Archives

Ref. TH. 949

# $\bar{p}p$ ANNIHILATION INTO PIONS IN A REGGEIZED MULTI-PERIPHERAL MODEL +)

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## A B S T R A C T

The phenomenological model of Chan et al. is applied to the calculation of the cross-sections and single particle angular and momentum distributions of the reaction $\bar{p}p \rightarrow n\pi$, where at most one neutral pion is allowed in the final state. By adjusting only three variable parameters we achieve good qualitative agreement with most experimental data, for multiplicity n between 2 and 9 at incident $\bar{p}$ momentum ranging from 1.61 to 7.0 GeV/c. Interpolation at 2.7 GeV/c and extrapolation to 12.0 GeV/c with the same parameters check satisfactorily with newly available experimental data at these momenta.

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+) Partly supported by a research grant from the Chinese University of Hong Kong, Hong Kong.

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68/1158/5 - TH. 949

23 October 1968

## 1. - INTRODUCTION

Recently, Chan, Loskiewicz and Allison [1] (hereafter referred to as CLA) have proposed a Reggeized multi-peripheral model of multi-pion production in $\pi p$ and Kp scatterings. Using three adjustable parameters, it successfully accounted for the essential features of single particle distributions over a wide range of energy and final state multiplicities. By including resonance formation into consideration Plahte and Roberts [2),3)] extended this model to calculate the cross-sections and two-body effective mass distributions of the same reactions, and were able to explain the pronounced backward peak in the baryon longitudinal momentum distributions. In this paper we report a straightforward application of the CLA model to $\bar{p}p$ annihilations into pions.

Some general features in the single-pion angular distributions have now emerged from the considerable experimental data [4)-24)] accumulated on the $\bar{p}p \rightarrow n\pi$ reaction : (i) the produced $\pi^-(\pi^+)$ tends to be emitted forward (backward) and along the $\bar{p}$ beam direction ; (ii) these asymmetry and collimation effects increase with higher beam momentum and lower final state multiplicity [13),16),17)]. Such features have very simple qualitative explanations in the CLA model. In addition, the model is found to also yield fairly satisfactory quantitative results, both in single-particle distributions and in cross-sections.

## 2. - PRELIMINARY REMARKS

The CLA model is essentially a phenomenological interpolation between high-energy peripheral scattering described by the multi-Regge behaviour and low-energy isotropic scattering dominated by phase-space behaviour. Each multiple production process is calculated from incoherently superimposed amplitudes of the following form [1] :

$$|A| \sim \prod_{i=1}^{n-1} \left(\frac{g_i s_i + ca}{s_i + a}\right)\left(\frac{s_i + a}{a}\right)^{\alpha_i}\left(\frac{s_i + b_i}{b_i}\right)^{t_i} \qquad (1)$$

where the symbols have already been explained in Ref. [1]. When fully Reggeized, this amplitude corresponds to the diagrams of Fig. 1(a) or (b). For $\bar{p}p$ annihilation into pions, clearly only baryon trajectories may be exchanged in such amplitudes. Since it is known [25] that the $\Delta_\delta$ trajectory is weaker in coupling strength than the baryon trajectory $N_\alpha$ by about one order of magnitude, we neglect $\Delta_\delta$ for simplicity. Experimentally, only final states with at most one $\pi^0$ are observed, which are thus uniquely labelled by the multiplicity n. The absence of double charge ($\Delta$) exchange then implies that there is only one graph contributing to each reaction of even multiplicity, while n numerically identical yet physically distinct amplitudes contribute to each reaction of odd multiplicity n. In both cases amplitude (1) can be considerably simplified :

$$|A| = G^2 g^{n-1} \prod_{i=1}^{n-1} \left(1 + \frac{h}{1 + s_i/a}\right)\left(1 + s_i/a\right)^{\alpha} \left(1 + s_i/b\right)^{\beta t_i} \qquad (2)$$

where we denote $c/g - 1$ by $h$ and replace the two energy scale factors $b_I$ and $b_E$ used in CLA by a single factor $b$. $G$ is, nominally, the ratio of "external" to "internal" high-energy coupling strength, but we will also absorb in it other constant numerical factors in the calculation of cross-sections. Energy is expressed in units of GeV and other physical quantities accordingly.

The parameters in Eq. (2) are chosen as follows. The Regge parameters $\alpha$ and $\beta$ of the linearized nucleon trajectory have been determined recently [25] at -0.38 and 0.88, respectively. h is not varied, but merely fixed at the value corresponding to the c/g ratio used by CLA, i.e., 0.077. For each multiplicity n a normalization constant $C_n$ is substituted for $G^2g^{n-1}$ in the calculations of the cross-sections, where $C_n$ is adjusted individually for the best fit. This affects only the multiplicity dependence of the cross-sections. For the rest of the data we may adjust only the two energy scale factors a and b. They have been chosen to be 0.1 and 3.0, respectively, so as to bring the best agreement to experimental data for multiplicity between 2 and 9 and at incident momenta 1.61 [4)-7)], 3.0 [8)-9)], 3.28 [10)-12)], 5.7 [13)-18)], and 7.0 GeV/c [19)]. Interpolation at 2.7 GeV/c [20)-22)] and extrapolation to 12 GeV/c [23)] are made after all parameters have been completely fixed, when additional data came to our attention.

The numerical computations rely heavily on a computer program for Monte Carlo integration written by James [26]. As pointed out in Ref. [1)], this is a heavy drawback when one tries to optimize the choice of parameters.

## 4. - CONCLUDING REMARKS

We have shown that the CLA model, without further elaboration, can well be applied directly to account for the essential features of the $\bar{p}p \to n\pi$ reaction. The only exception is the angular distribution for $n = 2$, which is far too isotropic, and must be explained by some other mechanism. Further improvements can certainly be achieved by various refinements, such as including the $\Delta_\delta$ trajectory in calculations, finding a proper treatment of the even-odd effect, and taking resonance formation into account, etc.

The last point has already been raised by CLA and systematically dealt with by Plahte and Roberts [2),3)], but so far does not seem to have affected our results very seriously.

The results we obtain are not very sensitive to the choice of parameters. For instance, a change of $a$ by a factor of two produces hardly noticeable changes in the results. However, it is essential to set $b$ much larger than $a$, so as to make the angular distributions sufficiently isotropic while maintaining a highly peripheral behaviour of the cross-sections. This is entirely different from the experience of CLA, who found it best to set both $a$ and $b$ somewhere between 0.5 and 1.2. It does not seem fruitful to speculate on the significance, if any, that can be attached to this fact at present.

The sensitivity of the model to the particular manner of interpolating between high and low-energy limits has been checked by introducing an extra parameter $\lambda$, so that Eq. (1) is written as

$$|A| \sim \prod_{i=1}^{n-1} \left(\frac{g_i x_i + c}{x_i + 1}\right) (1 + x_i)^{\alpha_i/\lambda} (1 + y_i)^{\beta_i t_i/\lambda} \qquad (5)$$

where $x_i = (s_i/a)^\lambda$ and $y_i = (s_i/b)^\lambda$. Clearly amplitude (5) has the same high and low-energy limits as amplitude (1), even though it is dependent on $\lambda$ for the energy range in between. Surprisingly, all of our results are strongly dependent on $\lambda$, and can be significantly affected by a change of 10% in $\lambda$ when it is approximately 1. Unfortunately, the method of computation again limits the possibility of further exploing the behaviour of the results when the adjustable parameters are varied for different values of $\lambda$.

Finally, it seems quite clear that it is well worth-while to extend the present calculations to other $\bar{p}p$ reactions, on which considerable experimental data are available, and to investigate angular correlation effects as well.

ACKNOWLEDGEMENTS

We wish to thank Professor J. Prentki and Professor W. Thirring for the hospitality extended to us in the Theoretical Study Division at CERN. It is a great pleasure to thank Dr. Chan Hong-Mo for constant encouragement and many enlightening discussions throughout the progress of this work, and for a careful reading of the manuscript. We are indebted to Dr. G. Fisher, Dr. A. Fridman, Dr. A. Frisk and Dr. J. Kinson for permission to use unpublished experimental data. Helpful discussions with Dr. C.B. Chiu, Dr. J. Diaz, Dr. E. Plahte and Dr. R. Roberts are gratefully acknowledged.

| $n =$ | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|
| $\sigma_n$ (mb) | 0.021 | 0.249 | 0.098 | 0.625 | 0.073 | 0.375 |
| $\sigma_n$ (mb) (Experimental) | 0.02 ±0.002 | 0.29 ±0.03 | - | - | - | - |
| $\langle P_T \rangle$ (Gev/c) | 0.51 | 0.47 | 0.42 | 0.42 | 0.38 | 0.34 |
| A = F/B | 1.97 | 1.77 | 1.29 | 1.33 | 1.21 | 1.42 |
| C = P/E | 5.25 | 3.56 | 3.00 | 2.26 | 1.98 | 2.00 |

Table Predicted Results at 12 Gev/c

## REFERENCES AND FOOTNOTES


1) Chan Hong-Mo, J. Loskiewicz and W. Allison - CERN Preprint TH. 866 (1968).

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19) T. Ferbel et al. - Nuovo Cimento 38A, 12 and 19 (1965).

20) D. Lyon - Iowa State University Ph.D. Thesis (1966).

21) D. Bohning - Iowa State University Ph.D. Thesis (1966).

22) J. Fisher and L. Libby - Private communication.

23) I. Borecka et al. - Report to the 1968 International Conference on High-Energy Physics, Vienna.

24) Experimental data on $\bar{p}p$ scatterings have been compiled in the following works :
A. Iwaki - Suppl.Progr.Theoret.Phys.(Kyoto), 41 and 42, 316 (1967) ;
A. Fridman - Z.Phys. 211, 250 (1968) ;
See also Ref. 17).
We have, however, relied exclusively on the original references.

25) V. Barger and D. Cline - Phys.Rev.Letters 21, 392 (1968).

26) F. James - A General Monte-Carlo Phase-Space Program, CERN Report 68/15 (1968).

27) There is an additional constant factor of dimension $(\text{energy})^2$ on the right of Eq. (3). We absorb it in the $G^2$ factor appearing in $|A|$.

28) The following work came to our attention while this work was being completed :
G. van Keuk - Zur Anwendung des Statistischen Modells mit Drehimpulserhaltung, DESY Preprint (1968).
Based on a statistical model with energy-momentum and angular momentum conservations, it calculates $\sigma_n(E)$ for $\bar{p}p$ annihilation into pions, for $n$ ranging from 3 to 7. Some of these results are comparable to those obtained in this work.

29) Various previous estimates show that the interaction range in $\bar{p}p$ annihilation must be at least $0.5\,\lambda_\pi$ to give satisfactory cross-sections, but this would be too large for $\bar{p}p$ scatterings without annihilation.
See U. Amaldi et al. - Nuovo Cimento 46, 171 (1966) and the work of G. van Keuk, Ref. 28).

30) The work by A. Fridman, Ref. 24), contains a calculation of the branching ratios for different charge configurations in the final state from statistical factors.

31) See the following references for the cloud-core model, which seems able to account for low-energy angular distributions at various multiplicities :
Z. Koba and G. Takeda - Progr.Theor.Phys.(Kyoto) 19, 269 (1958) ;
A. Stanjano - Nuovo Cimento 24, 774 (1962) and 28, 197 (1963) ;
A. Fridman - Ref. 24).

## FIGURE CAPTIONS

**Figure 1** Diagrams of multi-Regge amplitudes for reactions $\bar{p}p \rightarrow n\pi$ when (a) $n(=4)$ is even, (b) $n(=3)$ is odd, (c) a subenergy is small, and (d) a $\Delta_\delta$ trajectory is exchanged.

**Figure 2** The total cross-sections as functions of incident momentum for various multiplicities. Points connected by straight lines are calculated from the model.

**Figure 3** $C_n/g^{2(n-1)}$ as a function of $n$. The dashed line is $G^4$. Open circles indicate odd $n$. (a) all multiplicities considered, and $n' = 1$. (b) $C_2$ excluded, and $n' = 2$.

**Figure 4** The asymmetry parameter $A = F/B$ as functions of incident momentum for various multiplicities. Points connected by straight lines are calculated from the model.

**Figure 5** The collimation parameter $C = P/E$ as functions of incident momentum for various multiplicities. Points connected by straight lines are calculated from the model.

**Figure 6** Histograms of percentage single-pion angular distributions in the centre of momentum system. $\pi^-$ and reflected $\pi^+$ distributions are combined. Dashed lines are calculated from the model.

**Figure 7** Histograms of combined percentage transverse momentum distributions of all charged pions for various multiplicities at 5.7 GeV/c. The histograms are taken from experimental data, solid lines are calculated from the model, and dashed lines are computed from Eq. (4) with $a$ given by the calculated $\langle p_T \rangle$.

Figure 8 Average transverse momentum $\langle p_T \rangle$ at 5.7 GeV/c as a function of multiplicity. Points connected by straight lines are calculated from the model.

Figure 9 Histograms of percentage longitudinal momentum distributions at 5.7 GeV/c for $n = 4$ and $5$. The $\pi^-$ and reflected $\pi^+$ distributions are combined. Dashed lines are calculated from the model.

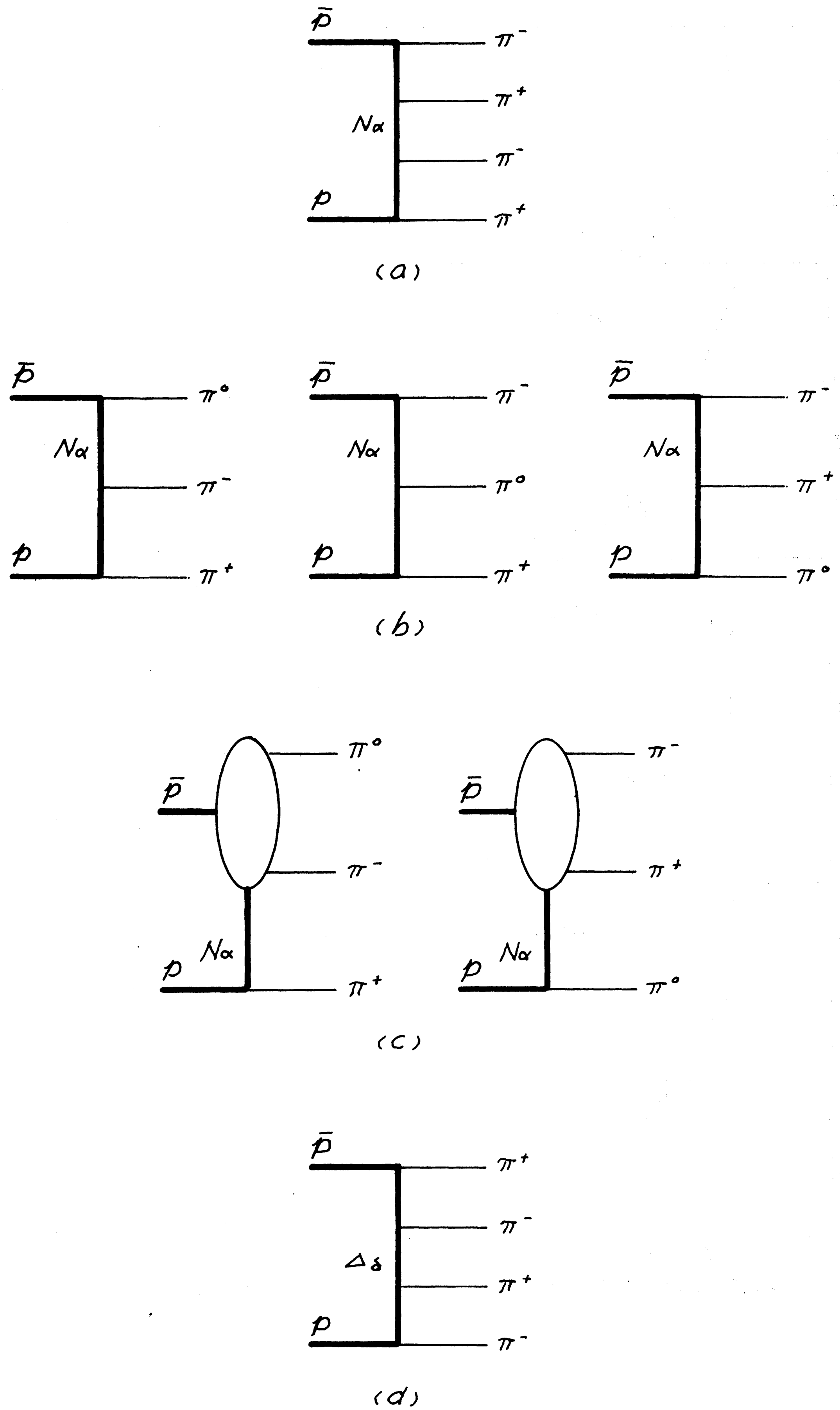
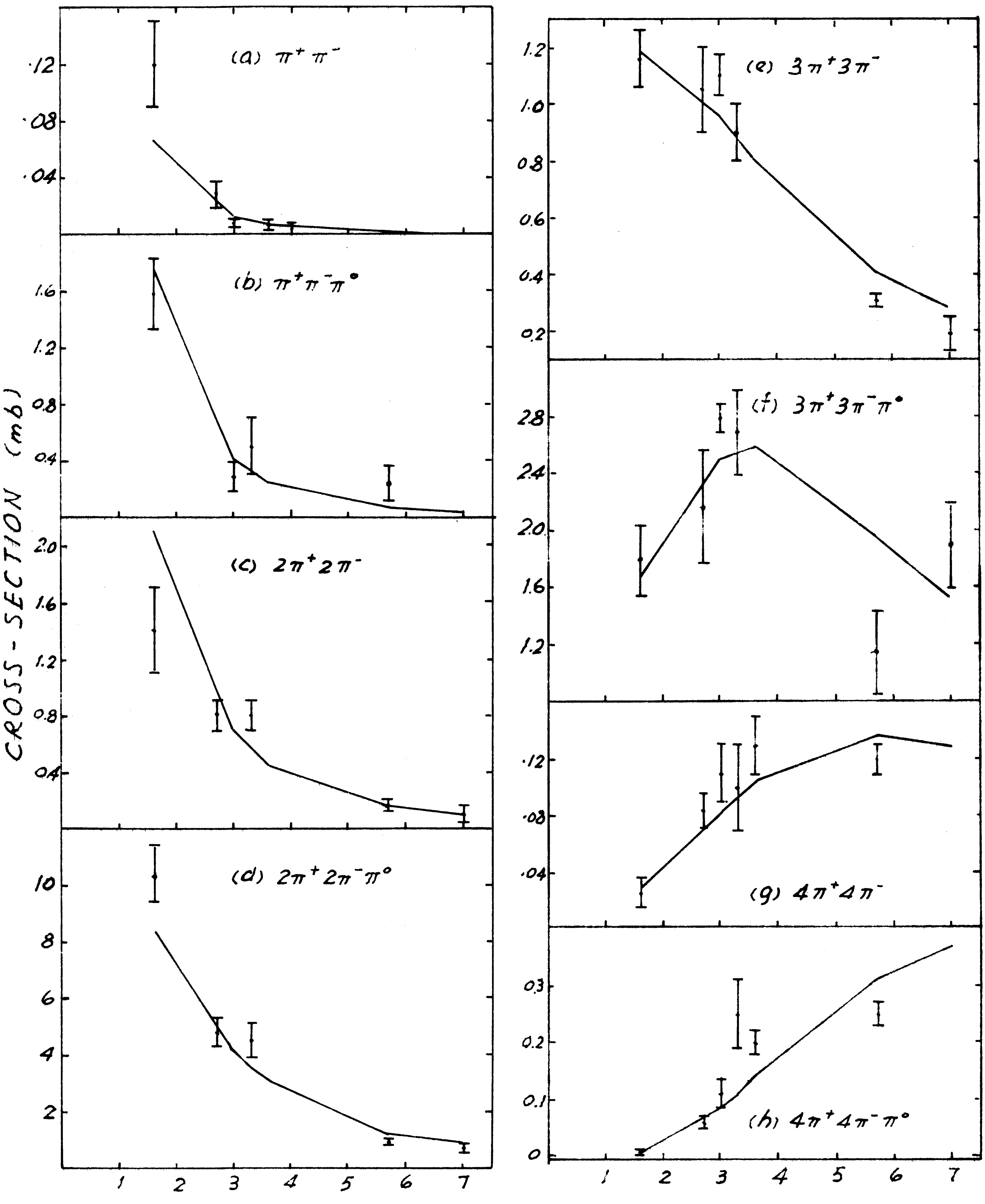



Fig. 1



(a) $\pi^+\pi^-$
(b) $\pi^+\pi^-\pi^0$
(c) $2\pi^+2\pi^-$
(d) $2\pi^+2\pi^-\pi^0$
(e) $3\pi^+3\pi^-$
(f) $3\pi^+3\pi^-\pi^0$
(g) $4\pi^+4\pi^-$
(h) $4\pi^+4\pi^-\pi^0$
CROSS - SECTION (mb)
LAB. MOMENTUM (GEV/C)
LAB. MOMENTUM (GEV/C)


Fig. 2

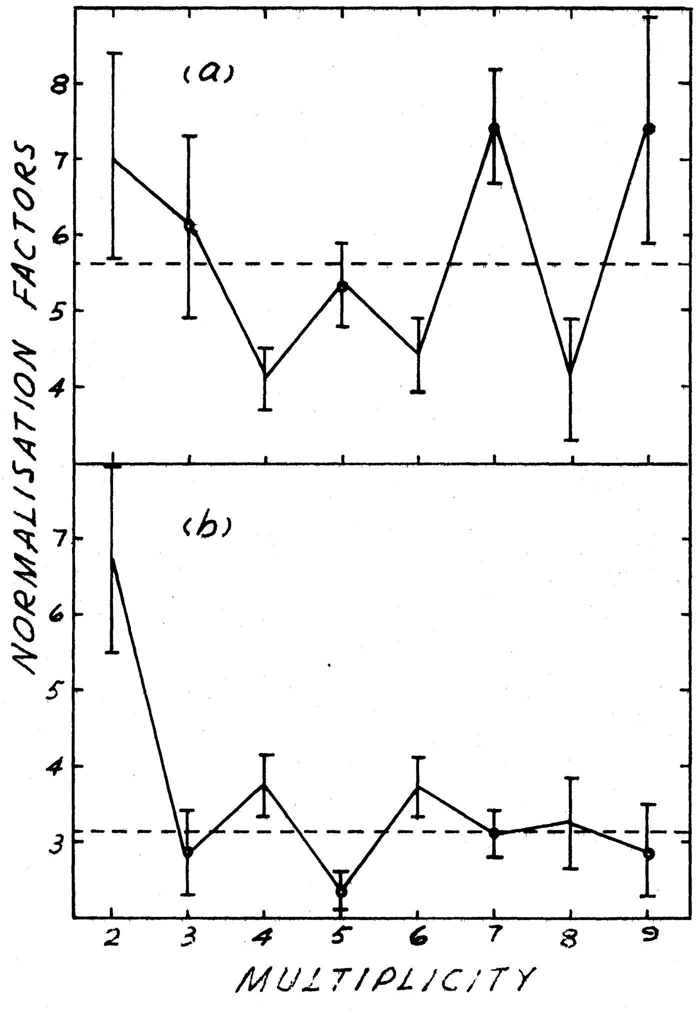

(a)
(b)
NORMALISATION FACTORS
8
7
6
5
4
7
6
5
4
3
2
3
4
5
6
7
8
9
MULTIPLICITY

Fig. 3

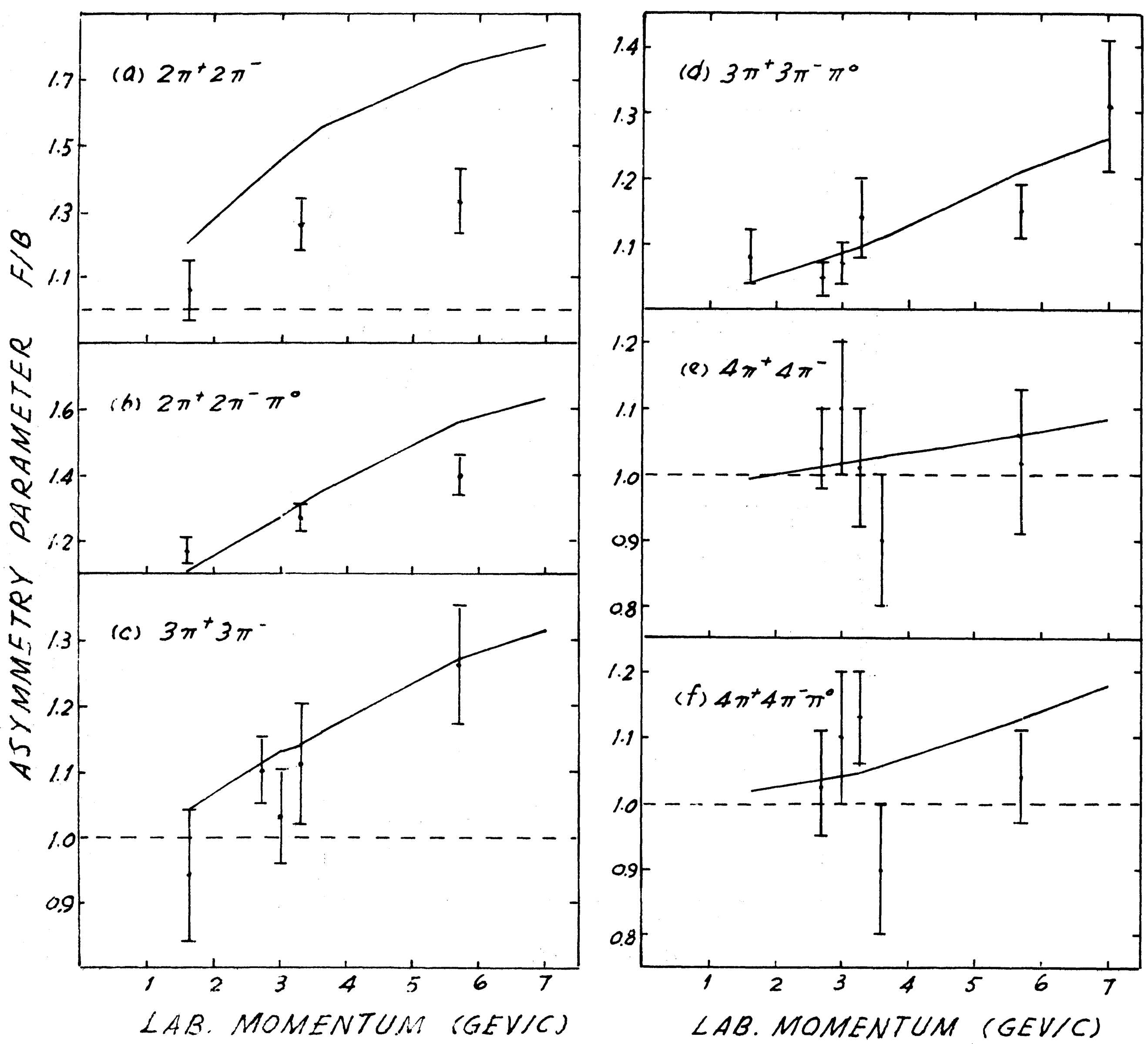

ASYMMETRY PARAMETER F/B
(a) $2\pi^+2\pi^-$
(b) $2\pi^+2\pi^-\pi^0$
(c) $3\pi^+3\pi^-$
(d) $3\pi^+3\pi^-\pi^0$
(e) $4\pi^+4\pi^-$
(f) $4\pi^+4\pi^-\pi^0$
1.7
1.5
1.3
1.1
1.6
1.4
1.2
1.0
0.9
0.8
1 2 3 4 5 6 7
LAB. MOMENTUM (GEV/C)
LAB. MOMENTUM (GEV/C)

Fig. 4

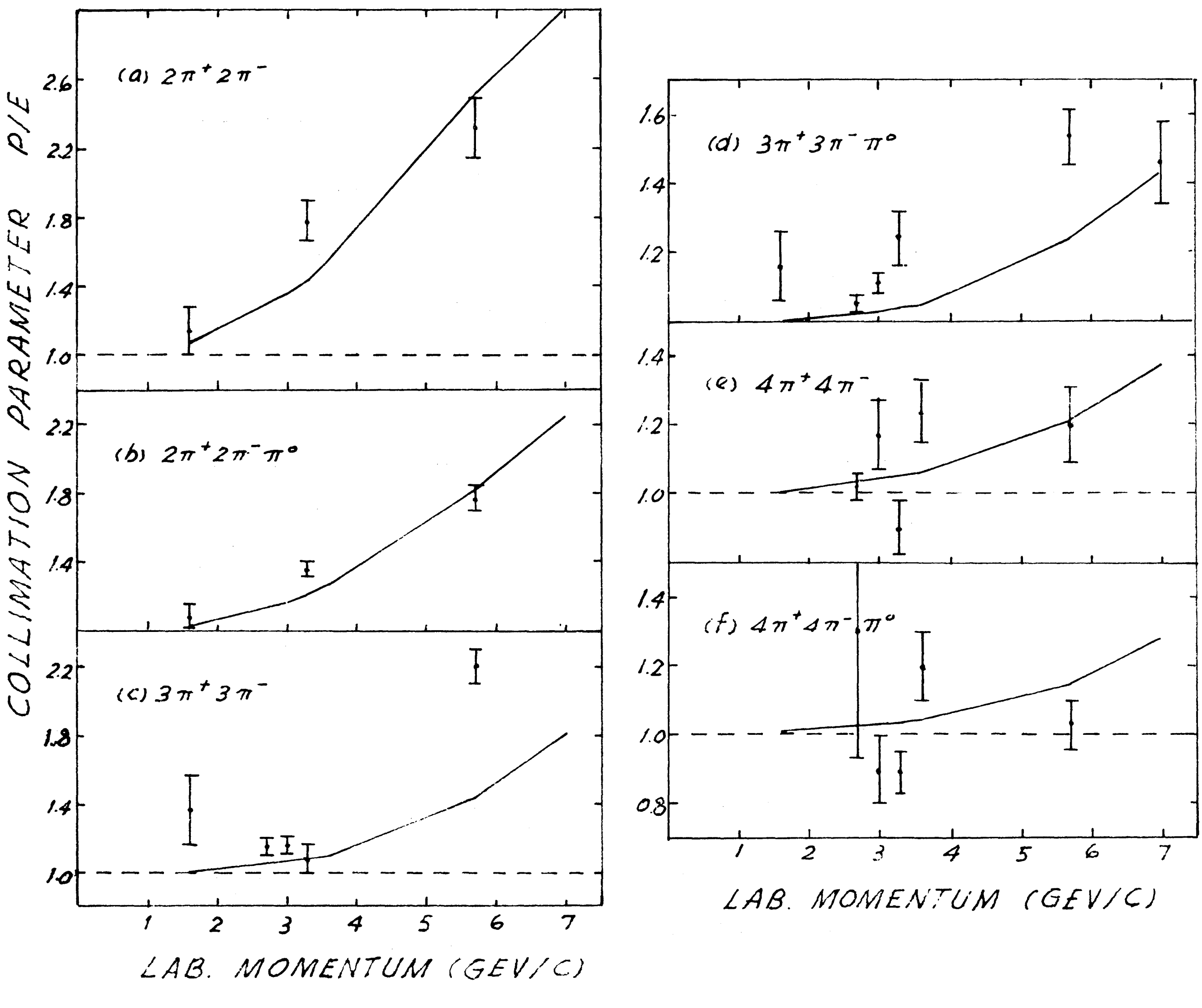

COLLIMATION PARAMETER P/E
(a) 2π⁺2π⁻
(b) 2π⁺2π⁻π°
(c) 3π⁺3π⁻
(d) 3π⁺3π⁻π°
(e) 4π⁺4π⁻
(f) 4π⁺4π⁻π°
LAB. MOMENTUM (GEV/C)
LAB. MOMENTUM (GEV/C)

Fig. 5

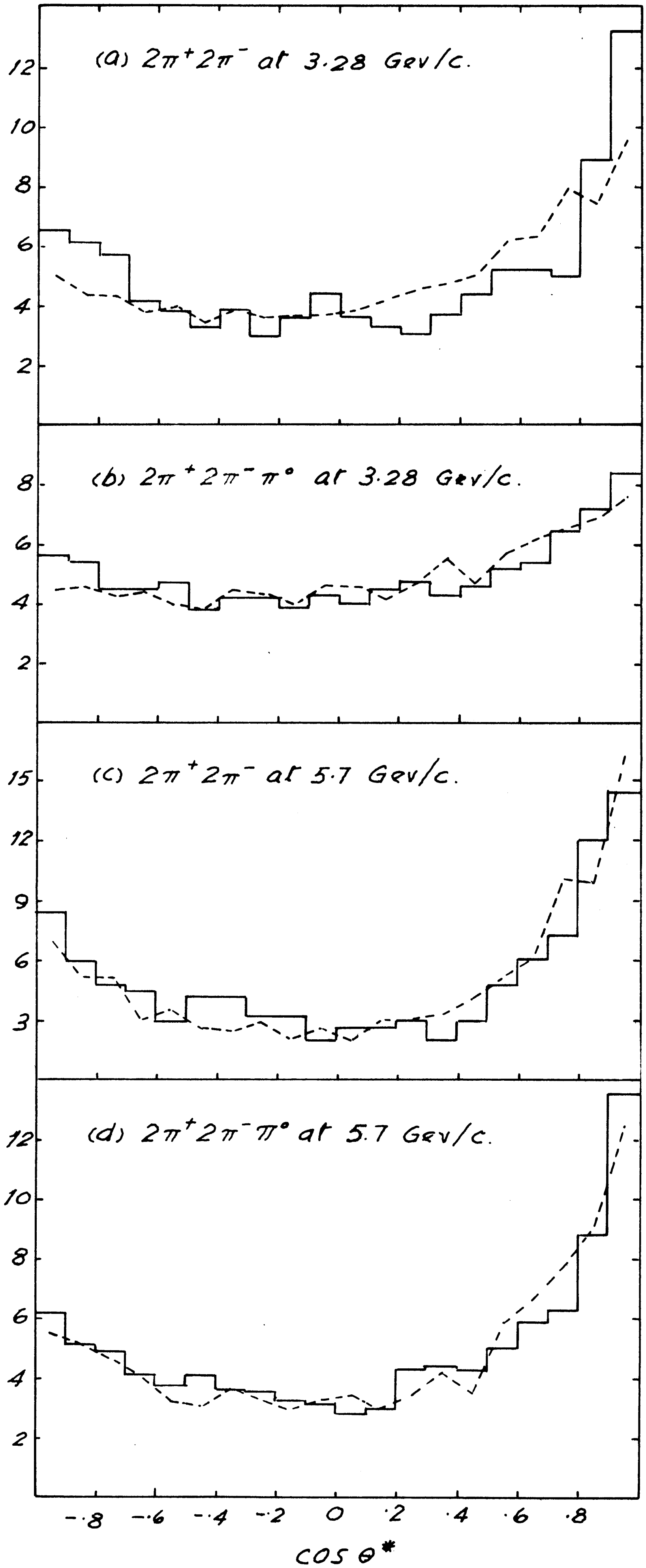
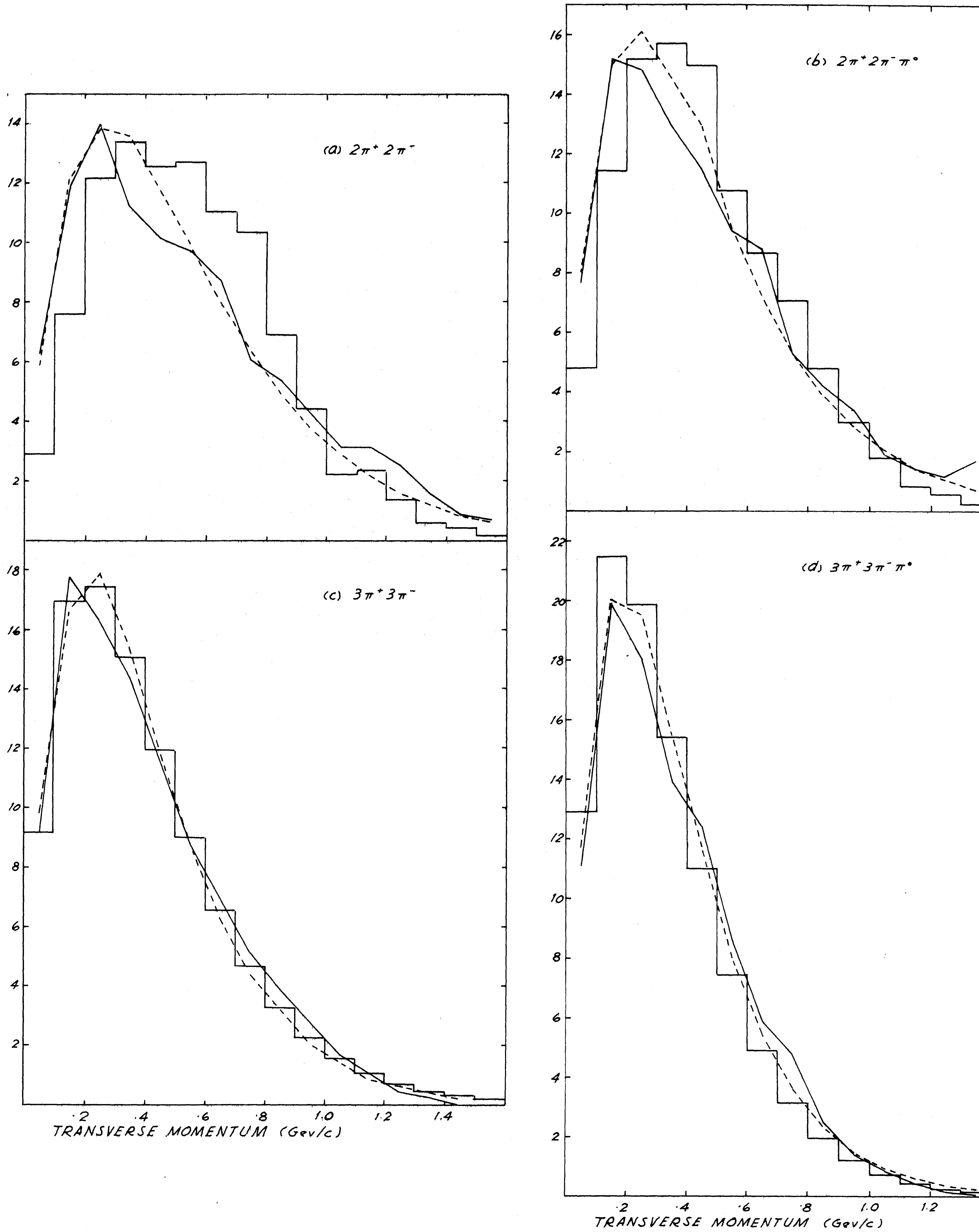

(a) 2π+2π− at 3.28 Gev/c.
12
10
8
6
4
2
(b) 2π+2π−π° at 3.28 Gev/c.
8
6
4
2
(c) 2π+2π− at 5.7 Gev/c.
15
12
9
6
3
(d) 2π+2π−π° at 5.7 Gev/c.
12
10
8
6
4
2
−.8
−.6
−.4
−.2
0
.2
.4
.6
.8
cos θ*

Fig. 6



(a) 2π⁺ 2π⁻
(b) 2π⁺ 2π⁻ π°
(c) 3π⁺ 3π⁻
(d) 3π⁺ 3π⁻ π°
TRANSVERSE MOMENTUM (Gev/c)
TRANSVERSE MOMENTUM (Gev/c)


Fig. 7

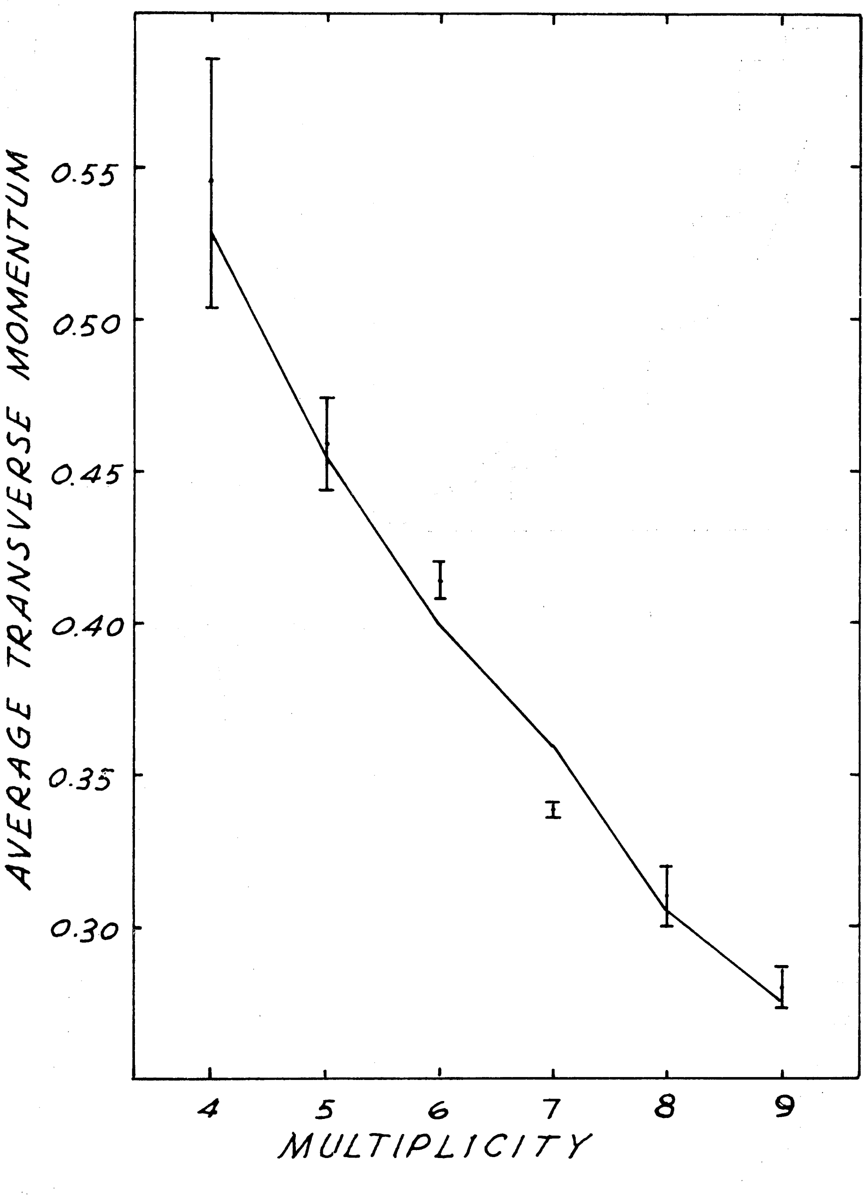
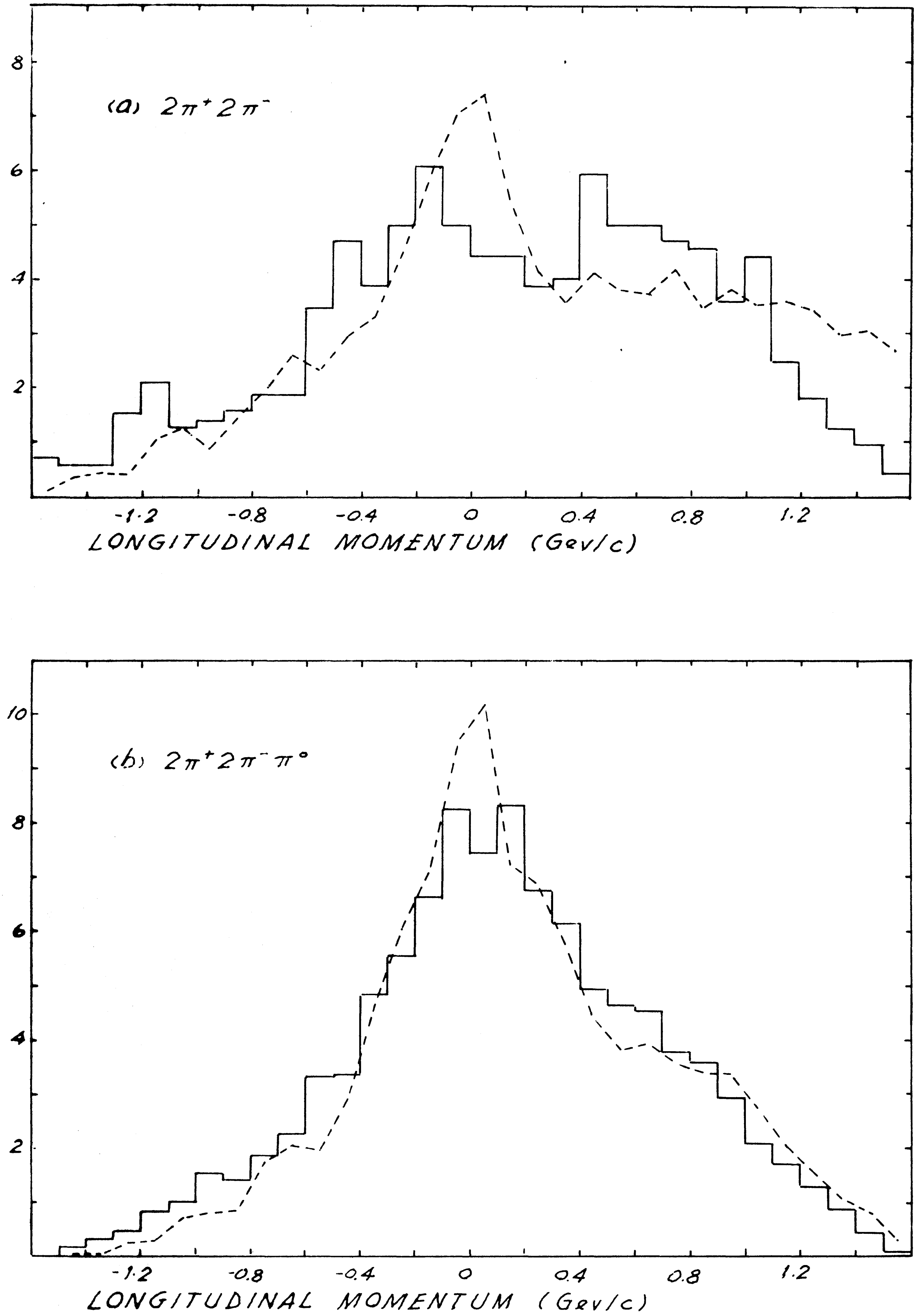

AVERAGE TRANSVERSE MOMENTUM
0.55
0.50
0.45
0.40
0.35
0.30
4
5
6
7
8
9
MULTIPLICITY

Fig. 8



(a) $2\pi^+2\pi^-$
8
6
4
2
-1.2
-0.8
-0.4
0
0.4
0.8
1.2
LONGITUDINAL MOMENTUM (Gev/c)
(b) $2\pi^+2\pi^-\pi^0$
10
8
6
4
2
-1.2
-0.8
-0.4
0
0.4
0.8
1.2
LONGITUDINAL MOMENTUM (Gev/c)


Fig. 9