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A SEARCH FOR CHARMED HADRONS USING A DIRECT-MUON TRIGGER*

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ABSTRACT

We present cross section upper limits for the production of narrow states produced in 15.5 GeV π^+N collisions, in coincidence with single muons. These limits are derived from an invariant-mass search involving all charged-hadron tracks in the final state, as observed in a large streamer chamber. We also give upper limits for the production of muon-associated Λ^0 and K^0 particles.

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In this letter we report on an experiment searching for long-lived heavy hadrons emerging from π^+N collisions, preferentially in conjunction with a "prompt" muon. The existence of such particles could be interpreted in terms of a new hadronic quantum number called CHARM, as postulated in 1964[1] on the grounds of lepton-hadron symmetry. This concept was later used[2] in a gauge theory to cancel the $\Delta S \neq 0$ neutral current in order to explain the observed very small $K^o_L - K^o_S$ mass difference and the small decay width for $K^o_L \to \mu\mu$. The discovery, in high energy neutrino interactions, of the $\Delta S = 0$ weak neutral current,[3] as well as the observation of "direct" lepton signals in hadron-hadron collisions,[4] made the existence of CHARM plausible, and motivated this experiment.[5]

Adopting the most straightforward tenets of charm phenomenology, we assumed particles carrying the new quantum number are produced in pairs in the strong interaction ("associated production"), with lifetimes $\tau \lesssim 10^{-13}$ sec., and accordingly narrow widths. They decay either (semi-) leptonically or hadronically, and may yield a predominance of events containing strange particles among the resulting hadrons.

These features made a charm search a logical sequel to μ-N inelastic scattering experiments we recently completed,[6] using a two-meter streamer chamber at SLAC. This experiment featured a μ trigger, nearly 4π acceptance for final state hadrons, and good mass resolution ($\frac{\Delta M}{M} \sim 1\%$). For the charm search, the μ beam was changed to a 15.5 GeV π^+ beam. The reaction is then assumed to proceed according to the scheme

$$
\begin{aligned}
&\pi^+ p \to C_1 \, \overline{C}_2 + \cdots \\
&\qquad\qquad\quad \overline{C}_2 \to \mu\nu + \cdots \text{ (or} \to \text{hadrons)} \\
&\qquad\quad C_1 \to \text{hadrons (or} \to \mu\nu + \cdots) \, .
\end{aligned}
\qquad (1)
$$

C_1, $\overline{C}_2$ (which can be mesonic or baryonic $C \neq 0$ states) are estimated to have masses which make their production possible at our center-of-mass energy $\sqrt{s} \sim 5.6$ GeV. One decay provides the triggering muon, the other the hadrons which, if charged, permit reconstruction of invariant masses. The assumed lifetime implies total decay widths below our measurement accuracy. Figure 1 shows the experimental apparatus; the 2m streamer chamber in a 16 kGauss magnetic field contains 16 polyethylene target blocks, each 2.0 x 1.5 x 0.6 cm^3, spaced 7 cm apart along the beam trajectory. Approximately 2m downstream from the chamber, a 1.5m thick lead wall acted as a hadron absorber and, together with four scintillation hodoscopes, as a muon identifier. To reduce the dominant trigger, muons originating from meson decay, the space between chamber and lead shield was filled with polyethylene wherever possible. The resulting trigger enhances the prompt-muon-associated events by approximately two orders of magnitude over untriggered experiments.

A total of 12,000 pictures was taken with the muon trigger, from a total of 15.5 x 10^6 π interactions in a one-week run. All events were then scanned, measured, and processed with a special streamer chamber version of the TVGP and SQUAW reconstruction programs. The triggering μ track was identified from on-line computer information. All other tracks originating at the interaction vertex (as well as vees from K^o or Λ^o decays) were then used in a general search for narrow peaks.

Over 350 different mass combination (2 - 6 body, including exotics) were looked at independent of any model assumption. All muon candidates, which are clearly identified by tracking through the absorber, are eliminated from the mass search; this reduces the combinatorial background considerably. A typical plot/ is shown in Figure 2a, and the K^o mass distribution in Figure 2b.

In the mass plots, the background levels are increased by combinatorial effects inherent in our search for invariant mass peaks. Combinatorial effects are aggravated by the lack of particle identification. Also, no kinematical fitting was attempted to eliminate events that contain multiple neutrals from our sample. However, any state with width less than our resolution and a sufficient production cross section will stand out above these backgounds.

We reduce the combinatorial backgrounds by assuming that only one pair of charmed hadrons was produced per event, and that only one of the pair decayed hadronically to charged particles. This implies that there can be at most one charmed entry in any mass interval from a single event for a given n-particle combination. Thus all plots were "masked" in such a way that no histogram bin contains more than one entry per event.

Using the known π^+N total cross section at 15.5 GeV/c, the experimental sensitivity for charmed particle production was determined to be 627 events/μb x B_L x B_H x Eff, where B_L and B_H are the branching ratios into muonic and charged hadronic modes, respectively. Eff is the detection efficiency for the muon. It is a strong function of the unknown charm production and decay distributions, mainly in transverse momentum ($p_\perp$) and energy (E) of the muon. This detection efficiency for the muon is shown in Figure 3.

The results of the mass search are displayed in Table I. Invariant mass distributions for 2, 3, 4, and 5 charged-particle systems were computed using assumed $\pi^\pm$, $K^\pm$, $p^\pm$ mass hypotheses. Table I lists, for each particle combination and for 3 mass ranges, the 97%-confidence upper limits to the cross sections for charmed-particle production, assuming a simple model for transverse momentum $p_\perp$ and energy E of the C-decay muon.

These upper limits were determined by scanning each mass region, in bins consistent with our mass resolution, for the bin that maximized the quantity $N_{total} - N_{background} + 2\sqrt{N_{total}}$.

We have looked at a total of some 70,000 mass combination bins. To evaluate the statistical significance of any one-bin peak in the effective-mass distributions, we have used the mass data to define a background curve for each bin i, by applying the procedure of running-mean-values over 11 bins from i - 5 to i + 5, with an effective constraint on the derivative.[8] This procedure, which is questionable only in regions of steeply changing population (e.g., at the lower end of phase space), avoids most pitfalls of model building for the background. Its inherent inaccuracy close to threshold persuaded us not to use the first 8 bins in any mass combination to set cross section limits.

To establish the 97% confidence limits for the weighted cross sections, $\sigma_{meas} = \sigma(C\bar{C}) \times B_L \times B_H \times Eff$ of Table I, the product $B_L \times B_H \times Eff$ was estimated to be $\sim .016$ using Eff $\simeq 0.16$ (hence $\sigma(C\bar{C}) \simeq 60\sigma_{meas}$).[7] This puts our sensitivity at the level of ~ 0.1 μb/event.

Figure 4a shows the distribution of standard deviations from the smoothed background curve, for a representative data sample. While we see no significant deviations from Poisson statistics, there are 3 bins with probability less than one over the number of bins studied, i.e. $\lesssim 1.3 \times 10^{-5}$. They are located at $m(K^-K^-) = 1.244$ GeV/c^2; $m(K^+K^-) = 1.984$ GeV/c^2; and $m(\bar{p}\pi^+\pi^+) = 1.750$ GeV/c^2. (Two of these are shown in Figures 4b,c.) The corresponding values for the production cross section with the assumed efficiencies and branching ratios are (2.3 ± .5)μb, (1.9 ± 0.4)μb, and (7.3 ± 0.9)μb, respectively. The quoted errors are statistical only. A detailed investigation of all events in these bins did not uncover any other telling feature such as additional strange-particle production. We feel that, because of its quantum numbers, the enhancement at $m(K^+K^-) = 1984\ \mathrm{MeV}/c^2$ is the most promising one for further investigation.

We also use the inclusive K^o and Λ^o production observed in this experiment to set upper limits on the cross sections

$$\begin{aligned} \pi^+N &\to K^o\,\mu + \ldots, \\ &\to \Lambda^o\,\mu + \ldots. \end{aligned} \qquad (p(\mu) \geq 2\ \mathrm{GeV}/c) \qquad (2)$$

Note that, in the conventional charm scheme, a large fraction of associated charm production will yield these signatures (cf. relation (1)). These upper limits are 10.0μb and 2.0μb, respectively.

While some sets of data are under additional scrutiny at this time, we see no conclusive evidence for muon-associated production of long-lived states decaying into 2,3,4, or 5 charged hadrons at the microbarn level. We are currently starting an improved version of this experiment, which will give us a tenfold increase in statistics while, at the same time, improving the muon enrichment by a factor of 3.

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7. To estimate these quantities, we adopt standard assumptions as outlined in Gaillard et al., Revs. Mod. Phys. 47, 277 (1975).
8. This procedure uses in part the smoothing package available with the SLAC KIOWA plotting program. (CGTM #146).

FIGURE CAPTIONS

1. Experimental apparatus showing 2m streamer chamber in 16kG magnetic field. Trigger hodoscopes and hadron absorber are arranged on both sides of beam line and pulsing system.

2. a) Invariant mass distribution for two positive plus two negative tracks, assuming all tracks are due to pions.

   b) Invariant mass distributions of measured vees, assuming both tracks are due to pions. The ensuing K^o mass peak has a width of 7 MeV/c^2 FWHM.

3. Trigger efficiencies due to muon detection, for given muon momentum, plotted vs. transverse momentum.

4. a) Distribution of standard deviations from a smooth background, for the invariant mass plots. The insert shows the high-deviation tail on an expanded scale.

   b) Invariant-mass plot for two oppositely charged tracks, assuming they are due to kaons, with a cut on the transverse momentum. Insert: expanded plot of region around $m(K^+K^-) \sim 2000$ MeV/c^2.

   c) Invariant-mass plot for one negative plus two positive tracks, assuming they are due to an antiproton and two π^+.

TABLE CAPTIONS

Upper limits for production of narrow hadronic states decaying into any charge combination of the particles indicated, excluding neutral pions and neutrons. Values quoted are in microbarns.

This table summarizes the information on some 350 charge and mass combinations, computed for three invariant-mass ranges: threshold to 1.5 GeV/c^2; 1.5 to 2.4 GeV/c^2; 2.4 to 3.1 GeV/c^2. They can be obtained from the authors on request.

TABLE I

$K\pi$	0.5 - 12
$K\pi\pi$	0.5 - 10
$K\pi\pi\pi$	1 - 12
$K\pi\pi\pi\pi$	1 - 7
$KK\pi$	1 - 13
$KK\pi\pi$	1 - 12
$KK\pi\pi\pi$	2 - 10
KK	0.5 - 10
KKK	1 - 11
$KKKK$	2 - 8
ΛK	1 - 4
$\Lambda K\pi$	1 - 4
$\Lambda K\pi\pi$	1 - 4
$P\pi$	2 - 13
$P\pi\pi$	2 - 12
$P\pi\pi\pi$	2 - 7
$P\pi\pi\pi\pi$	2 - 7
$\pi\pi$	0.5 - 9
$\pi\pi\pi$	0.5 - 7
$\pi\pi\pi\pi$	1 - 7
$\pi\pi\pi\pi\pi$	1 - 6

$\Lambda\pi$	1 - 3
$\Lambda\pi\pi$	1 - 3
$\Lambda\pi\pi\pi$	1 - 4
ΛP	4 - 5
$\Lambda\bar{P}$	< 2
PP	5 - 8
$P\bar{P}$	2 - 8
$\bar{P}\bar{P}$	2 - 3
$\bar{P}\pi$	1 - 9
$\bar{P}\pi\pi$	1 - 9
$P\bar{P}\pi$	3 - 15
$P\bar{P}\pi\pi$	3 - 7
PK	3 - 15
$PK\pi$	4 - 14
$PK\pi\pi$	5 - 13
$\bar{P}K$	1 - 6
$\bar{P}K\pi$	2 - 14

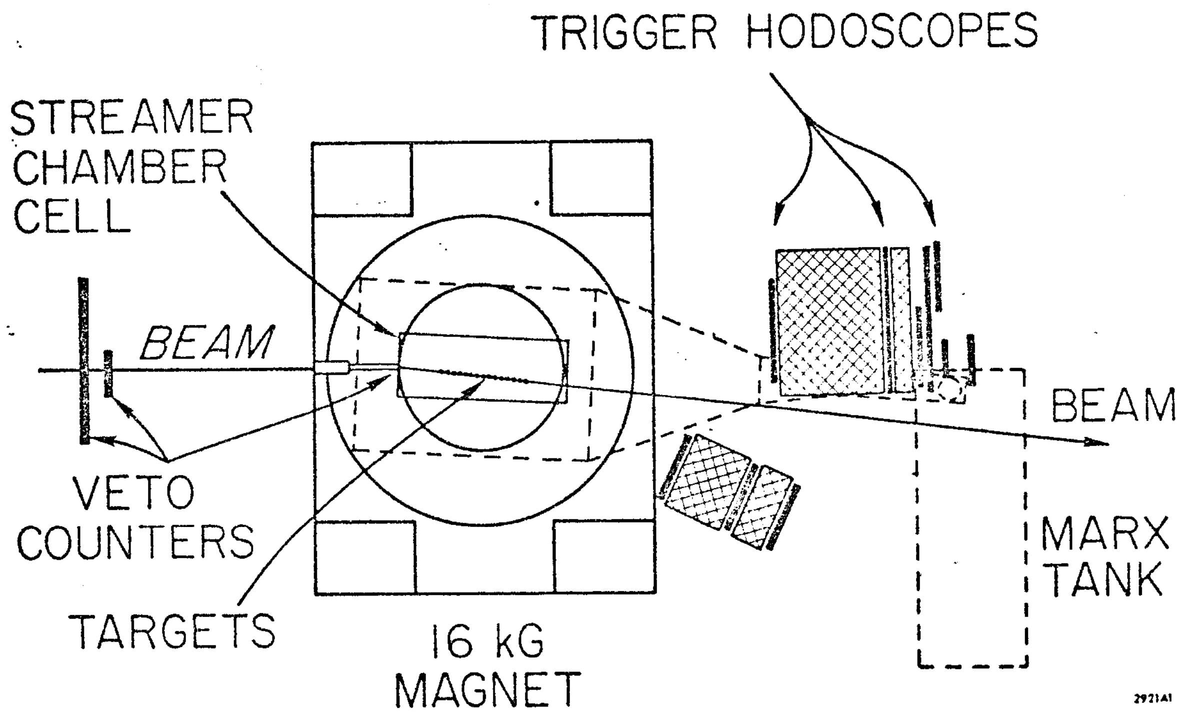

TRIGGER HODOSCOPES
STREAMER
CHAMBER
CELL
BEAM
BEAM
VETO
COUNTERS
TARGETS
16 kG
MAGNET
MARX
TANK
2921A1

Figure 1

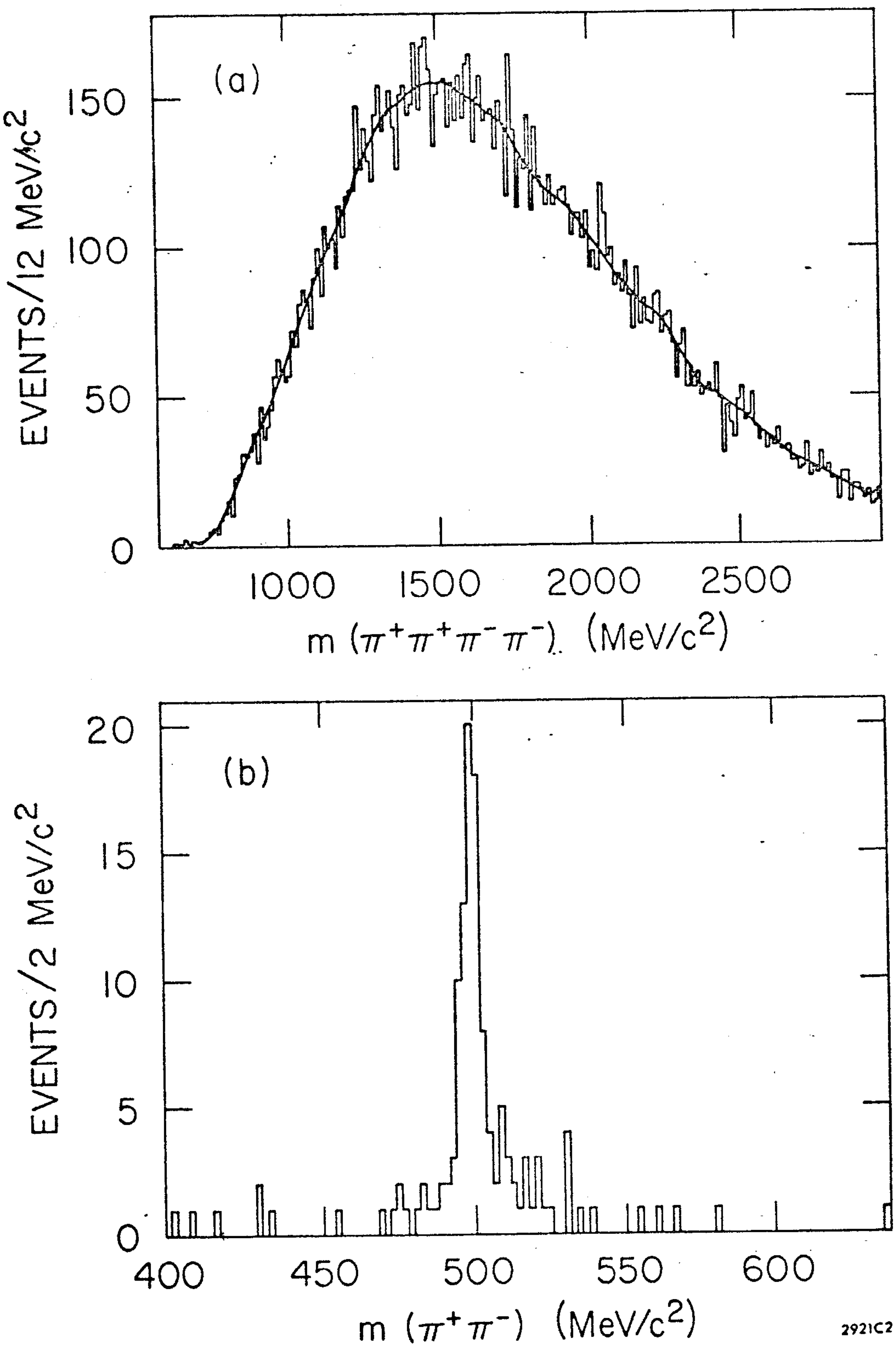
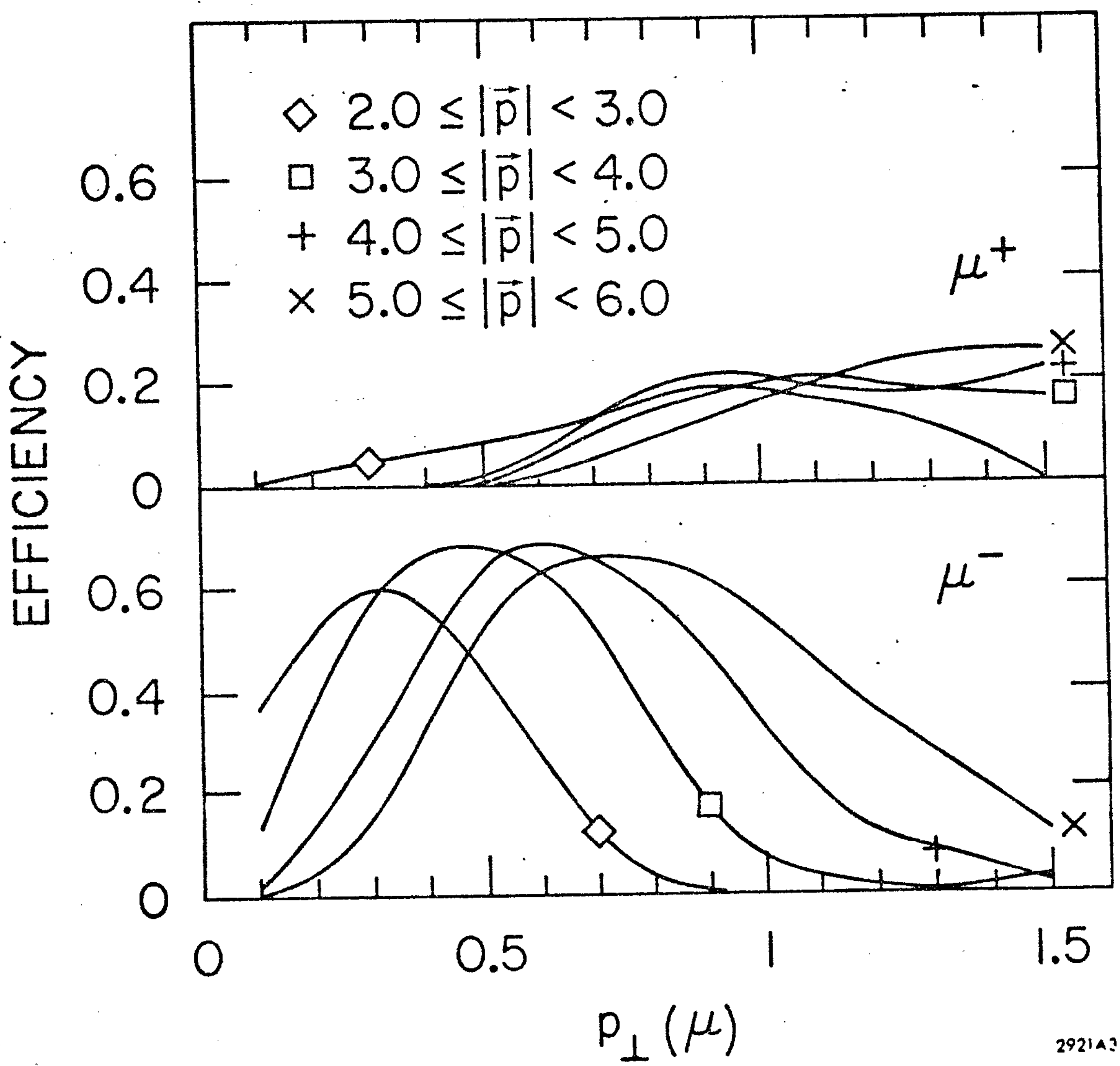
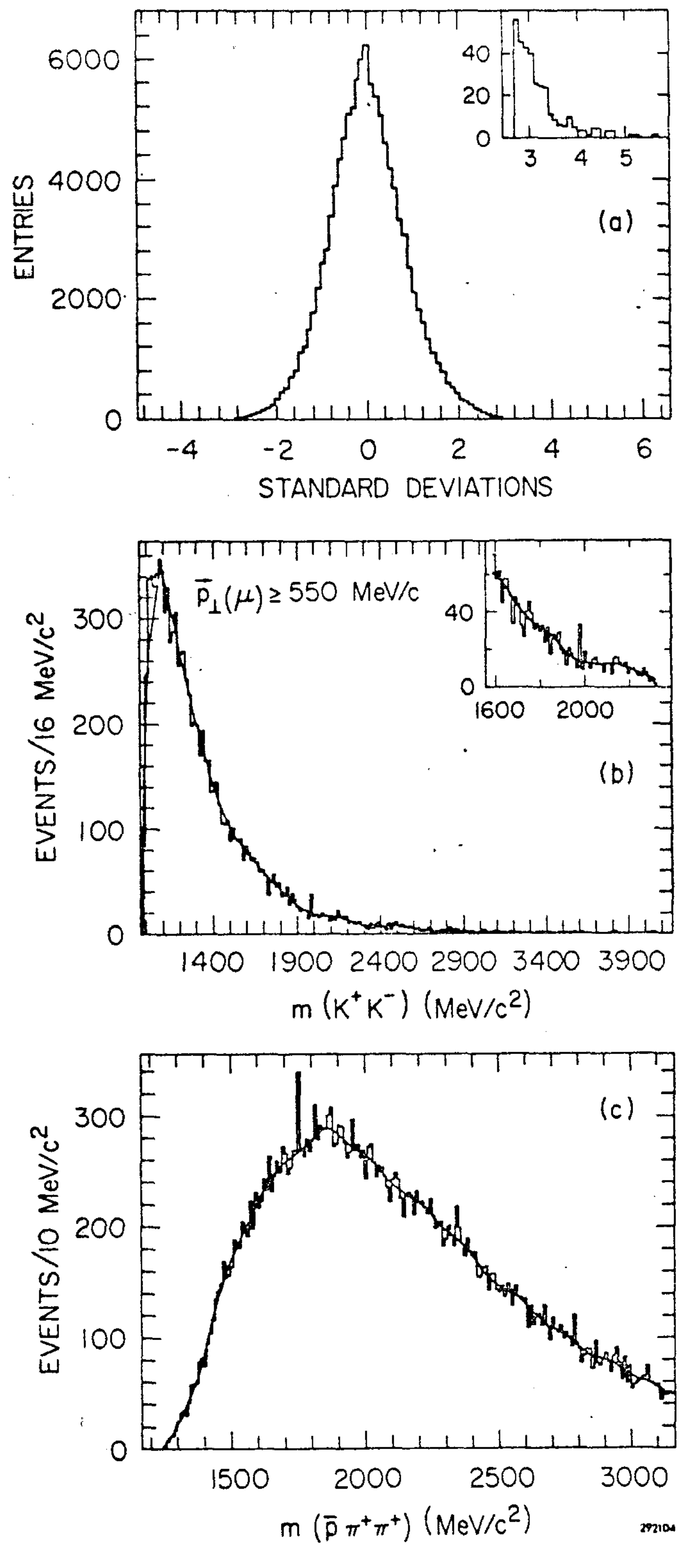

(a)
EVENTS/12 MeV/c^2
150
100
50
0
1000
1500
2000
2500
m ($\pi^+\pi^+\pi^-\pi^-$) (MeV/c^2)
(b)
EVENTS/2 MeV/c^2
20
15
10
5
0
400
450
500
550
600
m ($\pi^+\pi^-$) (MeV/c^2)
2921C2

Figure 2



◇ 2.0 ≤ |p| < 3.0
□ 3.0 ≤ |p| < 4.0
+ 4.0 ≤ |p| < 5.0
× 5.0 ≤ |p| < 6.0
μ+
μ−
EFFICIENCY
0.6
0.4
0.2
0
0.6
0.4
0.2
0
0
0.5
1
1.5
p⊥ (μ)
2921A3

Figure 3



ENTRIES
6000
4000
2000
0
-4
-2
0
2
4
6
STANDARD DEVIATIONS
40
20
0
3
4
5
(a)
EVENTS/16 MeV/c²
300
200
100
0
$\bar{p}_{\perp}(\mu) \geq 550$ MeV/c
1400
1900
2400
2900
3400
3900
m (K⁺K⁻) (MeV/c²)
40
0
1600
2000
(b)
EVENTS/10 MeV/c²
300
200
100
0
1500
2000
2500
3000
m ($\bar{p}\,\pi^+\pi^+$) (MeV/c²)
(c)

Figure 4