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CHARGE EXCHANGE AND THE REACTION $\bar{p} + p \rightarrow \bar{n} + n + \pi^+ + \pi^-$ OF 3.0, 3.6 and 4.0 GeV/c ANTIPROTONS(*)

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Photographs from the 81 cm Saclay hydrogen bubble chamber operating in 3.0, 3.6 and 4.0 GeV/c separated antiproton beams from the CERN proton synchrotron were used to study the reactions :

$$\bar{p} + p \rightarrow \bar{n} + n \qquad (1)$$

$$\bar{p} + p \rightarrow \bar{n} + n + \pi^+ + n^- \qquad (2)$$

$$\bar{p} + p \rightarrow \bar{n} + p + \pi^- \qquad (3) .$$

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ABSTRACT

The slope of the t-distribution for charge exchange is shown to be less than that for elastic scattering and the value of $(d\sigma/dt)$ at $t = 0$ is shown to be about the same as for the reaction $p + n \rightarrow n + p$, as would be expected from some models of crossing symmetry. For (2) the production of double isobars is found to be much less than in the related reaction $\bar{p} + p \rightarrow \bar{p} + p + \pi^+ + \pi^-$. An enhancement is observed in the $(n\ \pi^+\pi^-)$ and $(\bar{n}\ \pi^+\ \pi^-)$ systems which could be attributed to the 1688 MeV isobar(s) which is shown to decay partially by the (3/2, 3/2) isobar.

ANALYSIS OF DATA

Reaction (1) is observed in the bubble chamber as a zero prong interaction of the antiproton ("interaction") followed downstream by a neutral star ("star") with odd number of prongs. Reactions (2) and (3) are seen as two prong interactions followed by a similar star. Reaction (3) has been studied previously[(1)]. As it can be unambiguously identified independently of the analysis of the star, it can be used as a source of antineutrons of known momentum in order to determine the antineutron total cross section and the relative frequencies of the various antineutron reactions, and to define the detection efficiency of antiproton reactions associated with a star.

68,000 photographs of 3.0 and 3.6 GeV/c antiprotons were scanned twice for reaction (1), (2) and (3) and, in addition, 19,000 photographs of 4.0 GeV/c were scanned twice for reaction (2) and (3). Events with associated K-mesons were rejected. 578 neutral "stars" with an odd number of prongs were found downstream from a zero or two-prong antiproton interaction.

Reactions (1) and (2) must be separated by measurement and simultaneous kinematic fit of interaction and star, from the reactions where one or more additional π^0 are produced at the interaction, and from the spurious events arising by the chance coincidence of an antiproton interaction in the chamber and of a star produced by an antineutron coming from outside. The numbers of constraints of the fits, which depend on reactions at the interaction (Arab numbers) and at the star (Roman numbers) are given in Table I.

TABLE I

Kinematic constraints for the reactions studied

INTERACTION			STAR			
Type	$\bar{p}\, p \rightarrow$	Constraints at interaction	Type I	II	III	IV
			Odd number of 0 π^0	charged 1 π^0	pions k π^0, k > 1	and $\bar{p}\, p\, \pi^+$
3	$\bar{n}\, p\, \pi^-$	3	3^* 7	0 4	NFP ● $\leq 1^{\emptyset}$ Ø	3 7
3b	$\bar{n}\, p\, \pi^-\, \pi^0$	0	3 4	0 $1^{\square}$	NFP Ø	3 4
3c	$\bar{n}\, p\, \pi^-\, m\, \pi^0$ m > 1	NFP	NFP			
1	$\bar{n}\, n$	0^+	3 4	0 1	NFP	3 4
1b	$\bar{n}\, n\, \pi^0$	NFP	3 $1^{\square}$	0 NFP	NFP	3 $1^{\square}$
1c	$\bar{n}\, n\, m\, \pi^0$ m >1	NFP	NFP			
2	$\bar{n}\, n\, \pi^+\, \pi^-$	$0^{+\Delta}$	3 4	0 1 Ø	NFP 0	3 4
2b	$\bar{n}\, n\, \pi^+\, \pi^-\, \pi^0$	NFP	3 $1^{\square}$	0 NFP	NFP	3 $1^{\square}$
2c	$\bar{n}\, n\, \pi^+\, \pi^-\, m\, \pi^0$ m > 1	NFP	NFP			

FOOTNOTES

- • NFP No fit possible.
- * The upper number is the number of constraints at the star considered alone.
  The lower number is the overall number of constraints for the simultaneous fit at the interaction and at the star.
- ⊗ Using the momentum of the antineutron obtained at the interaction, the missing mass at the star can be computed and should be > 0 for the event to be accepted.
- □ Although the overall fit has one constraint, the solution at the interaction remains undetermined.
- ∅ Although the fit has one constraint, the solution at the star remains undetermined.
- \+ The zero constraint fit often gives two solutions. The fit at the star removes the ambiguity.
- Δ In the cases where the fit at the star does not remove this ambibuity, the solution giving the highest antineutron momentum is chosen, assuming a peripheral reaction.

The numbers of identified events are given by Table II, and the corresponding cross sections by Table III.

Of the 355 2-prong interactions, candidates for reactions (2) and (3), 245 were accepted and 110 had to be rejected : 81 gave no fit at production, 8 gave a negative missing mass at the star (Table I, reaction III) and 21 for miscellaneous reasons. Of the accepted events, 113 belong to reaction (3). The study of this reaction gives the antineutron cross sections averaged over antineutron momenta ranging from 2.0 to 3.7 GeV/c, (mean value 2.7). It also shows (Table II) that only about 30 o/o of the antineutron annihilations or inelastic processes occur without or with one π^0 only (reactions I and II). Thus, as inspection of Table I shows, only about 30 o/o of the events can be used to identify reaction (1).

Of the 223 zero prong interactions candidates for reaction (1), 30 were accepted as fitting reactions (I), (II) and (IV) at the star. The 182 others had to be rejected because they gave no acceptable fit, they had to be attributed to reactions (I, III), (Ib) or (Ic), or to spurious association. As the number of constraints for (I, II) is low, it is necessary to find out what fraction of events of reaction (1b) or (1c) could erroneously be interpreated as reaction (1). For this purpose, the 38 events found for reaction (3,I; 3,II; 3,IV) were amputated of their proton and negative pion, and an attempt was then made to fit them as reaction (1). When the star had no π^0 (reaction I and IV) no such faked fit was found. When the star had one π^0 (reaction II) a faked fit was found for about 10 o/o of the trials. Because of the similarity of the reactions for the fake and the real events, it can be concluded that the sample of charge exchange events is contaminated by 1 or 2 events from reactions (1b) or (1c).

For the study of reaction (2), 19 events were accepted as corresponding to reactions (2,I) and (2,II). In addition, 67 events were accepted for reaction (2,III) with the supplementary condition of a positive missing mass at the star as indicated in Table I. The fit at the interaction, which has more constraints, often gives two solutions. The solution with the highest antineutron momentum was chosen, assuming a peripheral reaction. This choice was justified by close examination of the two solutions of events of type (2,I) and (2,II) where the fit at the star removes the ambiguity, and also by comparing the laboratory spectrum of the antineutrons with the corresponding spectrum of the antiprotons in the similar reaction (4) (see below). As these kinematical conditions do not exclude all events of reactions (2b) and (2c), the contamination must be evaluated. Baltay et al.[2] have shown that, for antiprotons of 3 to 4 GeV/c, reactions (2b) and (2c) have a combined cross section of about 10 o/o of reaction (2). This is weakly confirmed by the fact that no event of type (2b, I) and only one of type (2b, IV) were found. Thus, the overall contamination of the sample is probably less than 10 o/o.

RESULTS

The distributions of $-t$, the square of the four-momentum transfer, are shown in Fig. 1 for the elastic[1] and the charge exchange scattering of antiprotons as obtained in the present experiment. It can be seen that the charge exchange cross-section has a much broader forward peak. At 1.61 GeV/c[3] similar results were found.

In Fig. 1, is also shown the differential cross-section for the neutron-proton charge exchange reaction $p + n \rightarrow n + p$ studied by Palevsky et al.[4]. It can be seen that in the limit of small $-t$ values, the differential cross-sections tend to become equal. Such behaviour of these two processes at high energy was predicted by Bialas and Czyzewski[5] on the basis of crossing symmetry and analycity of amplitudes.

A one-pion exchange calculation with absorption has been made by Ringland[6] who found good agreement with the experimental results as can be seen from the calculated curve on Fig. 1. Also the energy dependance of the charge-exchange cross-section agrees reasonably with the prediction of one pion-exchange model (Fig. 2). The dependence of the total, elastic, annihilations, inelastic, charge exchange and two pion annihilation cross-sections on the incident laboratory momentum are shown in Fig. 3.

TABLE II (see next page)

TABLE II

Number of events identified

INTERACTION		STAR					TOTAL	Number of events used ⊠
		Type I	II	III	IV	V		
		Odd number of charged pions						
Type	$\bar{p}\,p \rightarrow$	$0\ \pi^o$	$1\ \pi^o$	$k\ \pi^o$ $k > 1$	$\bar{p}p\ \pi^+$	Other inelastic		
3	$\bar{n}\,p\,\pi^-$	8	22	70	8	5	113	108
3b	$\bar{n}\,p\,\pi^-\ \pi^o$	4	8*	23▭	3	-	38	38
3	$\bar{n}\,p\,\pi^-\ m\ \pi^o$ $m > 1$	-	-	-	1	-	1	-
1	$\bar{n}\,n$	8	17Q	-	5	-	30	30
1b	$\bar{n}\,n\,\pi^o$	7	-	-	4	-	11	11
2	$\bar{n}\,n\,\pi^+\ \pi^-$	4	15Ø	67◇	5	2	93	91
2b	$\bar{n}\,n\,\pi^+\ \pi^-\ m\ \pi^o$ $m > 0$	-	-	-	1	-	-	-
TOTAL								

FOOTNOTES

* Including a contamination of $<$ 30 o/o of (3c)

▭ Including a contamination of $\sim$ 30 o/o of (3c)

Q Including a contamination of $\sim$ 10 o/o of (1b)

Ø Including a contamination of $<$ 10 o/o of (2b)

◇ Including a contamination of $\sim$ 10 o/o of (2b)

∅ Not using the stars of reaction V

TABLE III

Cross sections

INTERACTION		
N^{o}	$\bar{p}\,p \rightarrow$	cross section mb
I	$\bar{n}\,n$	2.0 ± 0.6
Ib,c	$\bar{n}\,n\,k\,\pi^{o}$ $k > 0$	1.4 ± 0.6
2	$\bar{n}\,n\,\pi^{+}\,\pi^{-}$	2.0 ± 0.7
2b,c	$\bar{n}n\pi^{+}\pi^{-}k\pi^{o}$ $k > 0$	0.3 ± 0.3

STAR		
N^{o}	$\bar{n}\,p \rightarrow$	cross section mb
I	$(m+1)\pi^{+}+m\pi^{-}+k\pi^{o}$	54 ± 14
II	$k \geq 0$	
III	$m \geq 1$	
IV	$\bar{p}\,p\,\pi^{+}$	4.6 ± 2.5
For 2.0 GeV/c < Mom.of $\bar{n}$ < 3.7 GeV/c		

Reaction (2) may be compared with the reaction

$$\bar{p} + p \rightarrow \bar{p} + p + \pi^{+} + \pi^{-} \qquad (4)$$

which is dominated by the production of the isotopic-spin favoured combinations $(p\,\pi^{+})$ and $(\bar{p}\,\pi^{-})$ of the (3/2, 3/2) isobar. This reaction (4) proceeds through double isobar production(2)(7)

$$\bar{p} + p \rightarrow N^{*++} + (\overline{N^{*++}}) \rightarrow \bar{p} + p + \pi^{+} + \pi^{-} \qquad (5)$$

in 55 o/o and 58 o/o of the cases for 3.25 and 3.6 GeV/c incident antiprotons respectively. For reaction (2), the $(n\,\pi^{-})$ and $(\bar{n}\,\pi^{+})$ states of the isobar are similarly favoured by isotopic spin. They are indeed found as shown by Fig. 4A. A fit to a Breit-Wigner distribution and a phase space background indicates that 43 ± 10 o/o of the events proceed via the production of one isobar. No corresponding enhancement is found in the $(n\,\pi^{+})$ and $(\bar{n}\,\pi^{-})$ effective mass distributions, these combinations having a smaller contribution of the I = 3/2 amplitude. A search for events showing double isobar production

$$\bar{p} + p \rightarrow N^{*-} + (\overline{N^{*-}}) \rightarrow \bar{n} + n + \pi^{+} + \pi^{-} \qquad (6)$$

gave a negative result (Fig. 4B). That isobars are produced frequently singly, but not doubly as in reaction (6) can be understood by observing that, whereas reaction (5) can proceed by the exchange of one unit of charge reaction, (6) requires the exchange of two. The small value of the cross section for reaction (6) can be related by SU 3 to the smallness of Ω production cross section by antiprotons[8].

The effective mass distribution for the $(n\ \pi^+\ \pi^-)$ and $(\bar{n}\ \pi^+\ \pi^-)$ combinations is shown in Fig. 5. There is a peak near 1700 MeV which may be assumed to be one or both of the isobars of mass about 1688 MeV[9]. A fit to the distribution indicates that in 48 ± 14 o/o of the reactions an 1688 MeV isobar is formed.

A question of some interest is whether this isobar decays by a cascade process, that is $N^{**} \rightarrow N^{*} + \pi \rightarrow \mathcal{N} + \pi + \pi$. In Fig. 6, the distribution of the $(n\ \pi^-)$ and $(\bar{n}\ \pi^+)$ effective masses for events in the 1688 peak is shown, which indicates that in about 30 o/o of the cases the (3/2, 3/2) isobar is formed. Taking events with $(n\ \pi^+\ \pi^-)$ and $(\bar{n}\ \pi^+\ \pi^-)$ masses higher and lower than the 1688 MeV isobar, there is appreciably less indication of decay by the formation of the $N^*_{3,3}$ isobar, but with the limited statistics available, this background is such that it is not possible to say what percentage of the 1688 MeV isobar events decay through the $N^*_{3,3}$ isobar. In reaction (3) no indication was found of production of ρ-mesons as has been noted for reaction (4) and for the reaction

$$p + p \rightarrow p + p + \pi^+ \pi^- \quad (10, 12).$$

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FIGURE CAPTIONS

Fig. 1 Differential cross-sections as a function of $-t$, the square of the four-momentum transfer. The errors are statistical.

Fig. 2 Total charge exchange cross-section as a function of laboratory momentum. The line drawn is the $(p_{lab})^{-2}$ dependence of the cross-section predicted approximatively by the O.P.E. model and normalised using the cross-section of 1.5 mb at 3 GeV/c obtained from the results of Ringland[6]. The one standard deviation limit at 7 GeV/c is taken from Ref. (13).

Fig. 3 Cross-section as a function of incident antiproton laboratory momentum for the total[14], elastic[14], total annihilation[13,15,16,17], total inelastic (non-annihilation)[13,15,16,17], charge exchange[3,13] and for annihilation into two charged pions[15,16].

Fig. 4 (A) Effective mass distributions of all $(\pi^+\bar{n})$ and $(\pi^-\bar{n})$ combinations. (B) If one of the $(\pi^+\bar{n})$ or $(\pi^- n)$ combinations has a mass near that of the $N^*_{3,3}$ isobar, then the effective mass of the other combination is plotted.

Fig. 5 $(\pi^+\pi^- n)$ and $(\pi^+\pi^-\bar{n})$ effective mass distribution.

Fig. 6 If the $(\pi^+\pi^- n)$ effective mass is near 1688 MeV, then the $(\pi^- n)$ effective mass is plotted and if the $(\pi^+\pi^-\bar{n})$ effective mass is near 1688 then the $(\pi^+\bar{n})$ effective mass is plotted.

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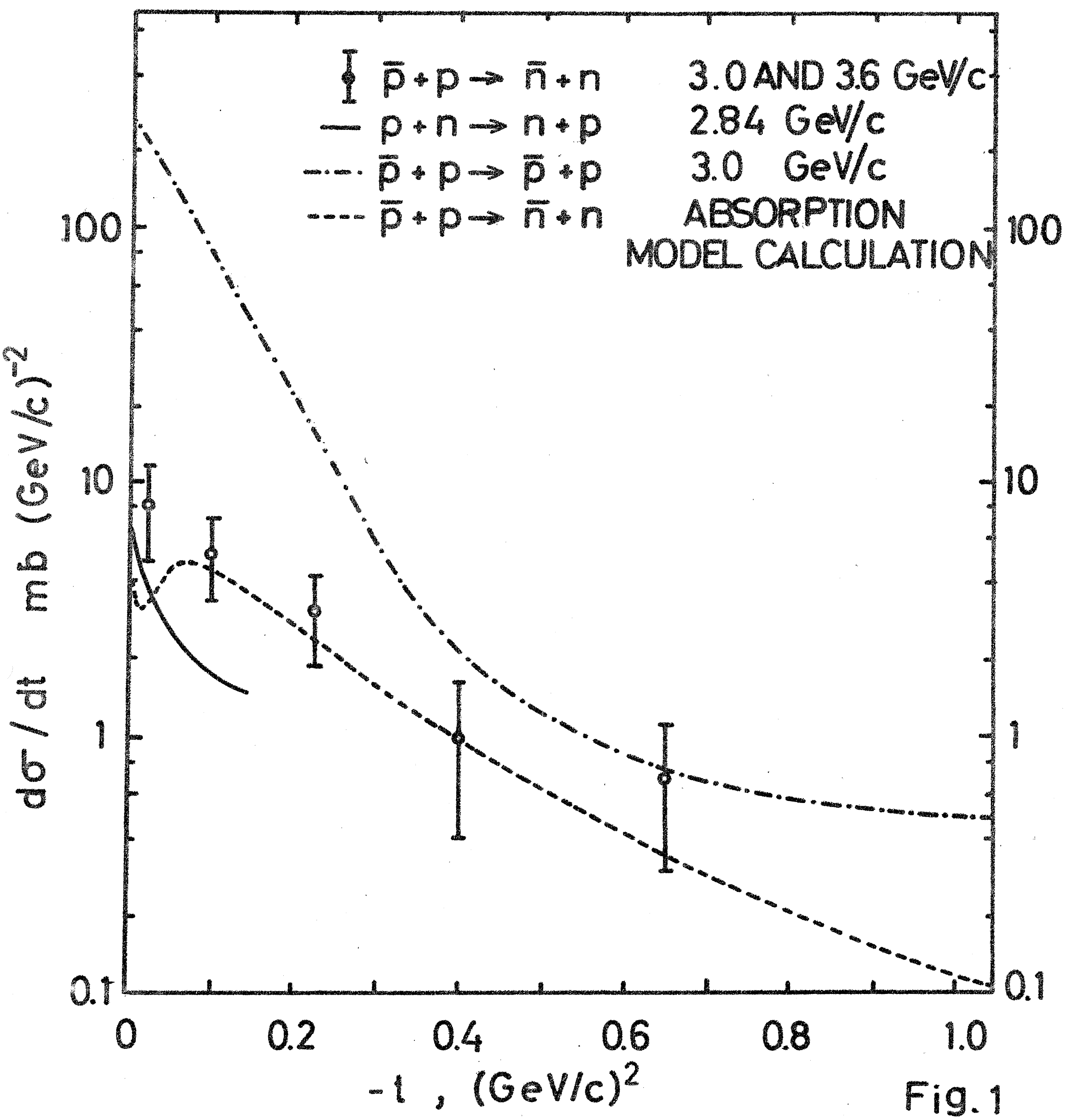

Fig. 1

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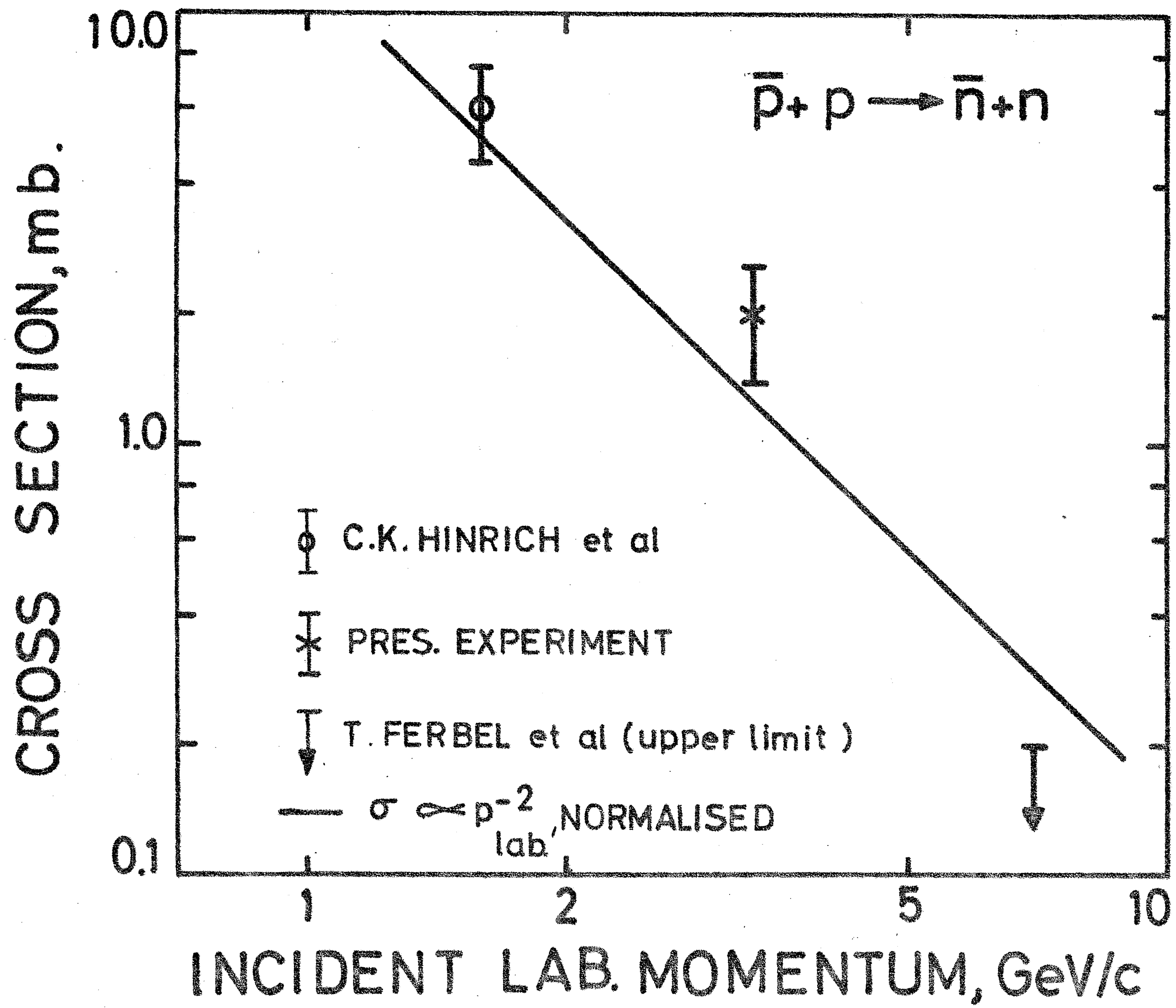

FIG. 2

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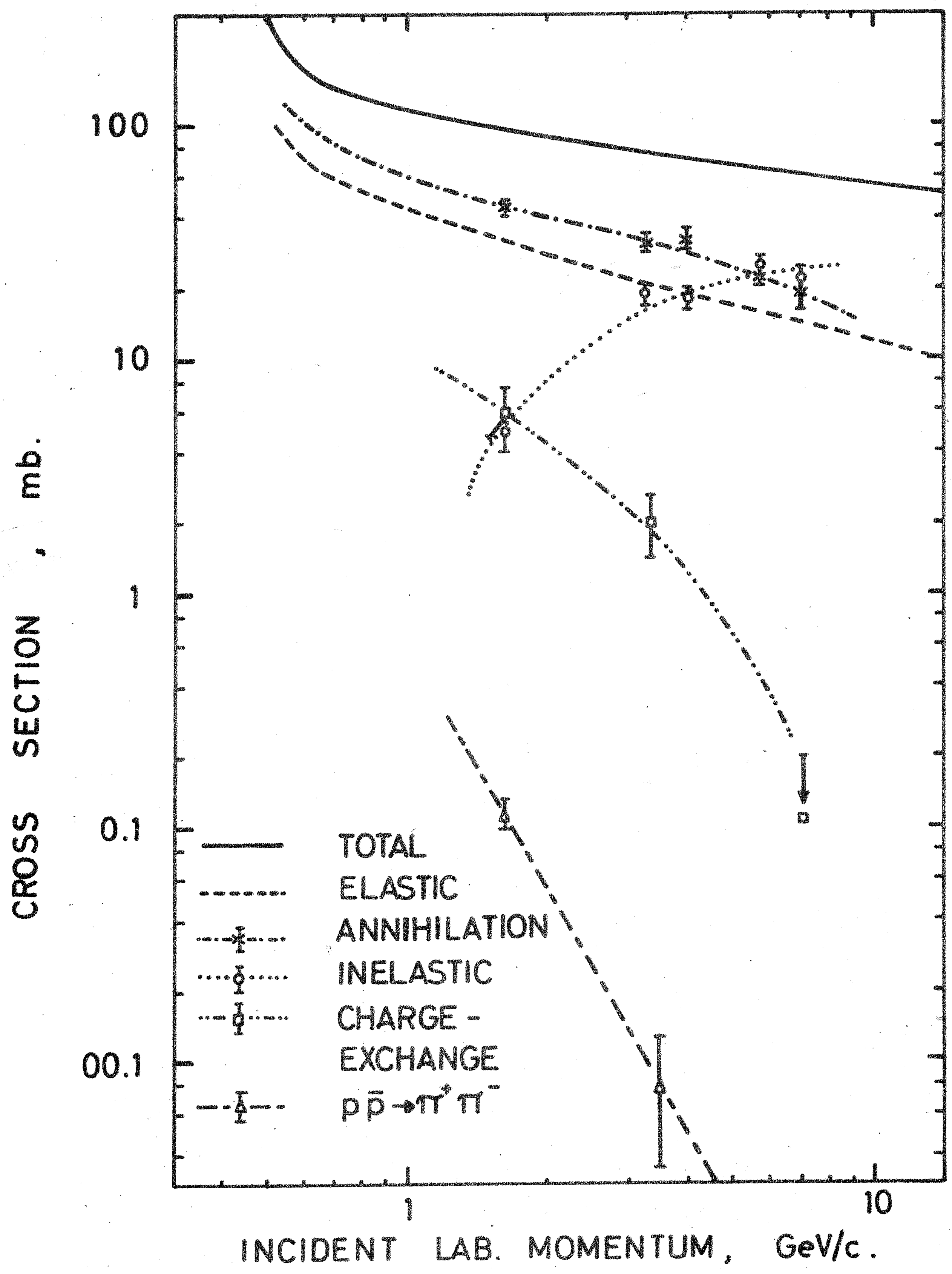

Fig. 3

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$\bar{p}+p \longrightarrow \bar{n}+n+\pi^{+}+\pi^{-}$

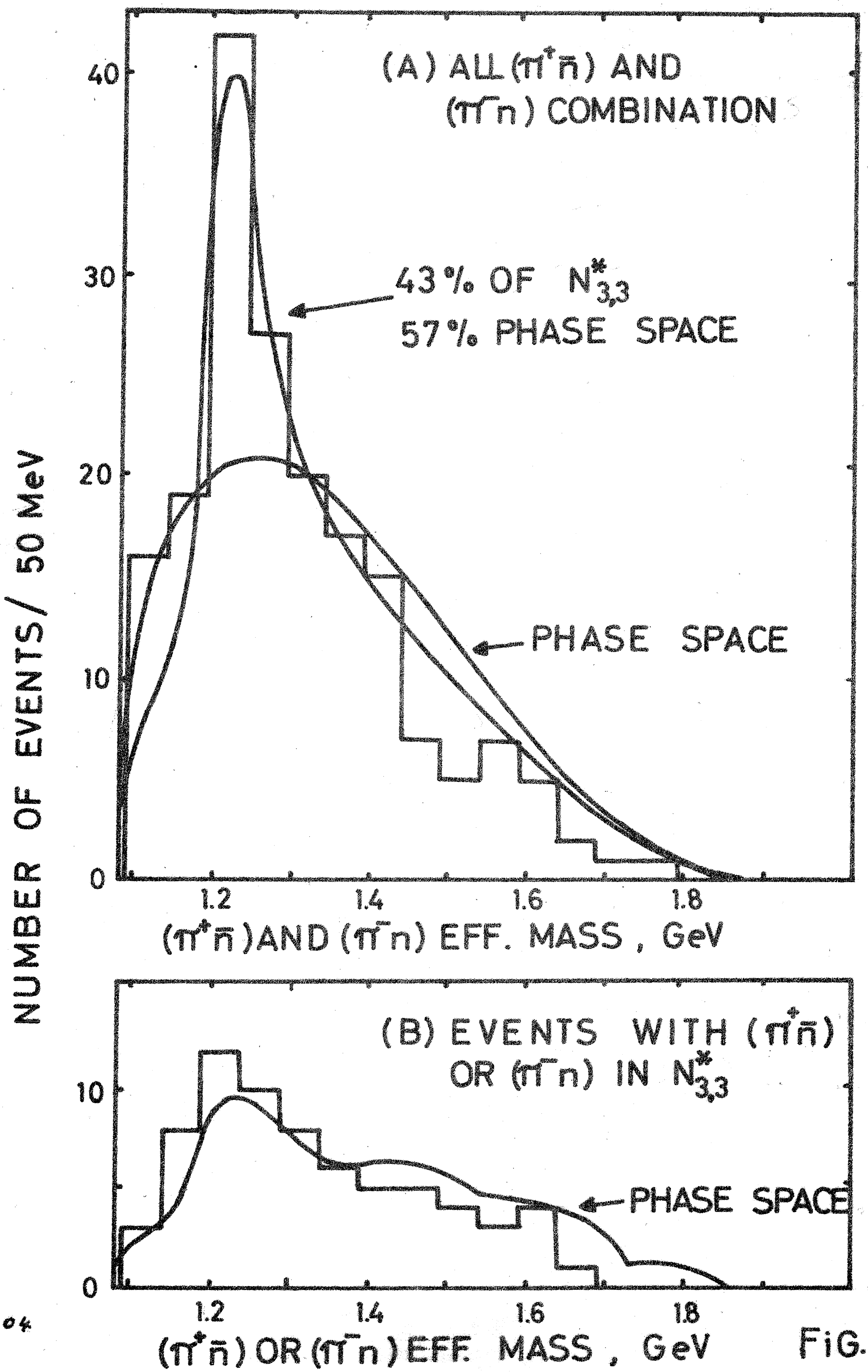

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FIG. 4

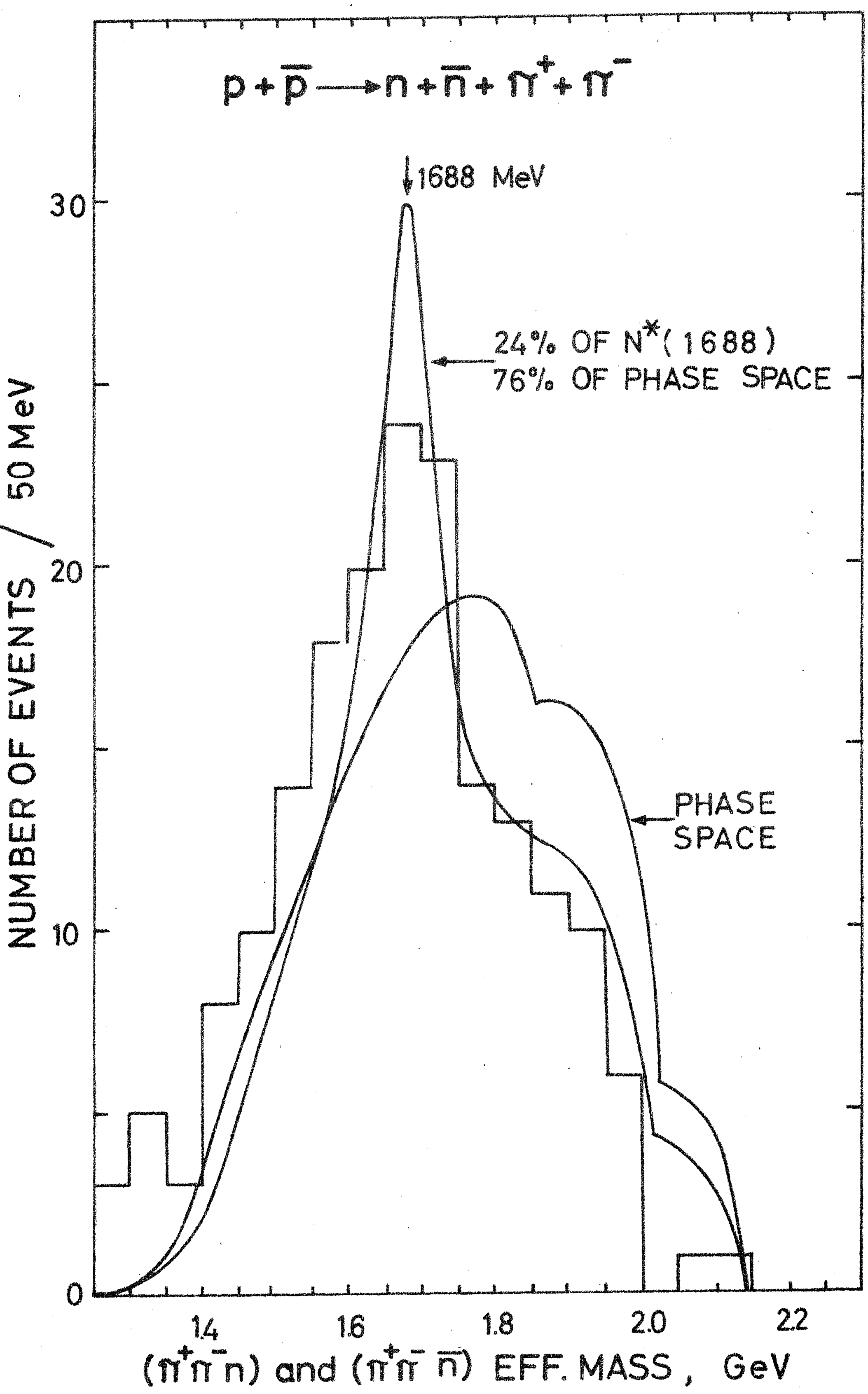

FiG. 5

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$p + \bar{p} \rightarrow n + \bar{n} + \pi^{+} + \pi^{-}$

IF $1.60 < \pi^{+}\pi^{-}n < 1.75$ GeV, PLOT $\pi^{-}n$
IF $1.60 < \pi^{+}\pi^{-}\bar{n} < 1.75$ G V, PLOT $\pi^{+}\bar{n}$

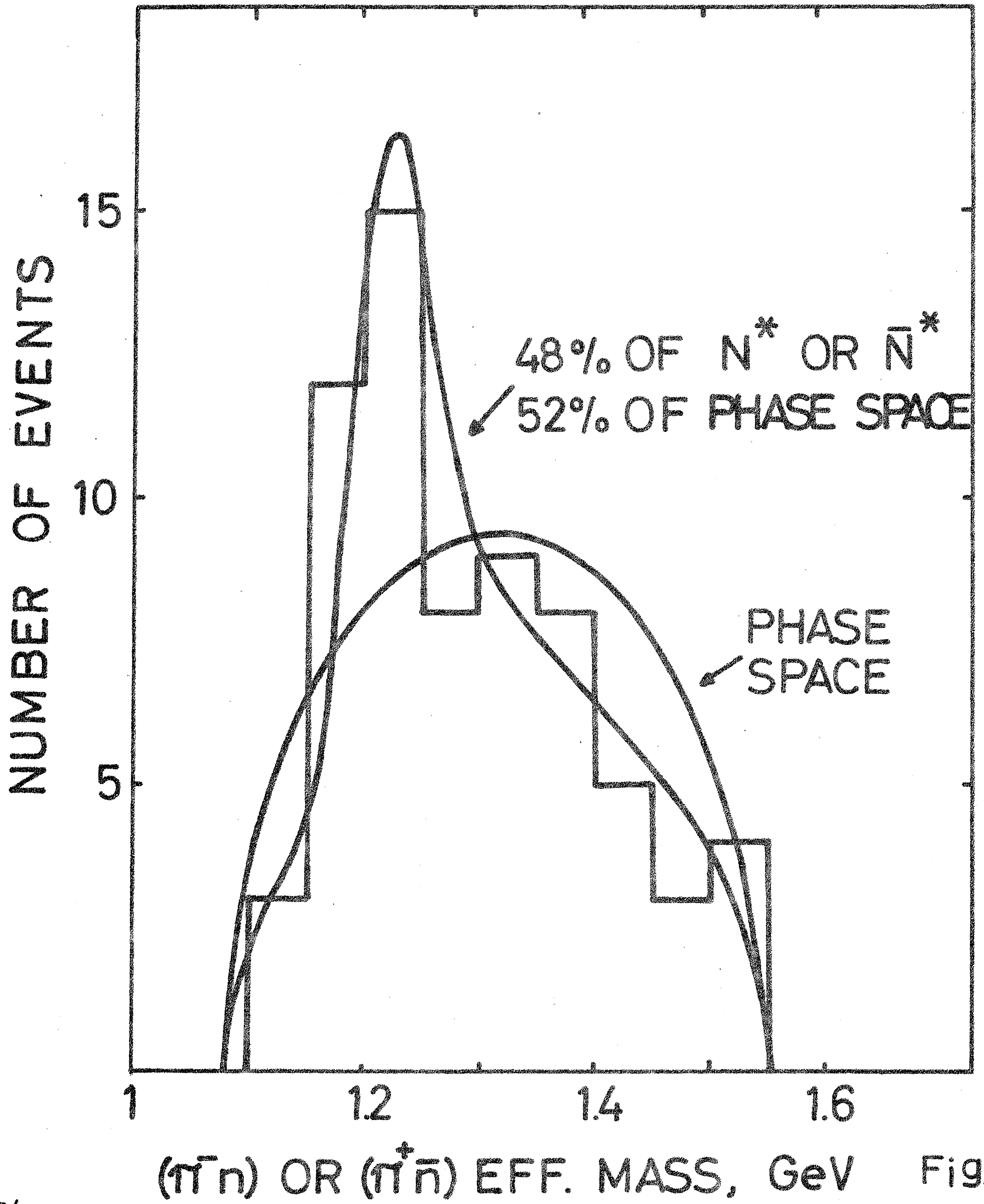

Fig. 6

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