed $\Psi(4160)$ state[10]. Theoretical predictions[11,12] of 3.810 and 3.840 GeV/c^2 for the mass of the charmonium $^3D_2$ state are much closer to the observed 3.836 GeV/c^2 mass of our enhancement, and that is our preferred interpretation.

The alternative interpretation of the 3.836 GeV/c^2 enhancement as a four quark state would mean that the decay into $J/\Psi\pi^+\pi^-$ would proceed naturally via a ρ state. However, the peaking in mass of the di-pion in the 3.837 GeV/c^2 enhancement toward the ρ mass does not necessarily indicate the presence of a ρ in the decay process, since the mass spectrum may be peaked toward the high end of the spectrum by effects in this D wave decay akin to those discussed by Brown and Cahn for S wave decays. Although we could, in principle, test for the presence of a ρ in the decay process by comparison of the $J/\Psi\pi^0\pi^0$ with the $J/\Psi\pi^+\pi^-$ decay modes (since the ρ does not decay into $\pi^0\pi^0$), the combination of small branching ratio and small acceptance for the $J/\Psi\pi^0\pi^0$ mode makes this study difficult. While a spin parity analysis might also distinguish between the standard charmonium decay and four quark state hypotheses, the low statistics of the 3.836 GeV/c^2 enhancement do not permit such an investigation.

Conclusions

We have examined the $J/\Psi\pi^0$, $J/\Psi\pi^\pm$, $\Psi'\pi^\pm$, $J/\Psi\pi^+\pi^-$, $J/\Psi\pi^\pm\pi^0$, and $J/\Psi\pi^\pm\pi^\pm$ mass combinations produced in 300 GeV/c $\pi^\pm$ and proton Li interactions in a search for $c\bar{c}$ or $q\bar{q}\,c\bar{c}$ states. We have observed an enhancement in the $J/\Psi\pi^0$ mass spectrum at 3.525 GeV/c^2 in both our pion and proton beam data. The overall significance of this effect is 2.5σ in the composite pion and proton data. We conclude that the enhancement is due to the recently reported $^1P_1$ state of charmonium. When looking at the $J/\Psi\pi^+\pi^-$ mass spectrum from our pion beam data, we have observed the decay $\Psi' \to J/\Psi\pi^+\pi^-$ and a 2.8σ structure at a mass of 3.836$\pm$0.013 GeV/c^2. The $J/\Psi\pi^+\pi^-$ mass spectrum from our proton beam data does not contradict the presence of such an enhancement, although statistics are too low to allow an independent confirmation. If the 3.836 GeV/c^2 structure is eventually confirmed by other data, an interpretation as the previously unobserved $^3D_2(2^{--})$ state of charmonium is favored. We find no evidence for any structure in the $J/\Psi\pi^\pm\pi^\pm$, $J/\Psi\pi^\pm\pi^0$, $J/\Psi\pi^\pm$ and $\Psi'\pi^\pm$ mass spectra. Finally, we find no effects in our data that require a four quark explanation, although decisive tests of a four quark hypothesis are precluded by lack of statistics.

Acknowledgments

We wish to thank the U.S. Department of Energy, the Natural Sciences and Engineering Research Council of Canada, the Quebec Department of Education, and the Scientific Affairs

Division of the North Atlantic Treaty Organization for their support of this experiment. In particular, we wish to acknowledge the administration and staff of the Fermi National Accelerator Laboratory for their help.

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Figure Captions

1. Dimuon mass spectra from a)π^- ,b), π^+, c)proton, and antiproton interactions with Li at 300 GeV/c

2. E/p vs. electromagnetic detector active converter energy for charged pion candidates.

3a) All di-photon mass combinations in events containing a $J/\Psi \to \mu\mu$ b) Expected π^0 mass resolution from the Monte Carlo simulation, superimposed on background-subtracted di-photon combinations in the π^0 mass region.

4a) $J/\Psi\pi^0$ mass spectrum from the composite pion and proton beam data; b) $J/\Psi\pi^0$ mass spectrum from the pion beam data; c) $J/\Psi\pi^0$ mass spectrum from the proton beam data.

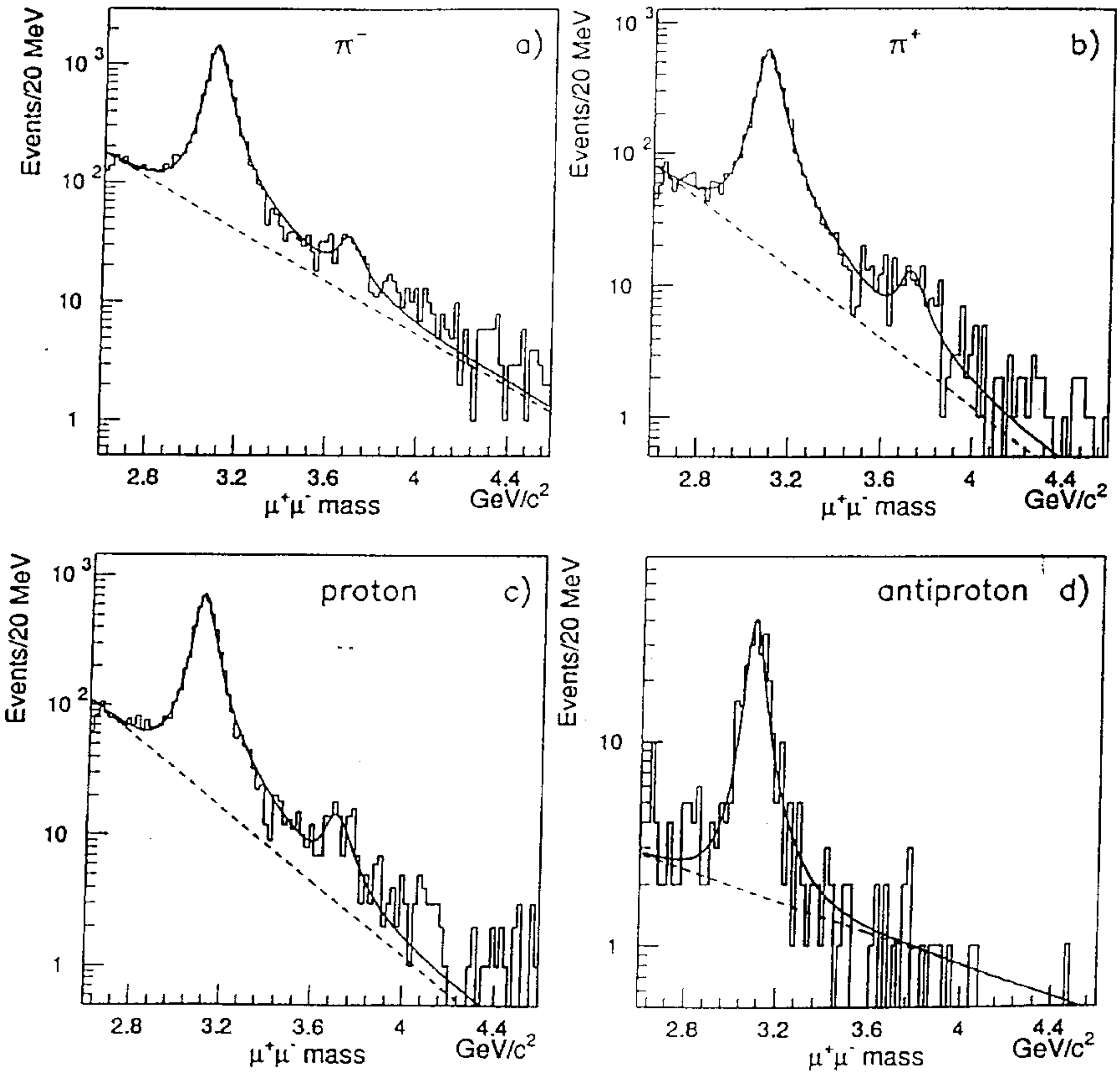
5a) $M(\mu\mu\pi^\pm)$-$M(\mu\mu)$ mass difference spectrum for $J/\Psi \to \mu\mu$ events from the composite positive and negative beam data sample; b) Threshold mass region for $M(\mu\mu\pi^\pm)$ - $M(\mu\mu)$ mass difference spectrum for composite positive and negative beam data.

6a) $M(\mu\mu\pi^\pm)$ - $M(\mu\mu)$ mass difference spectrum for $\Psi' \to \mu\mu$ events from composite positive and negative beam data sample; b) Threshold mass region for $M(\mu\mu\pi^\pm)$ - $M(\mu\mu)$ mass difference for composite negative and positive data.

7a) $J/\Psi\pi\pi$ mass spectra from 300 GeV/c πLi interactions; b) $J/\Psi\pi^+\pi^-$ mass spectrum from 300 GeV/c pLi interactions.

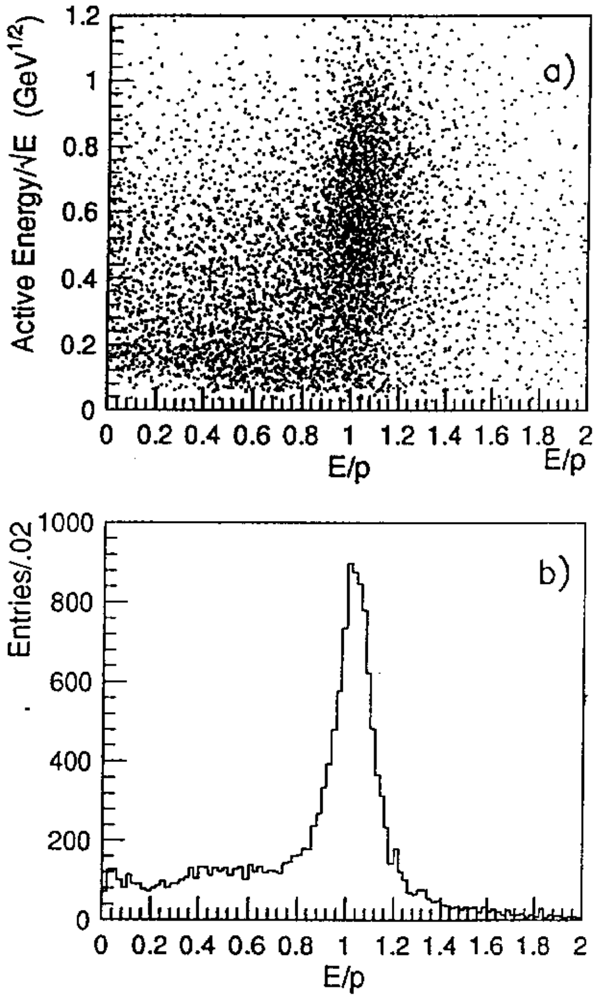
8a) $\pi^+\pi^-$ mass spectrum from $J/\Psi\pi^+\pi^-$ events in the Ψ' mass region; b) $\pi^+\pi^-$ mass spectrum from $J/\Psi\pi^+\pi^-$ events in the 3.837 GeV/c^2 mass region.

9. $J/\Psi\pi^0\ \pi^\pm$ mass spectrum from the $\pi^\pm$Li data



Events/20 MeV
π^-
a)
10^3
10^2
10
1
2.8
3.2
3.6
4
4.4
$\mu^+\mu^-$ mass
GeV/c^2
π^+
b)
proton
c)
antiproton
d)

Figure 1



Active Energy/√E (GeV^1/2)
a)
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
E/p
E/p
Entries/.02
b)
0 200 400 600 800 1000
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
E/p

Figure 2

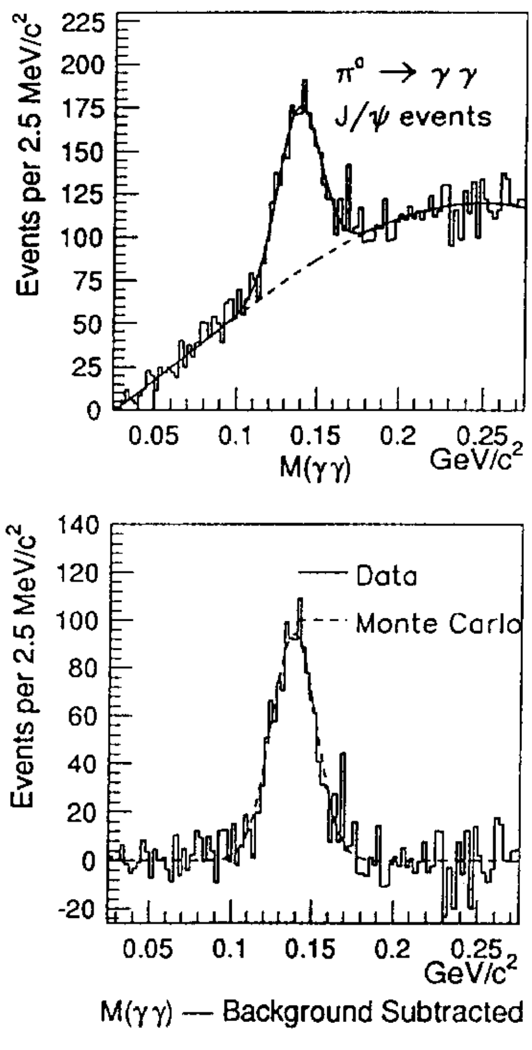
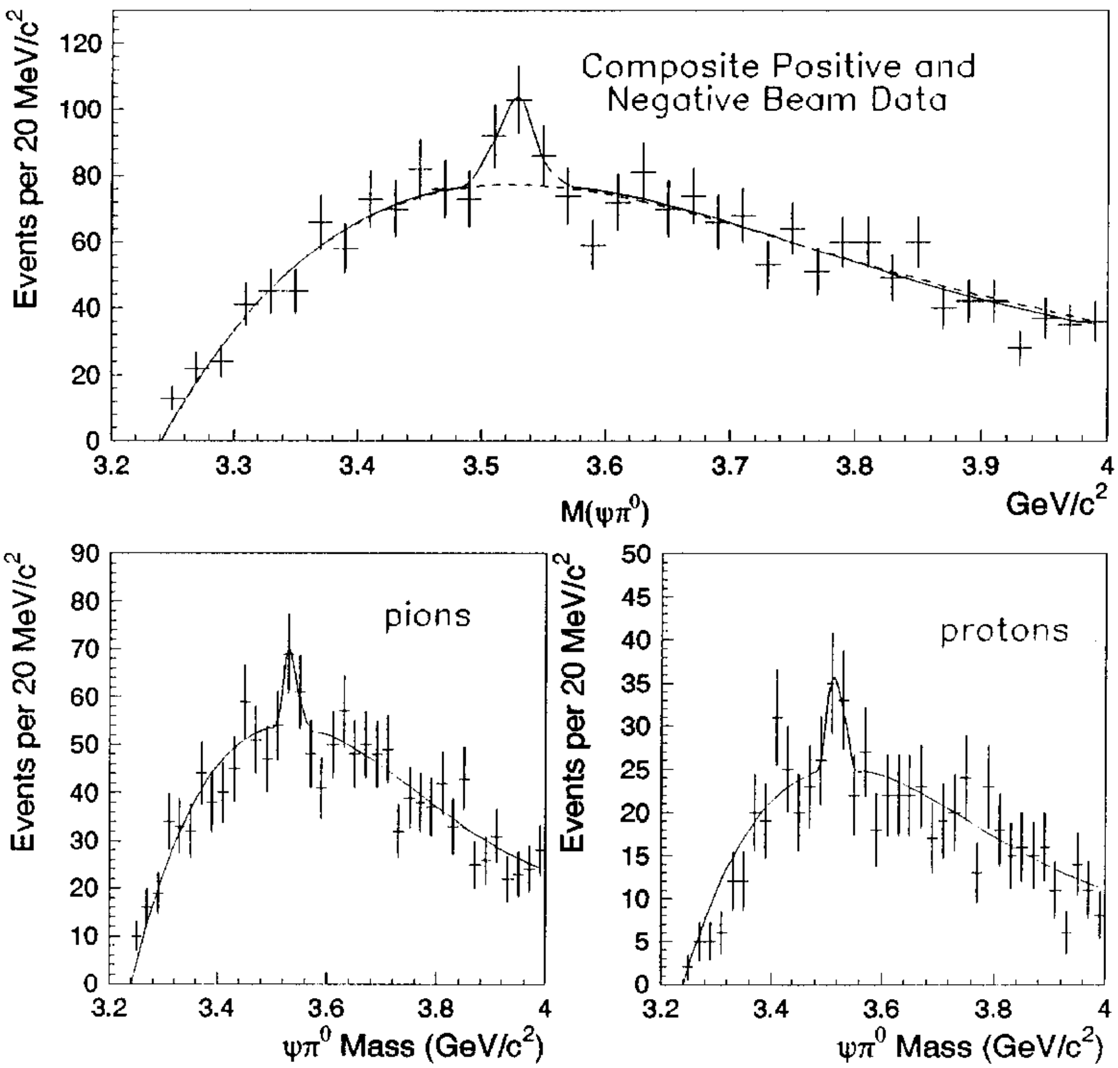

Events per 2.5 MeV/c²
225
200
175
150
125
100
75
50
25
0
π° → γ γ
J/ψ events
0.05
0.1
0.15
0.2
0.25
GeV/c²
M(γγ)
Events per 2.5 MeV/c²
140
120
100
80
60
40
20
0
-20
Data
Monte Carlo
0.05
0.1
0.15
0.2
0.25
GeV/c²
M(γγ) — Background Subtracted

Figure 3



Events per 20 MeV/c^2
Composite Positive and Negative Beam Data
M($\psi\pi^0$)
GeV/c^2
pions
protons
$\psi\pi^0$ Mass (GeV/c^2)

Figure 4

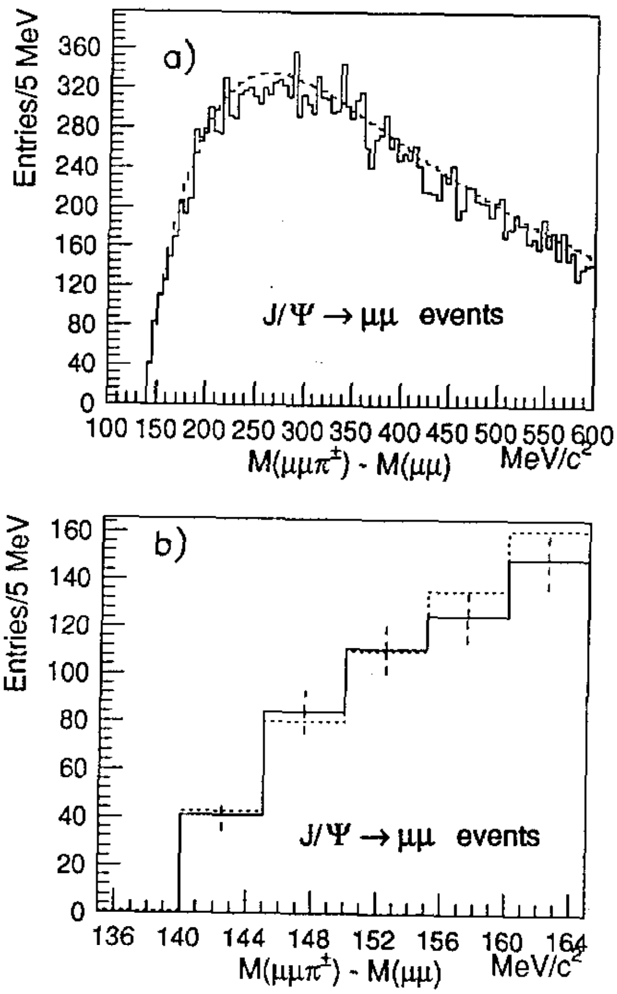
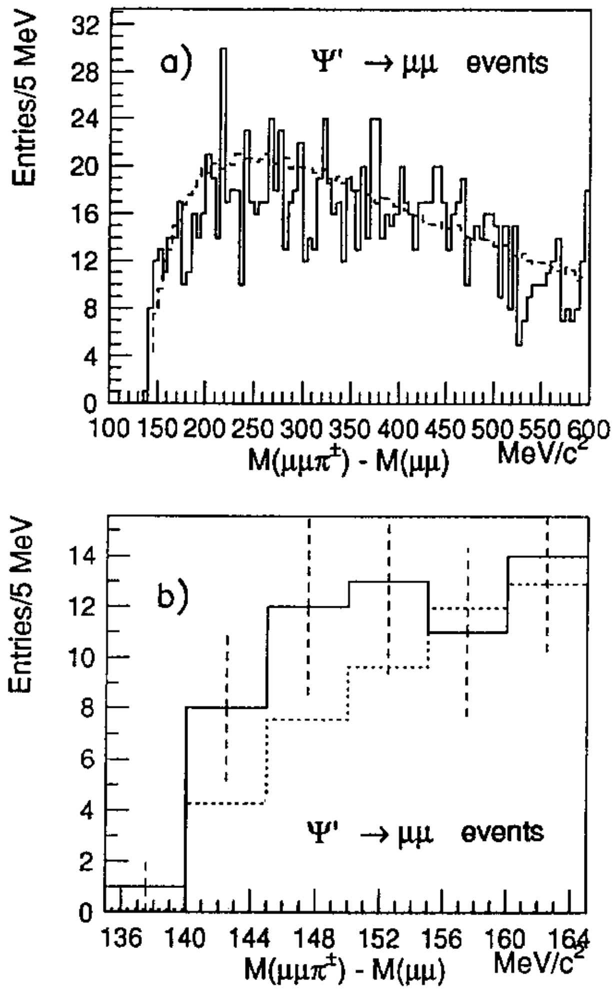

a)
Entries/5 MeV
360
320
280
240
200
160
120
80
40
0
100 150 200 250 300 350 400 450 500 550 600
M(μμπ±) - M(μμ)
MeV/c²
J/Ψ → μμ events
b)
160
140
120
100
80
60
40
20
0
136 140 144 148 152 156 160 164
M(μμπ±) - M(μμ)
MeV/c²
J/Ψ → μμ events

Figure 5



a)
Ψ' → μμ events
Entries/5 MeV
32
28
24
20
16
12
8
4
0
100 150 200 250 300 350 400 450 500 550 600
M(μμπ±) - M(μμ)
MeV/c²
b)
Ψ' → μμ events
Entries/5 MeV
14
12
10
8
6
4
2
0
136 140 144 148 152 156 160 164
M(μμπ±) - M(μμ)
MeV/c²

Figure 6

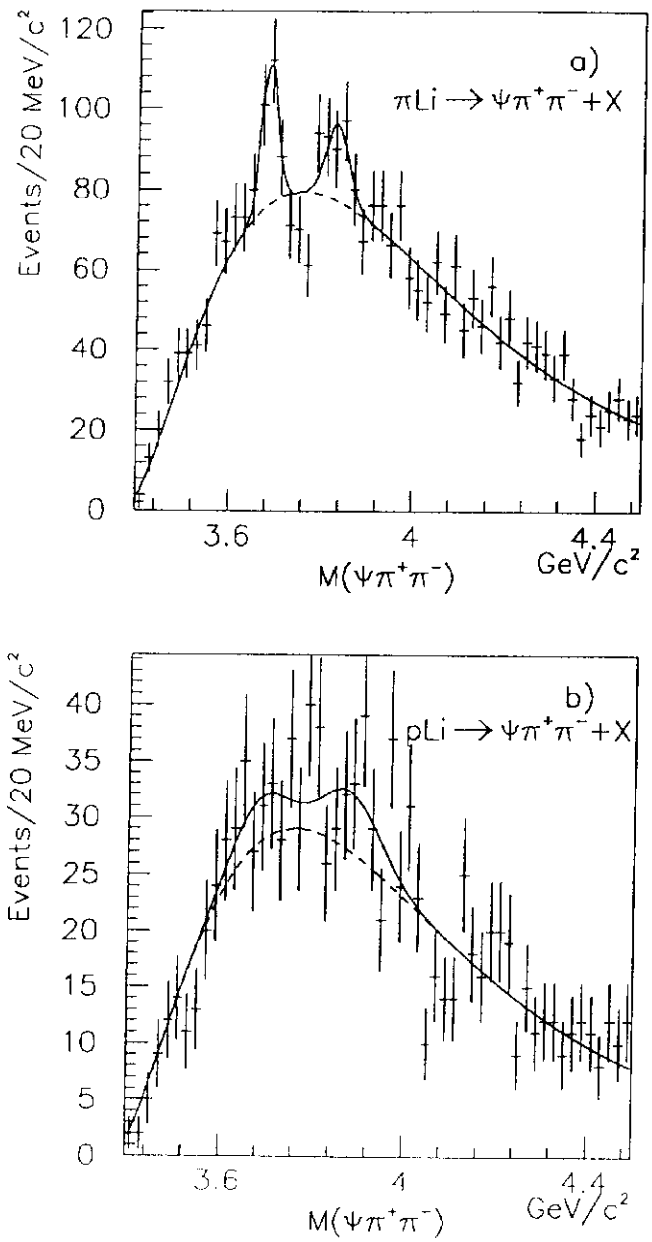
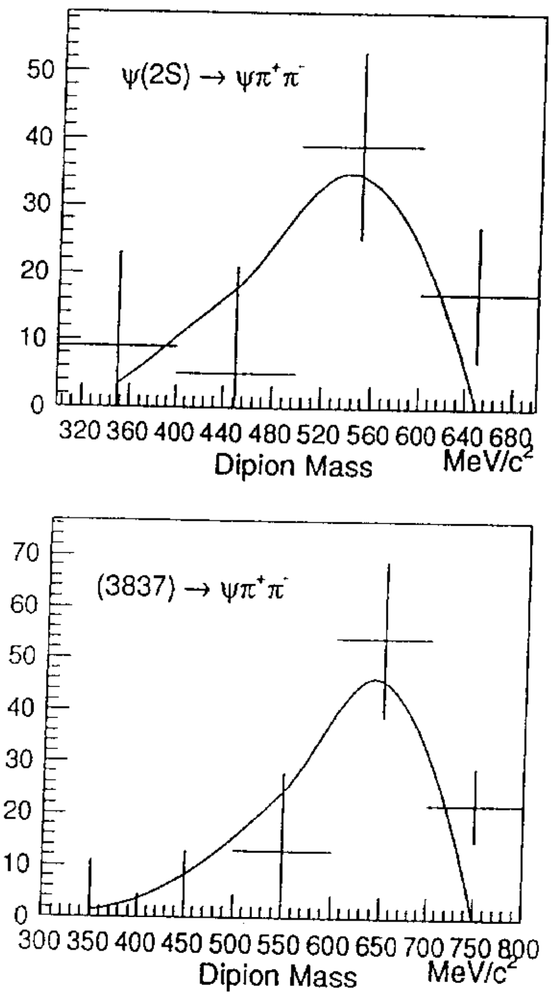

a)
πLi → ψπ⁺π⁻ + X
Events/20 MeV/c²
0
20
40
60
80
100
120
3.6
4
4.4
M(ψπ⁺π⁻)
GeV/c²
b)
pLi → ψπ⁺π⁻ + X
Events/20 MeV/c²
0
5
10
15
20
25
30
35
40
3.6
4
4.4
M(ψπ⁺π⁻)
GeV/c²

Figure 7



ψ(2S) → ψπ⁺π⁻
0
10
20
30
40
50
320 360 400 440 480 520 560 600 640 680
Dipion Mass
MeV/c²
(3837) → ψπ⁺π⁻
0
10
20
30
40
50
60
70
300 350 400 450 500 550 600 650 700 750 800
Dipion Mass
MeV/c²

Figure 8

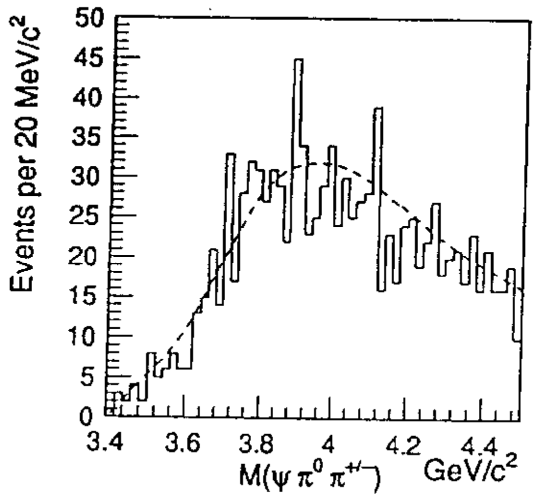

Events per 20 MeV/c²
50
45
40
35
30
25
20
15
10
5
0
3.4
3.6
3.8
4
4.2
4.4
M(ψ π⁰ π⁺/⁻)
GeV/c²

Figure 9