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PION AND NUCLEON DISSOCIATION IN $\pi^- p \to \pi^-\pi^+\pi^- p$ AT 205 GeV/c*

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Abstract.—In a 48,000-picture exposure of the Fermilab 30-inch hydrogen bubble chamber to a 205 GeV/c π^- beam, we have measured 169 events of the reaction, $\pi^- p \to \pi^-\pi^+\pi^- p$, with a cross section of 635±61 μb. This reaction proceeds almost entirely via low mass $\pi^- \to 3\pi$ and $p \to p\pi\pi$ dissociation. Factorization is satisfied for $p \to p\pi\pi$ dissociation in πp and pp interactions.

Introduction.—The reaction $\pi^- p \to \pi^-\pi^+\pi^- p$ has been studied extensively below 25 GeV and the $\pi^- \to \pi^-\pi^+\pi^-$ dissociation part of it has been observed previously up to 40 GeV [1,2]. We show that this first $\pi^- p$ exclusive multiparticle reaction to be isolated at Fermilab energies proceeds almost entirely via pion and nucleon dissociation into low mass states with partial cross sections and other characteristics similar to those observed in 16-40 GeV $\pi^- p$ interactions. We have presented preliminary results in ref. [3]. The beam, the film analysis procedures, the geometrical reconstruction and

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kinematical fitting of events (using TVGP and SQUAW) and various checks on the accuracy and precision of the measurements are described in refs. [3-5]. Ref. [6] discusses pion dissociation in the inclusive reaction $\pi^- p \rightarrow pX^-$. Some corresponding data from Fermilab pp experiments may be found in ref. [7].

Background Analysis.—At 205 GeV 4-constraint fits are less efficient than at lower energies in eliminating background in the reaction $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$. We have made a study of possible backgrounds [4] using several techniques: (a) simulating missing neutral particles by dropping two or more tracks from measured 6- and 8-prong events and subjecting the events so obtained to the same kinematical fitting and analysis procedures as the real events; (b) by fitting to the hypothesis $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$ those 4-prong events observed with associated $\gamma \rightarrow e^+ e^-$ pairs or strange particle decays; (c) by analyzing transverse momentum imbalance and missing-mass distributions [3,4]; (d) by simulating digitizations of tracks from possible background and signal reactions and processing these Monte-Carlo simulated events as we do the real ones. Thirteen different reactions were simulated. Only a few background reactions were found [4] to have significant feed-through into the 4C channel; for these, cross checks are available from the measured events and the events from which tracks were dropped. The most potentially contaminating reactions were those that produced a low mass $\pi^- \pi^0$, $\pi^- \pi^0 \pi^0$, $\pi^- \pi^+ \pi^- \pi^0$, or $\pi^- \pi^+ \pi^- \pi^0 \pi^0$ combination in the forward direction. Fortunately, however, the production of an even number of forward pions requires G-parity exchange, which is expected to be small compared with diffractive processes at these energies. This is substantiated by the observation that $\rho^0 \Delta^0$ production does not contribute significantly to the $\pi^- \pi^+ \pi^- p$ final state, as shown below.

We conclude from this study that background to events fitting $\pi^- \pi^+ \pi^- p$

with $\chi^2 < 15$ is 10±6% for target dissociation, defined as $M_{p\pi^+\pi^-} < 3.3$ GeV, and 15±3% for beam dissociation, defined as $M_{\pi^-\pi^+\pi^-} < 3.3$ GeV; the latter background is concentrated mainly in the $1.8 < M_{3\pi} < 3$ GeV region, as discussed further below. No events which fit $\pi^-p \to \pi^-\pi^+\pi^-p$ with $M_{p\pi^+\pi^-} < 3.3$ GeV and $\chi^2 < 15$ also fit the reaction $\pi^-p \to \pi^-K^+K^-p$. We cannot exclude experimentally a possible 10-30% contribution of $\pi^-K^+K^-p$ to the beam dissociation sample; however, the only known $\pi^+\pi^-$ state which also has a significant branching ratio (5%) to K^+K^- is the f^o, which, as shown below, contributes little to our data. Therefore we neglect $\pi^-K^+K^-p$ background in both target and beam dissociation samples. We neglect contamination from $\pi^-p \to \pi^-p\bar{p}p$ and from any reactions caused by the K^- (1.4%) and $\bar{p}$ (0.2%) beam components.

Results: Cross Sections.—We find a cross section of 635±61 μb for $\pi^-p \to \pi^-\pi^+\pi^-p$ at 205 GeV after subtracting the above background estimates and making corrections [4] of 5.5±0.6% for loss of short recoil protons, and 7.4±2% for fitting inefficiency. This cross section is 18±2% of the total 4-prong cross section of 3.5 mb at 205 GeV and 2.6% of the 24 mb total cross section. For comparison, at 20 GeV [1] the 4-prong cross section is 8.52±0.25 mb, of which only 10%, or 880^{+62}_{-89} μb, is $\pi^-p \to \pi^-\pi^+\pi^-p$. The cross section for $\pi^-\pi^+\pi^-p$ falls more slowly at high beam momentum than below 20 GeV (Fig. 1), as might be expected if it is increasingly dominated by diffractive processes. Similar behavior is observed [8-10] for elastic scattering, also shown in Fig. 1; e.g., elastic scattering and $\pi^-\pi^+\pi^-p$ cross sections fall by the same fraction, ~ 30%, between 20 and 205 GeV.

Characteristics of the $\pi^-\pi^+\pi^-p$ Final State.—Fig. 2 shows $M_{\pi^-\pi^+\pi^-}$ vs the smaller of the two $M_{p\pi^+\pi^-}$ combinations for each $\pi^-\pi^+\pi^-p$ event. Two distinct clusters of events are observed, one with low $M_{3\pi}$ which we associate with pion dissociation and the other with low $M_{p\pi\pi}$ which we associate with nucleon dissociation. To the 635 μb $\pi^-\pi^+\pi^-p$ cross section, pion dissociation ($M_{3\pi} < 3.3$ GeV) contributes about 2/3 (416±50 μb) and nucleon dissociation ($M_{p\pi^+\pi^-} < 3.3$ GeV) contributes about 1/3 (184±33 μb). There are no events common to both categories (thus defined) and only 5.5% (35±12 μb) falls in neither category [4,11]. No events fall simultaneously in the ρ^0 region of $M_{\pi^+\pi^-}$ and the Δ^0 region of M_{π^-p}, leading to a 90% confidence upper limit of 8.5 μb for the $\pi^-p \to \rho^0\Delta^0$ cross section at 205 GeV.

Pion Dissociation.—It is clear from Fig. 2 and the $M_{3\pi}$ projection in Fig. 3a that the pion dissociation sample is dominated by a peak near 1.1 GeV. This peak is associated mainly with ρ^0 as shown by the $M_{\rho^0\pi}$ distribution (shaded in Fig. 3a) and the $M_{\pi^+\pi^-}$ distribution of Fig. 4a. The ρ^0 decay angular distribution (Fig. 4b) for $M_{3\pi} < 1.2$ GeV is consistent with predominance of the $\cos^2\theta$ term expected for the A_1 S-wave $\pi\rho$ state and has an asymmetry similar to that observed at lower beam momenta [1]. In the 3π rest system the azimuthal angle about the beam direction of the normal to the 3π decay plane [4] is consistent with isotropy, also as observed at lower energies. Based on lower energy results [2], we do not expect to see with our limited statistics a significant A_3 peak in Fig. 3a, nor a significant $f^0 \to \pi^+\pi^-$ signal in Fig. 4a. We see no significant $\pi\pi$ mass peaks above the ρ^0, nor 3π mass peaks above the A_1.

Fig. 5a shows partial cross sections vs beam momentum for three $M_{3\pi}$ bands. The cross section at 205 GeV for the A_1 region, $0.8 < M_{3\pi} < 1.2$ GeV, is 188±30 μb; for the region $1.2 < M_{3\pi} < 1.4$, it is 83±20 μb, and for the third region ($1.4 < M_{3\pi} < 2.0$ GeV) it is 95±25 μb. In obtaining the 205 GeV cross sections we have subtracted the estimated neutrals background shown by the dashed curve in Fig. 3a. Thus the production cross section above ~ 20 GeV for the A_1 mass region is constant within errors as would be expected for a diffractive process. The cross section for the higher mass regions may fall somewhat with beam momentum.

The distribution [4] of the square of the four-momentum transfer t from beam to 3π system for the A_1 region has an exponential slope of 11.6±2.7 GeV^{-2} for $0.02 < -t < 0.3$ GeV^2, consistent with that observed [1] at 20 GeV (13.0±1.4 GeV^{-2}). For $M_{3\pi} < 3.3$ GeV the slope is 9.2±1.2 GeV^{-2} for $0.02 < -t < 0.5$ GeV^2, similar to the slope of 8.8±0.4 GeV^{-2} that we observe for elastic scattering.

Target Dissociation.—The $p\pi^+\pi^-$ mass spectrum (Fig. 3b) shows a prominent peak near 1.55 GeV associated with the peaks in the Δ^{++} and Δ^0 mass regions in Figs. 4c,d. The slope of the distribution of four-momentum transfer t from target to $p\pi\pi$ system is 12.8±2.4 GeV^{-2} for $M_{p\pi\pi} < 3.3$ GeV and $-t < 0.3$ GeV^2. The cross section for $1.4 < M_{p\pi\pi} < 1.8$ GeV is 95±19 μb, which is roughly half of the 184±33 μb target dissociation cross section. For comparison, at 20 GeV [1] the cross section for the same mass region is 113±11 μb, which is less than one-third of the cross section (366±32 μb) for $M_{p\pi\pi} < 3.3$ GeV. Fig. 5b shows that the lower $p\pi\pi$ mass region is produced with cross section falling only slowly if at all with beam momentum above 20 GeV while the higher $M_{p\pi\pi}$ region falls by a factor two from 20 to 205 GeV. Thus the $p \to p\pi\pi$ dissociation cross section behaves similarly to the $\pi \to 3\pi$ as a function of beam momentum and of three-body mass.

Factorization.—As a test of factorization we compare nucleon dissociation, $p \to p^* \to p\pi^+\pi^-$ for $M_{p\pi\pi} < 3.3$ GeV in $\pi^-p \to \pi^-p\pi^+\pi^-$ and $pp \to pp\pi^+\pi^-$ [7] at 205 GeV. If these two reactions as well as π^-p and pp elastic scattering are mediated by the same factorizable exchange (e.g., Pomeron), then we expect:

$$\sigma(\pi^-p \to \pi^-p^*)/\sigma(pp \to pp^*) = \sigma(\pi^-p \to \pi^-p)/\sigma(pp \to pp) .$$

The right-hand side is 0.47±0.03 (i.e., 3.22±0.18 mb/6.80±0.20 mb) and the left-hand side is 0.63±0.15 (i.e., 184±33 μb/290±50 μb). Thus, factorization is satisfied within errors. We expect the $M_{p\pi\pi}$ distributions also to be similar. The dotted histogram of Fig. 3b shows $M_{p\pi^+\pi^-}$ for 205 GeV $pp \to p\pi^+\pi^-p$ [7] normalized by one-half the ratio of π^-p to pp elastic scattering cross sections (both beam and target dissociation are plotted for pp). Fair agreement is apparent with the solid histogram ($M_{p\pi^+\pi^-}$ for 205 GeV $\pi^-p \to \pi^-\pi^+\pi^-p$), except perhaps for the 1.55 GeV peak region. Factorization in $\pi^-p \to pX$ vs $pp \to pX$ at 205 GeV is discussed in [12].

Conclusions.—The reaction $\pi^-p \to \pi^-\pi^+\pi^-p$ has a cross section of 635±61 μb at 205 GeV. It is dominated by peripheral $\pi \to 3\pi$ and $p \to p\pi\pi$ dissociation into low mass states, with mass, momentum transfer and angular distributions similar to those observed for corresponding low mass states produced from 16 to 40 GeV. The cross sections for low mass ($M < 3.3$ GeV) 3π and $p\pi\pi$ states are 416±50 μb and 184±33 μb, respectively. For $M_{3\pi} < 1.2$ GeV and $M_{p\pi\pi} < 1.8$ GeV the cross sections are consistent with being independent of beam momentum above ~ 20 GeV. The $\pi^-\pi^+\pi^-p$ and elastic scattering cross sections both fall from 20 to 205 GeV by approximately 30%. A test of factorization is satisfied for target dissociation in πp and pp reactions.

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FIGURE CAPTIONS

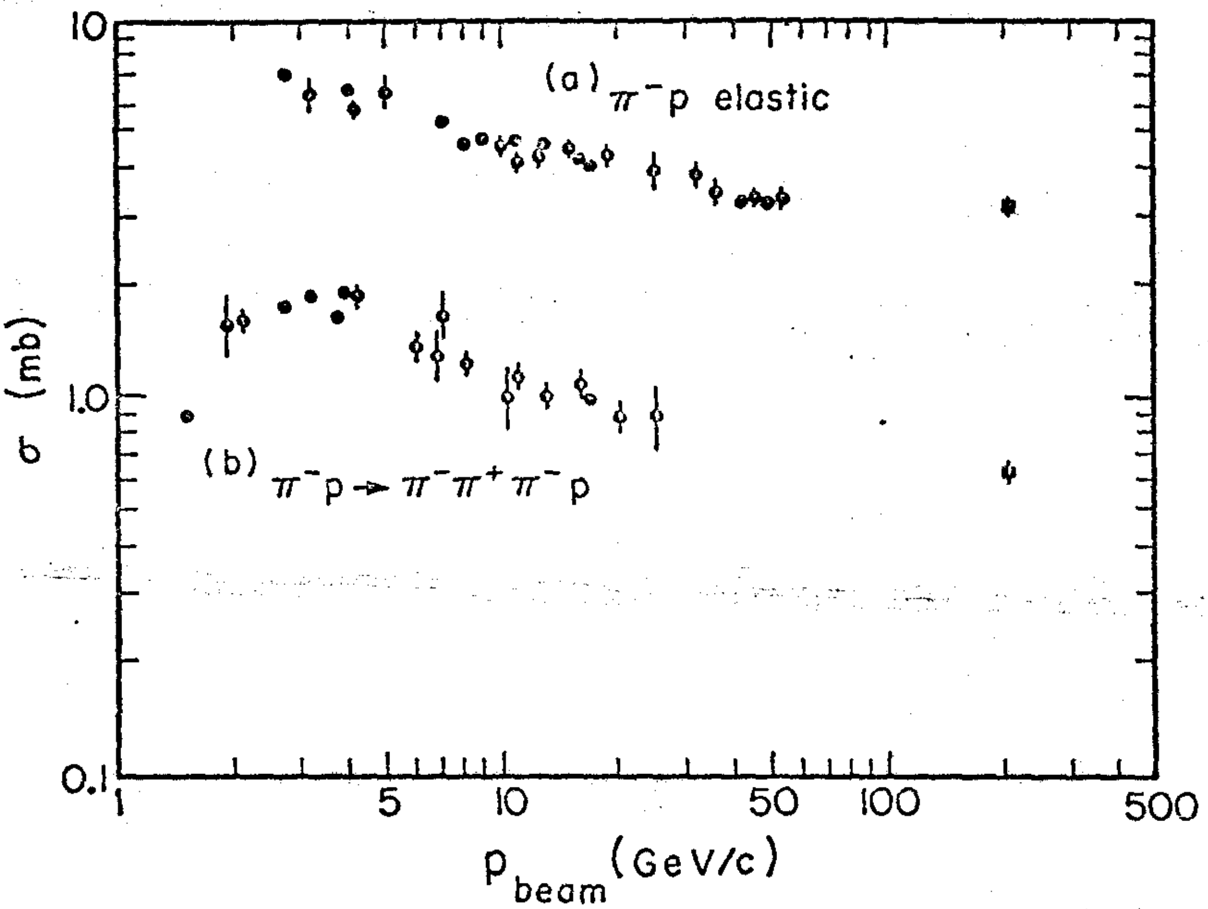
Fig. 1. Cross sections for (a) $\pi^- p \to \pi^- p$ and (b) $\pi^- p \to \pi^- \pi^+ \pi^- p$ vs beam momentum. Data are from [1,8,9,10].

Fig. 2. Mass of $\pi^-\pi^+\pi^-$ vs the smaller of the two $p\pi^+\pi^-$ masses for events fitting $\pi^- p \to \pi^-\pi^+\pi^- p$ with $\chi^2 < 15$. The mass resolution is ~7 MeV for small $M_{p\pi\pi}$ and ~ 70 MeV for small $M_{3\pi}$.

Fig. 3. (a) Mass of 3π system. The dashed curve is background from events with undetected neutral particles, estimated by dropping two tracks from 6-prong events. Events with either or both $M_{\pi^+\pi^-}$ between 0.61 and 0.92 GeV (ρ^0 region) are cross-hatched. (b) Mass of $p\pi^+\pi^-$ system. The dotted curve is from 205 GeV $pp \to p\pi^+\pi^- p$ [7] normalized by 0.5 times $(\sigma(\pi^- p \to \pi^- p)/\sigma(pp \to pp))$.

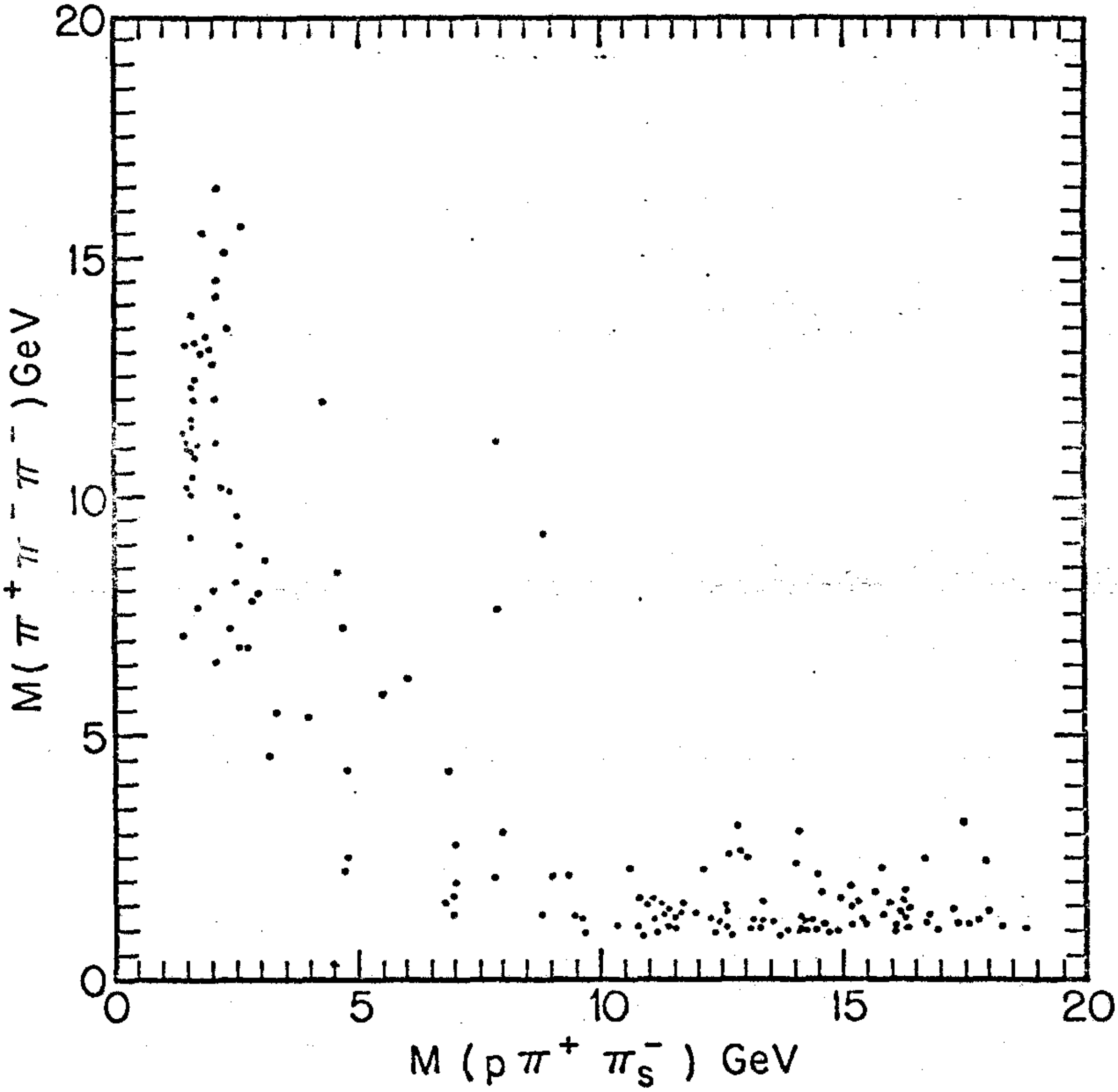
Fig. 4. (a) $\pi^+\pi^-$ mass for $M_{3\pi} < 3.3$ GeV; $\pi^-\pi^-$ mass is shaded. (b) Polar angle between the beam and outgoing π^- directions in the ρ^0 rest system for $M_{3\pi} < 1.2$ GeV and $0.61 < M_{\pi^+\pi^-} < 0.92$ GeV. (c) $p\pi^+$ mass for $M_{p\pi\pi} < 3.3$ GeV, (d) $p\pi^-$ mass for $M_{p\pi\pi} < 3.3$ GeV.

Fig. 5. (a) $\pi^- p \to \pi^-\pi^+\pi^- p$ cross section vs beam momentum for three bands of 3π mass, (b) for two bands of $p\pi^+\pi^-$ mass.



XBL 745-3123

Fig. 1



XBL 745-3124

Fig. 2

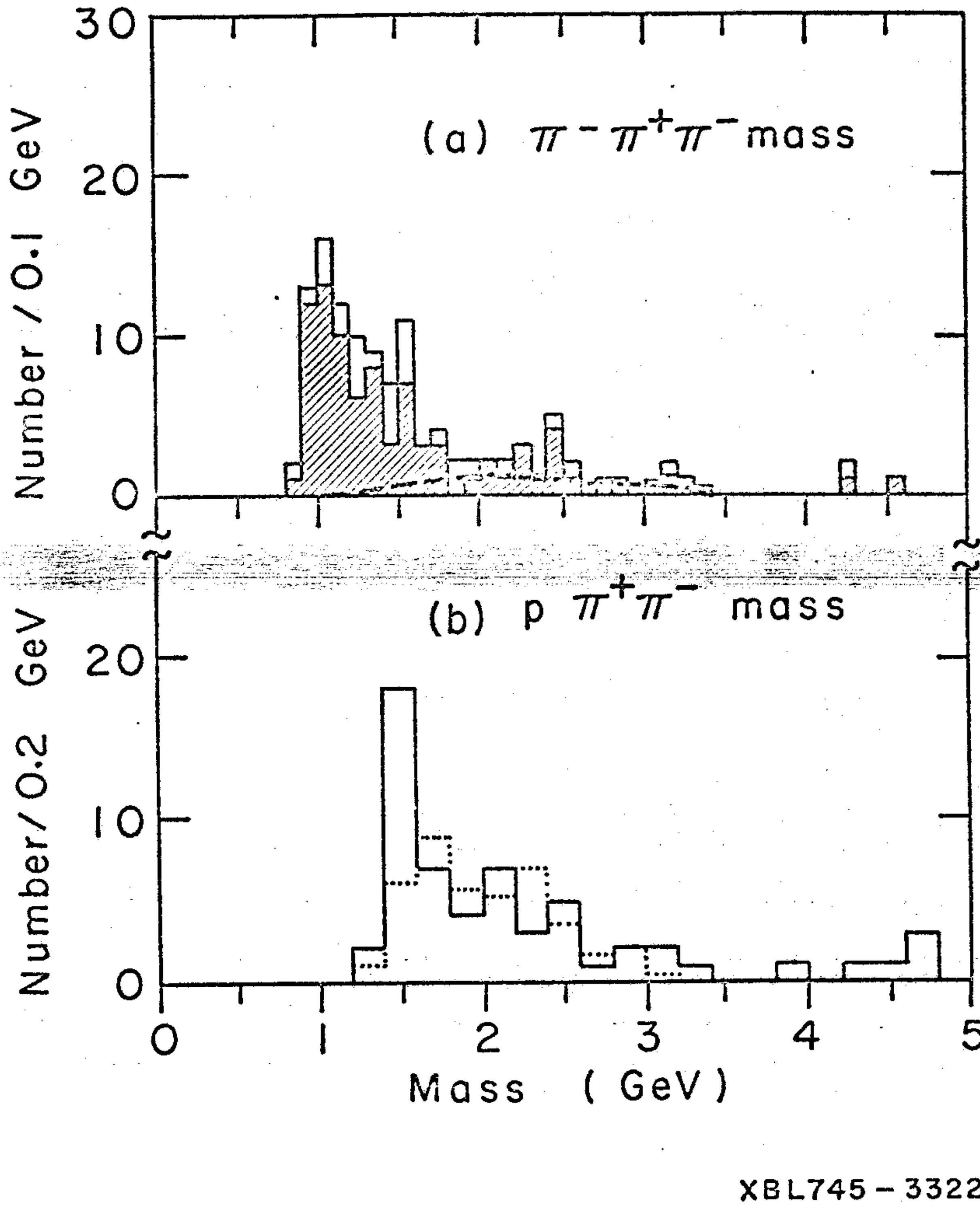

(a) $\pi^- \pi^+ \pi^-$ mass
Number / 0.1 GeV
30
20
10
0
(b) p $\pi^+ \pi^-$ mass
Number/0.2 GeV
20
10
0
0
1
2
3
4
5
Mass (GeV)
XBL745-3322

Fig. 3

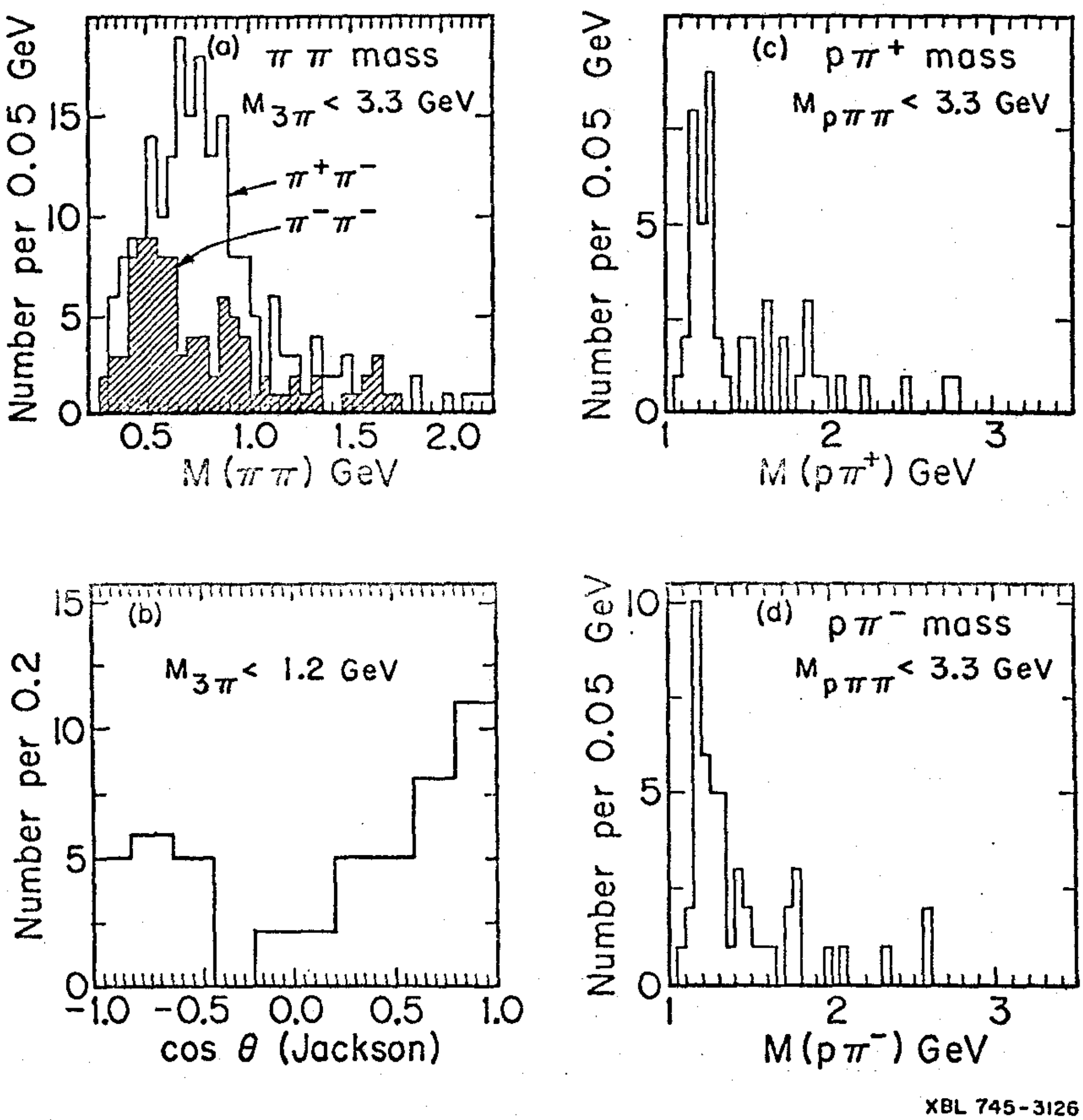

(a) π π mass
M3π < 3.3 GeV
π+π−
π−π−
Number per 0.05 GeV
M (π π) GeV
(c) pπ+ mass
Mpππ < 3.3 GeV
Number per 0.05 GeV
M (pπ+) GeV
(b)
M3π < 1.2 GeV
Number per 0.2
cos θ (Jackson)
(d) pπ− mass
Mpππ < 3.3 GeV
Number per 0.05 GeV
M (pπ−) GeV
XBL 745-3126

Fig. 4

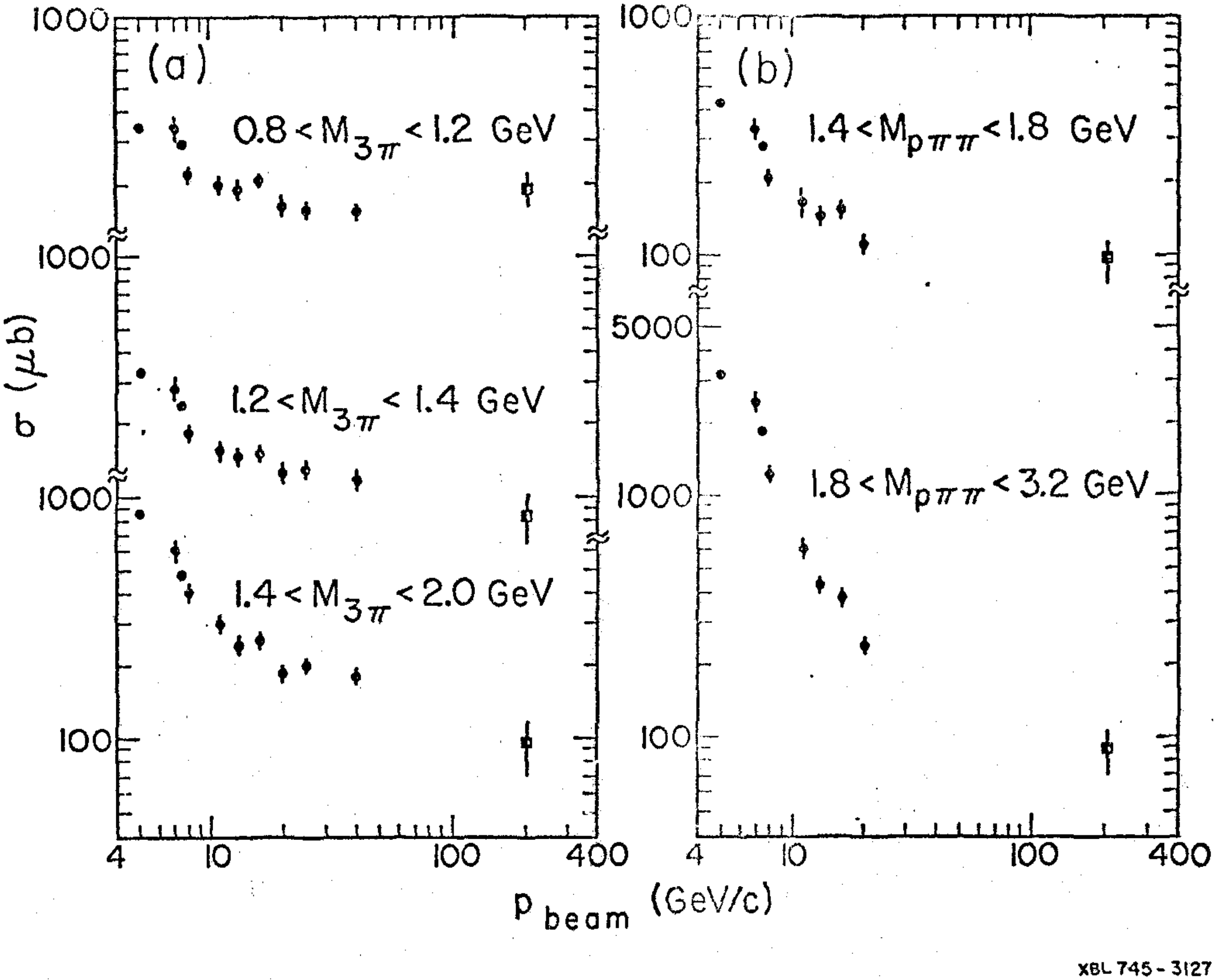

(a)
0.8 < M3π < 1.2 GeV
1.2 < M3π < 1.4 GeV
1.4 < M3π < 2.0 GeV
(b)
1.4 < Mpππ < 1.8 GeV
1.8 < Mpππ < 3.2 GeV
σ (μb)
1000
1000
1000
100
100
5000
1000
100
4
10
100
400
4
10
100
400
p beam (GeV/c)
XBL 745 - 3127

Fig. 5