BOSON RESONANCES WITH MASS CLOSE TO THE TWO NUCLEON MASS: THE S REGION

E. Castelli
(Roma-Trieste Collaboration)
Istituto di Fisica dell'Università, Trieste
Istituto Nazionale di Fisica Nucleare, Sezione di Trieste

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ABSTRACT

The experimental situation of the 1876-2000 MeV/c^2 region is revised discussing both the production and formation type experiments.

The difficulties of a firm statement about the S-meson existence are pointed out.

1) INTRODUCTION

The study of meson resonances with mass (M) larger than two nucleon masses ($2\ M_N \cong 1876\ \mathrm{MeV/c^2}$) can be engaged both in production and formation-type experiments.

The second case is possible because of the availability of antiproton ($\bar{p}$) beams. Indeed these states will show up as direct channel resonances in the antinucleon-nucleon ($\bar{N}\,N$) system provided of course they couple to the $\bar{N}\,N$ system.

The so-called S region is covered by an $\bar{p}$ beam in the 0-800 MeV/c momentum range (if the target nucleon is at rest), corresponding to $2\ M_N < \sqrt{s} < (2\ M_N + M_\pi)$ where s is the total energy in the c.m.s. and M_π is the pion mass. Therefore in this range the $\bar{p}$-proton ($\bar{p}p$) interaction leads to annihilation, elastic scattering and charge exchange processes. Moreover broad resonances with $M < 2\ M_N$ can give some effects in this $\bar{N}\,N$ physical region.

The discovery and spin parity determination of the high mass mesonic states in particular in the S region is of considerable interest because of the following reasons:

1) The leading boson trajectories can have the daughter Veneziano (1968) trajectories. These daughters may be arranged in towers of approximately the same mass (Barger 1969). If the meson of the leading trajectory in the S region exists, it has spin $J = 4$; therefore there is room for lower spin states.

2) It has been predicted the existence of non relativistic bound and resonant states (quasinuclear mesons) in the $\bar{N}N$ system (Bogdanova 1972). The investigation of the low energy $\bar{N}N$ interaction enables to check this theory.

A lot of experimental work has been carried out both in the production and formation experiments. Despite the number of experiments, of years and of people involved in this research the experimental situation is very confused.

Some interesting experimental results have been presented three and two years ago at various international conferences. Up to now these data have not been definitively published; this fact demonstrates the caution with which it is necessary to move on.

For all these reasons at the moment there is no definitive conclusion about the existence of resonant states in this energy region.

The production experiments will be briefly discussed in Section 2.

In Section 3 the formation experiments will be analyzed in some details; the discrepancies and the interesting results will be pointed out. Due to the low energy of the $\bar{p}$ beam the data refer only to bubble chamber work.

It will appear that this energy region is promising but also that a lot of work is still necessary. The conclusions will be made with a sort of boundary condition: the confirmed experimental results will be stressed while the interpretation and the speculations about some still moot signals will be completely missing.

2) PRODUCTION EXPERIMENTS

a) Missing Mass Spectrometers (MMS)

In Fig. 1 the results of the CERN MMS in the S region are shown (Chikovani 1966). In the reaction $\pi^- p \to p X^-$ at 12 GeV/c for $0.22 < |t| < 0.36$ $(GeV/c)^2$ - $|t|$ is the square of the four momentum transfer to recoil - a peak is observed at $M = 1929 \pm 14$ MeV/c^2 and width $\Gamma \leq 35$ MeV/c^2. The signal is visible only when X^- decays into three charged particles and possible neutrals with a statistical significance of ~5 standard deviations.

In Fig. 2 the results of the Northeastern-Stony Brook double-arm spectrometer are displayed (Bowen 1973). As in the previous case the reaction studied is $\pi^- p \to p X^-$; the incident energies are 11, 13.4 and 16 GeV/c with $0.2 < |t| < 0.3$ $(GeV/c)^2$. The spectrum obtained at 13.4 GeV/c is shown and the drawn bumps indicate the structure expected on the basis of published CERN MMS data. The authors say: "Our data do not support the existence of S meson".

Kienzle (1973), who in the 1966 was an author of the CERN MMS papers, has recently revised these data. This revision brings the CERN MMS cross sections downward by a factor 4 ± 1.

With this new normalized cross section there is no significant disagreement between the Chikovani (1966) and Bowen (1973) data; however the last data, while statistically superior, yield resonant cross sections consistent with zero.

At last high energy data were obtained by Antipov (1972). Always the reaction $\pi^- p \to p X^-$ was studied at 25 and 40 GeV/c for $0.17 < |t| < 0.35$ $(GeV/c)^2$. In Fig. 3 the results are shown. No narrow structure is visible.

b) Bubble Chamber

The Aachen, Berlin, Cern collaboration (Boesebeck 1968) finds a small bump in the $\pi^+\pi^\circ$ invariant mass with $M = 1900\pm40$ MeV/c^2 and $\Gamma = 216\pm105$ MeV/c^2 in the analysis of the reaction $\pi^+ p \to p \pi^+\pi^\circ$ at 8 GeV/c. In Fig. 4 this bump is shown.

The $\pi^- p \to p \pi^+\pi^-\pi^-\pi^\circ$ reaction at 11.2 GeV/c was studied by the Genova-Hamburg-Milano-Saclay collaboration (Caso 1970). If the events in Δ^{++}, η and ω regions are excluded and if only the events in the ρ band are selected the invariant mass of the 4 pions has a peak in the S region. These data are visible in Fig. 5; the mass and the width are $M = 1973\pm15$ and $\Gamma = 80$ MeV/c^2.

In the $\pi^+ p \to p \pi^+\pi^\circ$ reaction at 13.1 GeV/c (Kramer 1970) the $\pi^+\pi^\circ$ effective mass shows a bump for $M = 1975\pm12$ MeV/c^2 and $\Gamma = 45\pm20$ MeV/c^2. The results are shown in Fig. 6.

At the XVI International Conference on High Energy Physics, NAL - Batavia 1972, Diebold (1972) reported on the reactions

$$\begin{aligned} \pi^- p &\to X^- p \\ &\to X^- p\, \pi^\circ \end{aligned}$$

at 12 GeV/c studied by the Hawaii group (Wohlmut 1972). No signal for the S meson is visible in their data, as is shown in Fig. 7, a typical distribution of this work.

The situation on the production experiments is summarized in Table I.

TABLE I

Production Experiments

	Reference	Reaction	Incident momentum GeV/c	t limits $(GeV/c)^2$	Experimental resolution (FWHM) MeV	Mass (MeV)	Width (MeV)	Decay Mode
M M S	Chikovani 1966	$\pi^- p \to pX^-$	12.0	$0.22 < \lvert t \rvert < 0.43$	22 ± 2	1929±14	< 35	3c
	Bowen 1973	$\pi^- p \to pX^-$	11.0,13.4,16.0	$0.2 < \lvert t \rvert < 0.3$	~30	/	/	/
	Antipov 1972	$\pi^- p \to pX^-$	25.0,40.0	$0.17 < \lvert t \rvert < 0.35$	~50	/	/	/
Bubble Chamber	Boesebeck 1968	$\pi^+ p \to p\pi^+\pi^0$	8.0		40	1900±40	216±105	$\pi^+\pi^0$
	Caso 1970	$\pi^- p \to p\pi^+\pi^-\pi^-\pi^0$	11.2		~40	1973±15	80	$\rho^-\pi^+\pi^-$
	Kramer 1970	$\pi^+ p \to p\pi^+\pi^0$	13.1		~40	1975 ±12	45±20	$\pi^+\pi^0$
	Wohlmut[a)] 1972	$\pi^- p \to X^- p$ $X^- p\pi^0$	11.8		20	/	/	/

a) Preliminary data

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3) FORMATION EXPERIMENTS

The S region in formation $\bar{p}$-nucleon ($\bar{p}N$) experiments up to now has been explored only with the bubble chamber technique.

The more accurate data in the $1900 < \sqrt{s} < 1970$ range on the $\bar{p}p$ total, elastic and annihilation cross section have been published by the CERN, Roma, Trieste collaboration (Amaldi 1966). On Fig. 8 a compilation is shown. No obvious structure is visible.

The inelastic $\bar{p}p$ total cross section has been measured by the Wisconsin group between 1880 and 1950 MeV/c² (Cline 1971a). In Fig. 9 these data are shown. This measurement has been questioned by Bizzarri (1972b): the cross section between 1880 and 1900 is grossly overestimated because of contamination of stopping antiproton annihilations.

The backward hemisphere $\bar{p}p$ elastic scattering has been studied in the range $1900 < \sqrt{s} < 1990$ MeV by the Wisconsin group (Cline 1968). The differential cross section near 180° and 90° shows energy dependent fluctuations. These fluctuations can be interpreted as direct channel narrow boson resonances. In Fig. 10 these data are visible.

These data show significant discrepancies with the previous published data by the CERN, Roma, Trieste collaboration (Conforto 1968). A comparison between the two sets of data is visible in Fig. 11 (Castelli 1969).

At the Kiev conference the Wisconsin group (Cline 1970) presented a measurement of the backward hemisphere $\bar{p}p$ elastic scattering. They collected approximately 2½ times as many events as their previous experiment (Cline 1968). In Fig. 12 the data are visible and the extrapolated 180° cross sections from a Legendre polynomial fit are shown in Fig. 13. The conclusion is that the rapid energy dependence of the cross section near 180° is strongly indicative of a meson state of mass $M = 1925$ and $\Gamma = 15$ MeV/c^2, and possibly an additional state at $M = 1945$ and $\Gamma = 54$ MeV/c^2 exists.

This resonant interpretation has been questioned by Lys (1970) because of the inconsistency with available $\bar{p}p$ total cross section measurements (Amaldi 1966 and Conforto 1968) and furthermore the 180° extrapolation is in error (Bizzarri - Discussion and Comments after Laloum 1972).

The Collège de France, Pisa collaboration (d'Andlau 1971) presented at the Amsterdam Conference a study of $\bar{p}p$ elastic scattering in the backward hemisphere below 650MeV/c. The data are displayed in Fig. 14 and 15. Their conclusion is that the resonant interpretation appears to be strongly favoured over any diffractive hypothesis; it could correspond to the so-called S meson; its mass and width would be $M = 1939$ and $\Gamma = 63$ MeV/c^2. A double structure is not excluded for $M_1 = 1929$ MeV/c^2, $\Gamma_1 = 36$ MeV/c^2 and $M_2 = 1954$ MeV/c^2, $\Gamma_2 = 12$ MeV/c^2.

The Roma, Trieste collaboration (Bizzarri 1972b) gives an upper limit to the resonant contribution of the single resonance in the $\bar{p}p$ backward scattering for $1915 < \sqrt{s} < 1950$ MeV. The limit is deduced from the energy dependence of the $\bar{p}p$ and $\bar{p}$-neutron ($\bar{p}n$) inelastic cross sections and it results smaller than the expected contribution from diffraction scattering. The conclusion is that the energy dependence of the 180° $\bar{p}p$ elastic cross section in the $1915 < \sqrt{s} < 1950$ MeV region cannot be directly related to the formation of s-channel resonances; therefore the detection of a possible resonance might be easier via the study of annihilation channels.

In order to illustrate the contribution of a naive diffractive model in Fig. 15 the dotted curve is plotted, as computed by Marzano using a crude boundary-condition model (see Discussion and Comments after Laloum 1972).

The data on the $\bar{p}n$ channel used by Bizzarri (1972b) derive from an $\bar{p}$-deuterium ($\bar{p}d$) experiment at low energy (Bizzarri 1973). Only annihilation events with a "spectator" proton too slow to give a visible track in the chamber have been considered (momentum $\leq$ 80 MeV/c), reducing this way the spread of the $\bar{p}n$ total energy in the c.m. system due to the neutron Fermi motion. In Fig. 16 these data are shown while in Figs. 17, 18 and 19 the complete set of data on the $\bar{p}d$ total cross section measurements are shown. Again no obvious structure is visible.

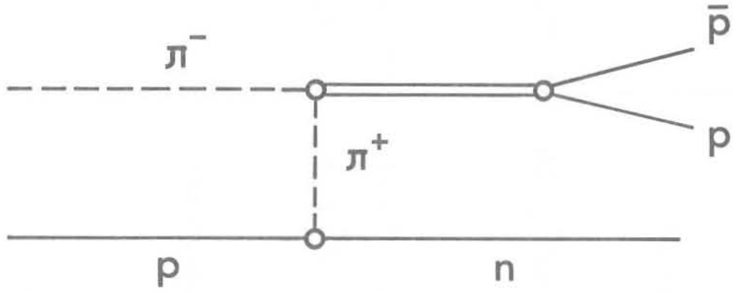
Up to now the results on the total and elastic differential cross section have been given. In the following some particular annihilation channels will be revised.

The $\bar{p}\, p \to \pi^-\pi^+$ and k^-k^+ total and differential cross sections have been measured by the Rome, Trieste collaboration (Bizzarri 1969). The results are shown in Fig. 20 and 21. These data are very interesting: for the $\pi^+\pi^-$ case as the energy increases the forward-backward asymmetry decreases, at $\sqrt{s} \cong 1900$ (i.e. for $\bar{p}$ incident of ~50 MeV/c) being about 1 (Fig. 22) . The statistic is low but nevertheless this behaviour is very surprising: over a $\sqrt{s}$ interval of about 60 MeV a rapid variation of at least one phase seems to be demonstrated.

The $\bar{p}p \to \pi^-\pi^+$ reaction has been studied in deuterium by Dickinson (1970). From 83 events of the type $\bar{p}d \to \pi^+\pi^-n$ the forward-backward asymmetry is calculated for 4 points between 1875 and 1920 MeV. The data, plotted in Fig. 23, are in agreement with the Roma, Trieste data (Bizzarri 1969).

This same reaction has been studied in the S region also by Wisconsin and Collège de France groups. These data up to now are not definitively published. A compilation presented by Cline (1971b) at the Meson Spectroscopy Workshops (ANL 1971) is shown in Fig. 24, where the Collège de France data (reported by Montanet (1969)) at 700 MeV/c are also shown. The agreement between the experiments is rather good.

The $\bar{p}p \to \pi^-\pi^+$ reaction can be analyzed if the inverse $\pi^-\pi^+ \to \bar{p}p$ reaction is studied as a $\pi\pi$ inelastic scattering with the extrapolation to the pion pole indicated in the diagram



In fact the inverse reaction has been recently observed by two spark chamber experiments. In Fig. 25 (Ayres 1972) and 26 (Grayer 1972) these data are shown as reported by Diebol (1972). Little evidence for narrow structure appears from these results.

The $\bar{p}p \to k\bar{k}$ reaction has also been studied in this mass range. The statistics in the $\bar{p}p \to k^+k^-$ channel is very poor. As for $\bar{p}p \to k^o_s k^o_\ell$ channel, the Wisconsin group (Benvenuti 1971) has measured its cross section and has found a significant enhancement at $\sqrt{s}$ = 1970 MeV/c^2. At the Batavia Conference the University of Massachusetts-Tokyo collaboration presented new experimental data (Carson 1972) and does not see any clear evidence for a resonant state. The results are shown in Fig. 27; note the low statistics involved in both the experiments.

At last the $\bar{p}p \to \bar{n}n$ charge-exchange differential cross section has been measured between 1900 and 1970 MeV (Bizzarri 1968). These data are reported only for completeness; because of low statistics no informations on S meson can be extracted.

TABLE II

Formation experiments (Buhble chamber)

References	Reaction	$\sqrt{s}$ limits (MeV)	Measured quantities	Mass, Width (MeV)	Comments
Amaldi 1966	$\bar{p}p$	1900-1970	σtot, σinel, σscatt		
Cline 1971a	$\bar{p}p$	1880-1950	σinel		questioned by Bizzarri 1972a
Cline 1968	$\bar{p}p\to\bar{p}p$	1900-1990	$\frac{d\sigma}{d\Omega}$ $(-1\leq\cos\Theta^*\leq 0.05)$	1925,10 and 1945,20	questioned by Castelli 1969
Conforto 1968	$\bar{p}p\to\bar{p}p$	1900-1970	$\frac{d\sigma}{d\Omega}$		
Cline 1970[a)]	$\bar{p}p\to\bar{p}p$	1900-1990	$\frac{d\sigma}{d\Omega}$ $(-1\leq\cos\Theta^*\leq 0.05)$	1925,15 and 1945,54	questioned by Lys 1970'
d'Andlau 1971[a)]	$\bar{p}p\to\bar{p}p$	1900-1970	$\frac{d\sigma}{d\Omega}$ $(-1\leq\cos\Theta^*\leq 0.05)$	1939,63 or 1929,36 1954,12	see Discussion and Comment after Laloum 1972
Bizzarri 1972b	$\bar{p}n$	1900-1970	σinel		upper limit
Bizzarri 1973[a)]	$\bar{p}d$	1900-1970	σtot, σinel, σscatt		
Bizzarri 1969	$\bar{p}p\to\pi^-\pi^+$ $\bar{p}p\to k^-k^+$	1900-1970	σtot, $\frac{d\sigma}{d\Omega}$		
Dickinson 1970[a)]	$\bar{p}d\to\pi^-\pi^+(n)$	1875-1920	$\frac{d\sigma}{d\Omega}$		
Ayres 1972[a)]	$\pi^-\pi^+\to\bar{p}p$	1860-2460	σtot, $\frac{d\sigma}{d\Omega}$		from $\pi^-p\to\bar{p}pn$ at 6 GeV/c
Grayer 1972	$\pi^-\pi^+\to\bar{p}p$	1860-3000	σtot, $\frac{d\sigma}{d\Omega}$		from $\pi^-p\to\bar{p}pn$ at 19 GeV/c
Benvenuti 1971	$\bar{p}p\to k^o_s k^o_\ell$	1880-2000	σtot	1968,35	
Carson 1972[a)]	$\bar{p}p\to k^o_s k^o_\ell$	1900-2000	σtot		
Bizzarri 1968	$\bar{p}p\to\bar{n}n$	1900-1970	$\frac{d\sigma}{d\Omega}$		

a) Preliminary data

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The results of the formation experiments are summarized in Table II.

4) CONCLUSIONS

The CERN MMS results (Focacci 1966) remains the strongest evidence for the existence of a narrow resonance in the S region.

Nevertheless from the short review of counter and bubble chamber production experiments discussed in Section 2 it is possible only a negative conclusion: in the production experiments these is no evidence for narrow effects in the S region.

In the formation $\bar{p}N$ experiments the situation is very confused. Some signals have been detected but in most of the cases these signals have been questioned and may be spurious.

Moreover in the $\bar{p}N$ formation experiments the centrifugal barrier effects can play a very important role and can therefore suppress the high angular momentum states. In order to illustrate this effect in Fig. 28 the leading meson trajectory is shown with the curve $J_{max}=kr+1$ (k is the c.m. momentum and r=1 fm is the interaction radius). J_{max} represents the maximum spin of the states partecipating to the reaction. If this suppression really happens the signals discussed can refer to low spin resonances, the daughters, perhaps grouped in towers. But to date these are speculations and not experimental results.

The backward peak in the $\bar{p}p$ elastic scattering is confirmed. However it has been shown that diffraction models can give structures in the backward direction. Therefore the interpretation of such a peak is ambiguous.

From the total cross section measurements the elasticity of a possible resonance is expected to be very low. Therefore a complete phase shift analysis seems very remote because of a large number of absorptive channels.

The more promising channels seem the annihilations into $\pi\ \pi$ and $k\ \bar{k}$, where the angular distributions appear to be very rich of informations. But it is necessary a lot of work in order to collect a statistically sufficient number of events.

A final personal conclusion of this talk is that there is no experimental evidence for narrow effects in the S region. The question of whether or not the signals observed in this region are one or more resonances is open.

In preparing this talk, I have benefited by the excellent reviews in which this subject has been discussed, mainly those by Montanet (1969), Cline (1971b), Laloum (1972) and Diebold (1972).

I wish also to thank Drs. R. Bizzarri and F. Marzano for interesting conversations and useful comments on this paper.

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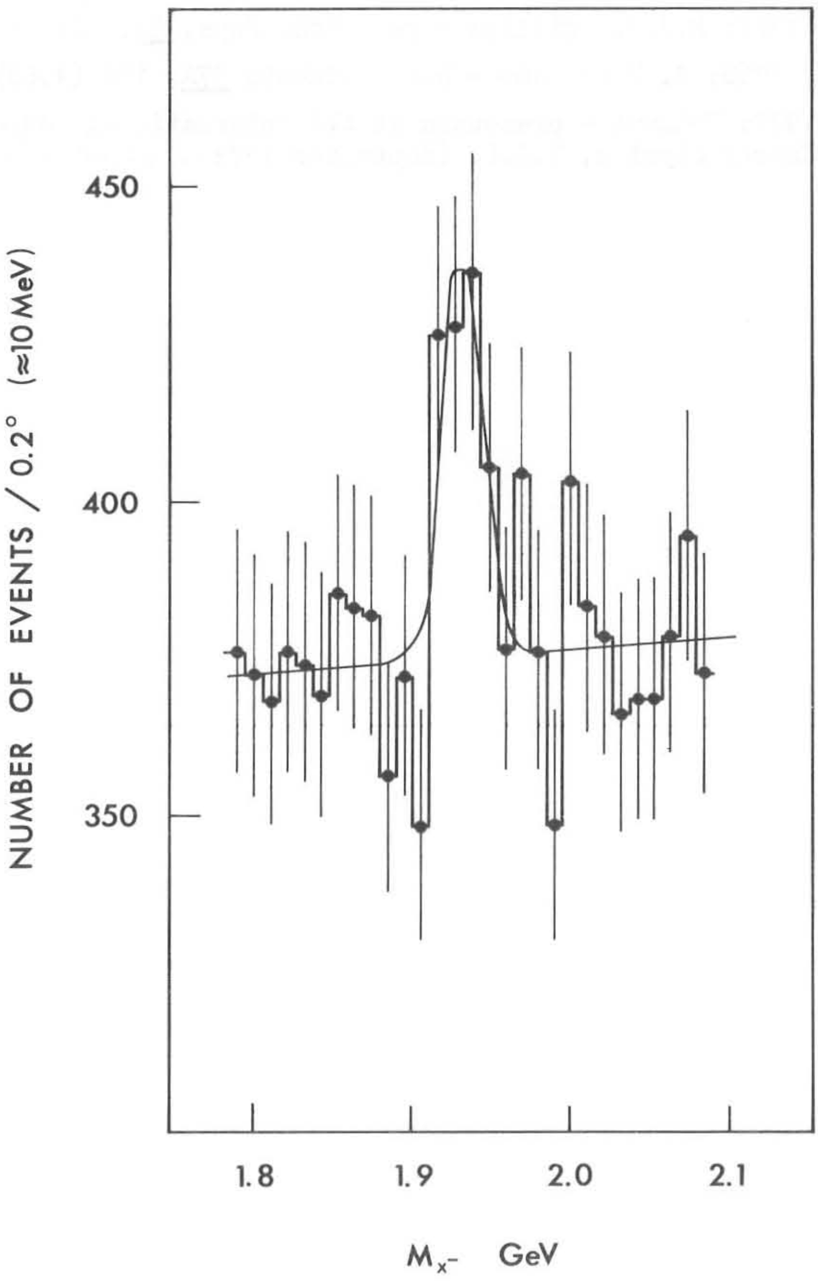

Fig. 1 - $\pi^- p - pX^-$ at 12.0 GeV/c. Evidence for the S boson (Chikovani 1966): M=1929±14 MeV, $\Gamma \leq 35$ MeV. The signal is seen for 3 charged decay products.

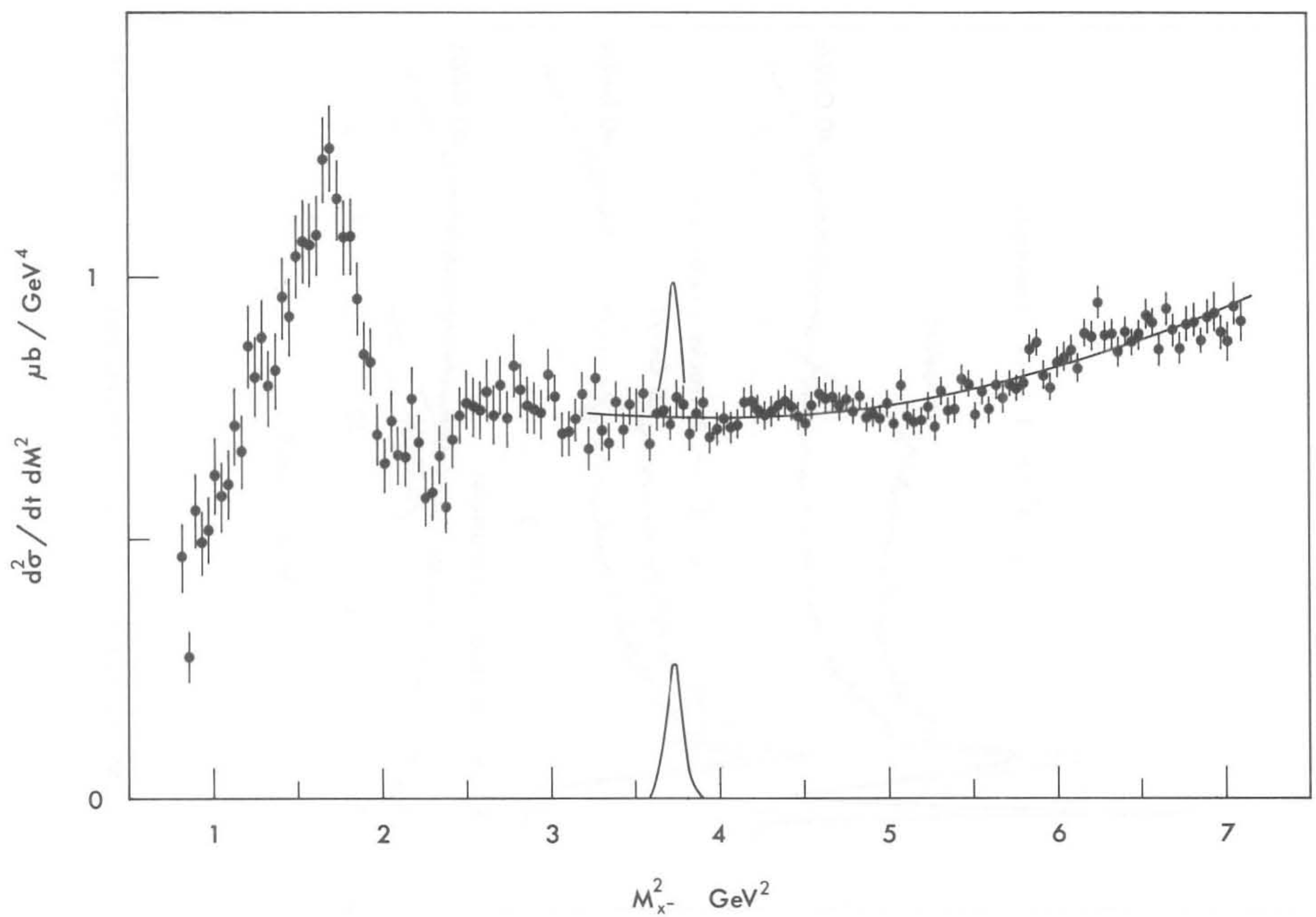

Fig. 2 - $\pi^- p \to pX^-$ at 13.4 GeV/c. Missing mass spectrum (Bowen 1973). The peak shows the result expected from the Foccacci (1966) published cross sections.

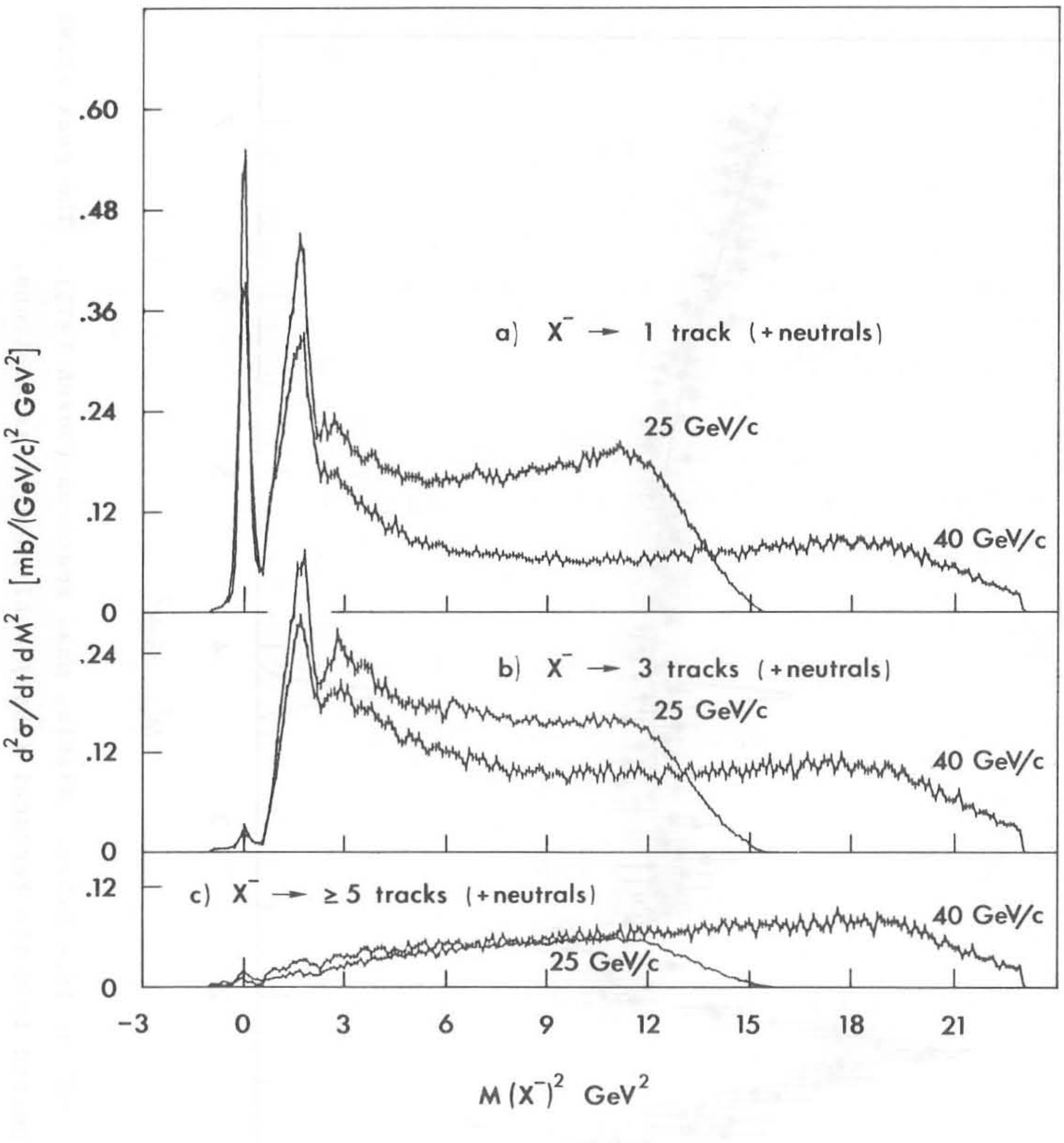

Fig. 3 - $\pi^- p - pX^-$ at 25 and 40 GeV/c. Missing mass spectrum (Antipov 1972).

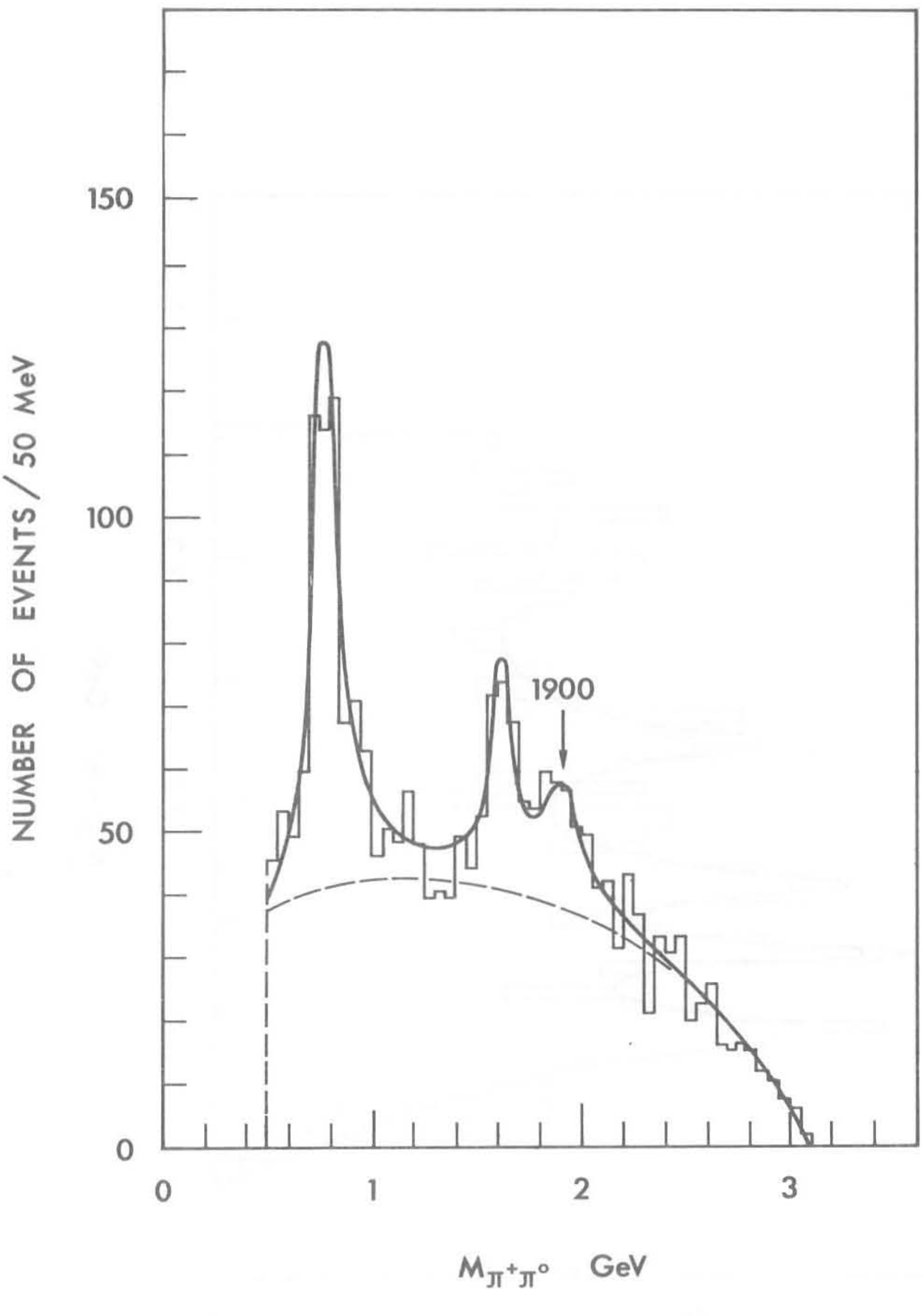

Fig. 4 - $\pi^+p - p\pi^+\pi^0$ at 8.0 GeV/c. Effective $\pi^+\pi^0$ mass distribution (Boesebeck 1968).

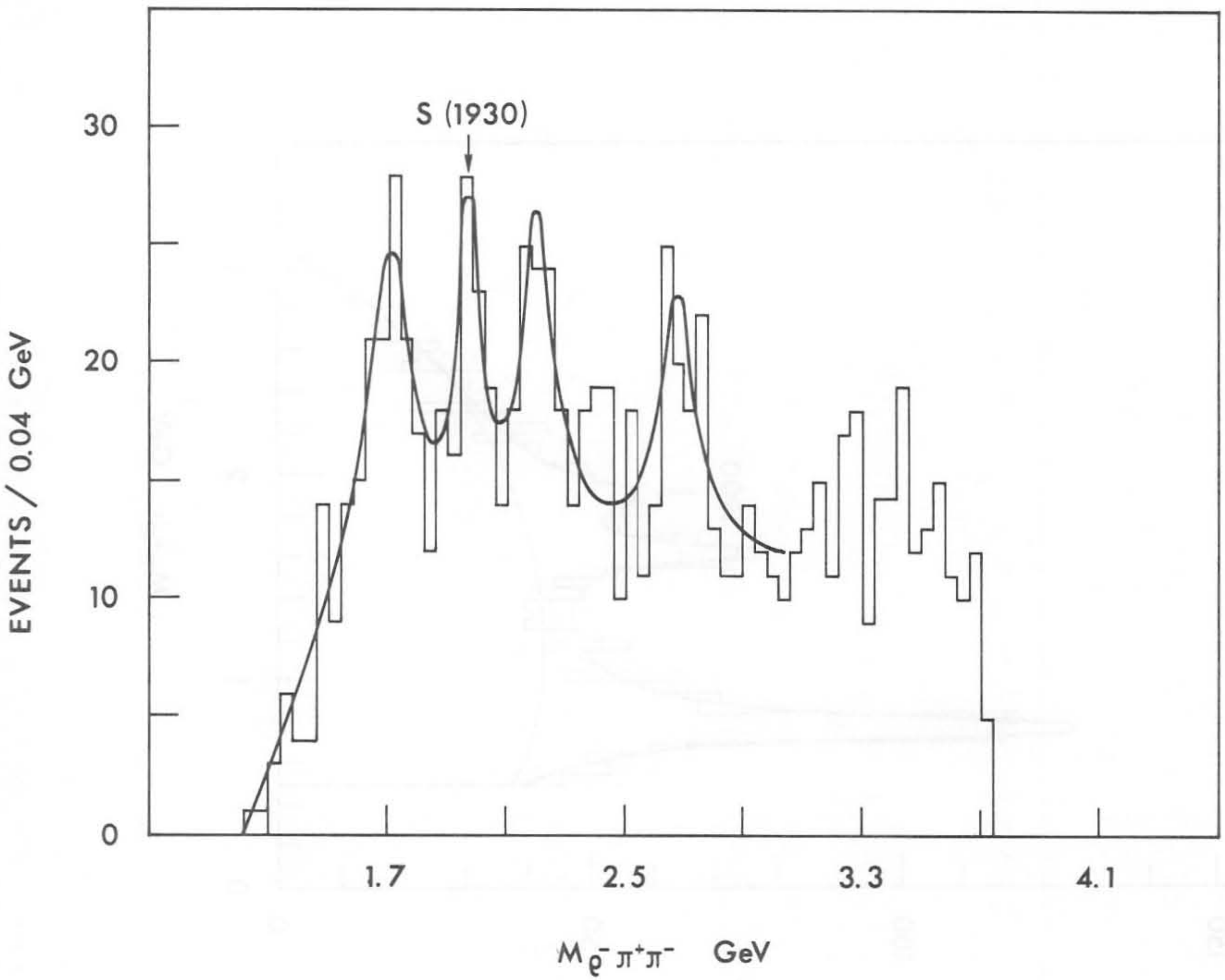

Fig. 5 - $\pi^- p \rightarrow p \pi^+ \pi^- \pi^- \pi^0$ at 11.2 GeV/c. Effective $\rho^- \pi^+ \pi^-$ mass distribution (Caso 1970).

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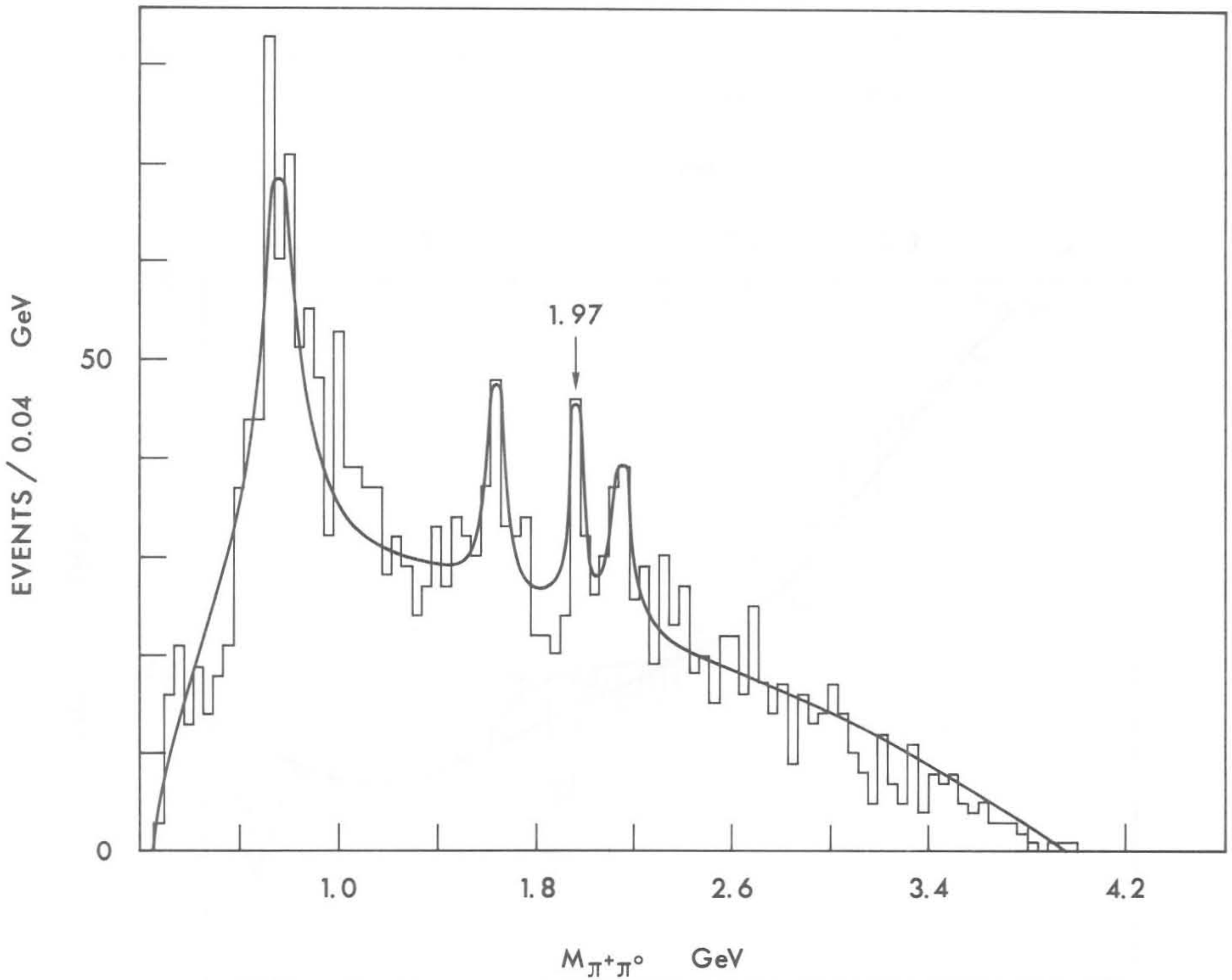

Fig. 6 - $\pi^+p - p\pi^+\pi^o$ at 13.1 GeV/c. Effective $\pi^+\pi^o$ mass spectrum (Kramer 1970).

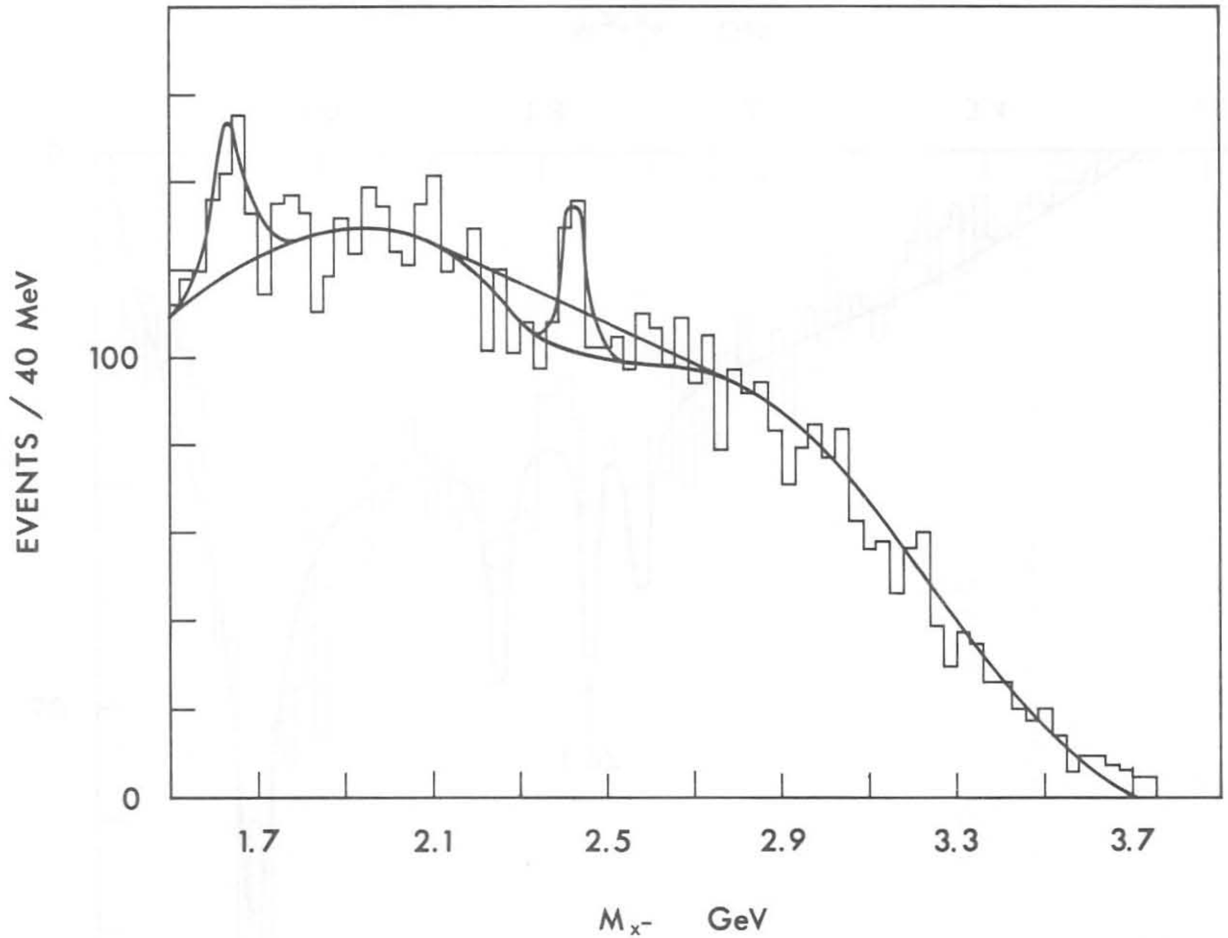

Fig. 7 - $\pi^- p - p\pi^-(m\pi^0)$, $m \geq 2$ at 11.8 GeV/c. Mass spectrum for $\pi^-(m\pi^0)$ with $m \geq 2$ (Diebold 1972 and Wohlmut 1972).

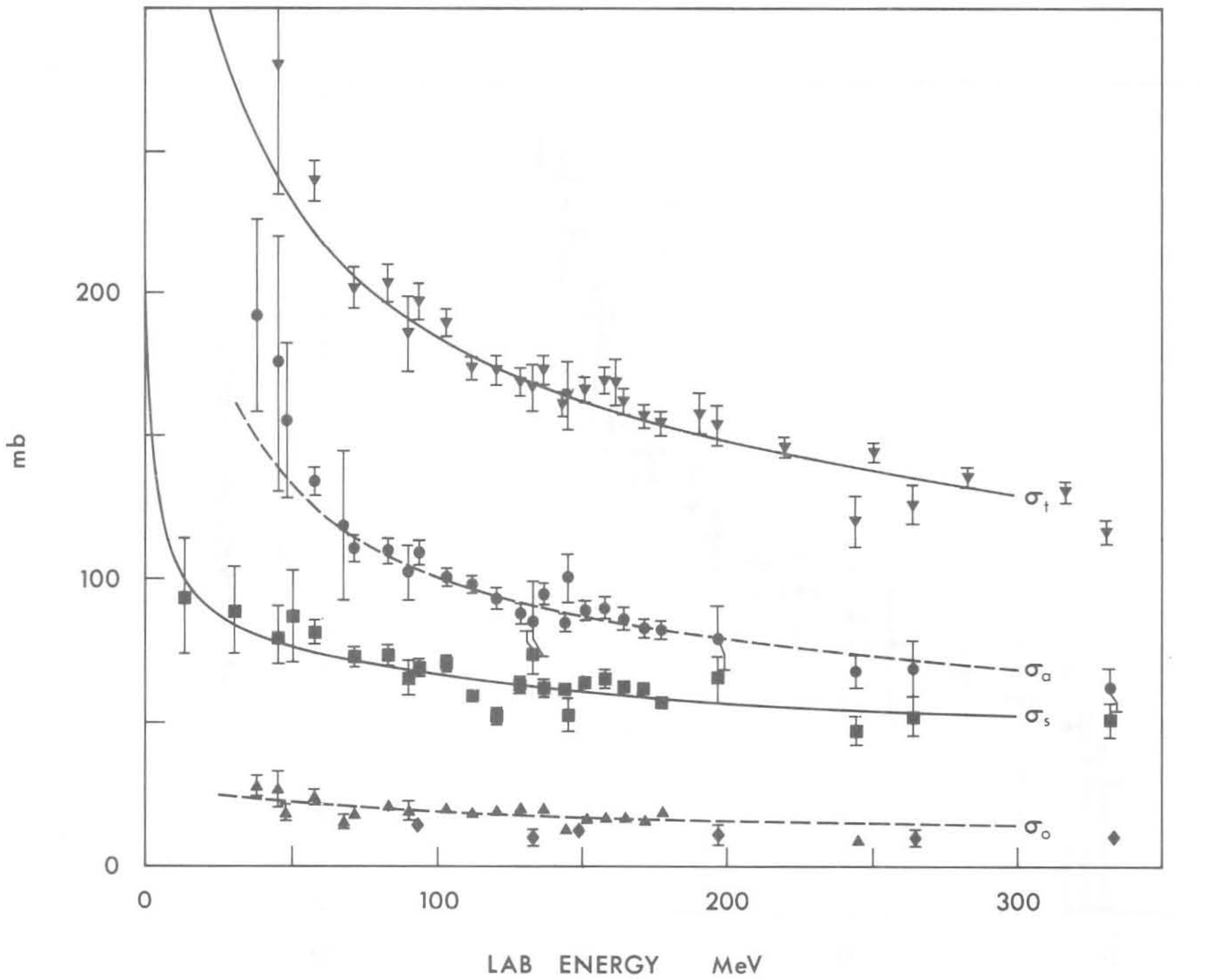

Fig. 8 - $\bar{p}p$ cross sections. A compilation of low energy data with theoretical curves (Bryan 1968).

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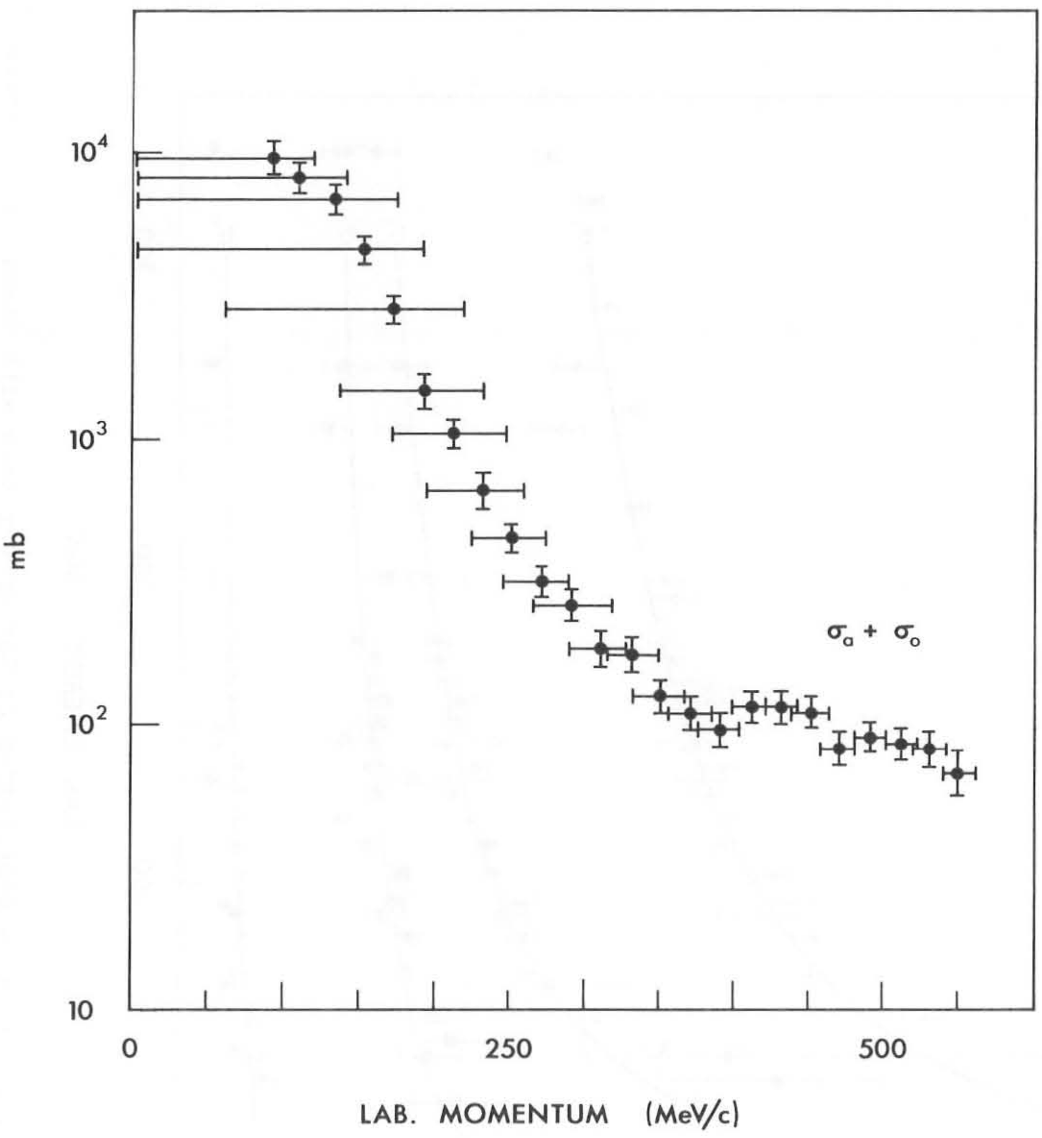

Fig. 9 - $\bar{p}p$ annihilation + charge exchange cross section (Cline 1971a).

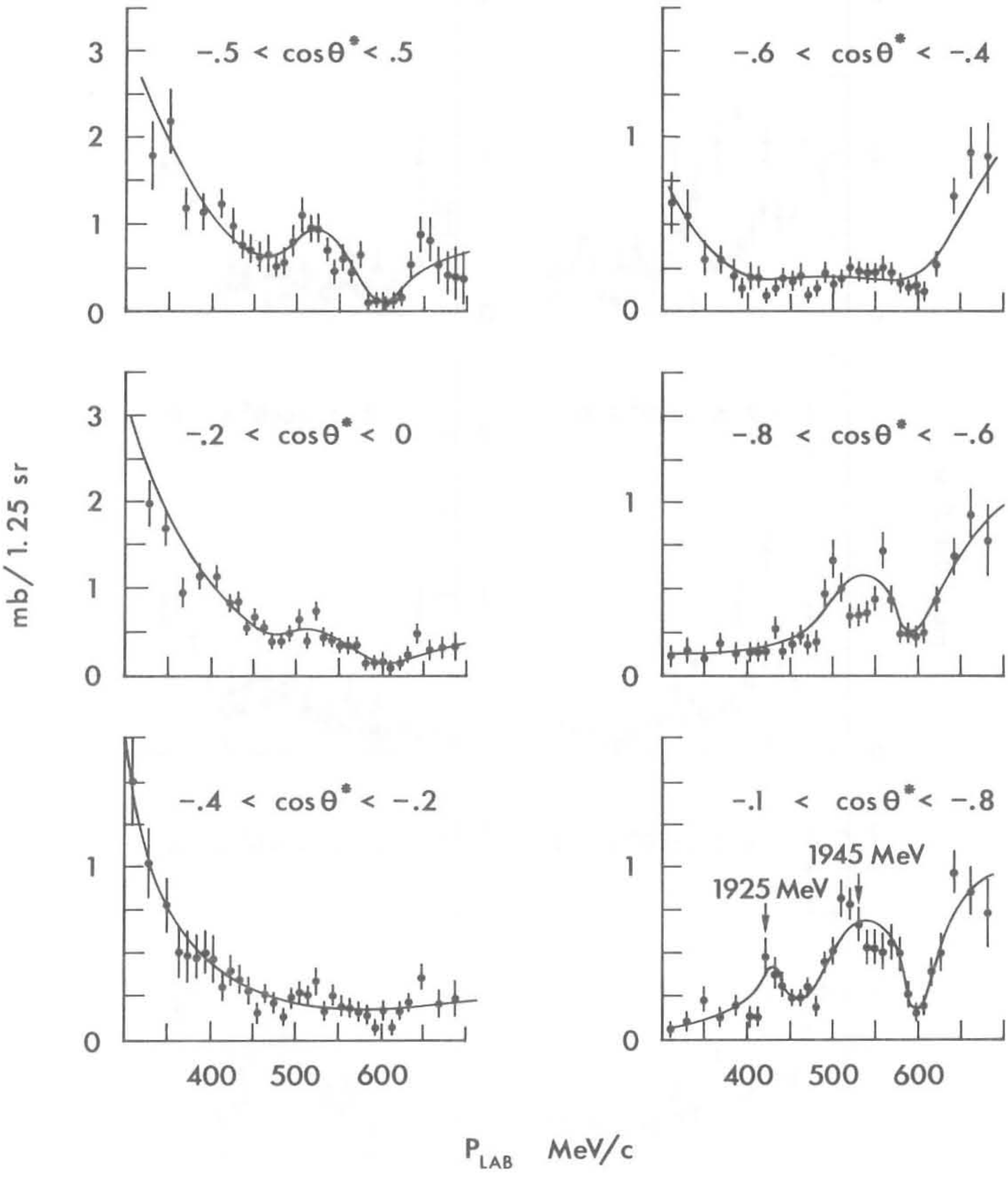

Fig. 10 - Energy dependence of $\bar{p}p$ elastic differential cross section for various $\cos\theta^*$ cuts (Cline 1968).

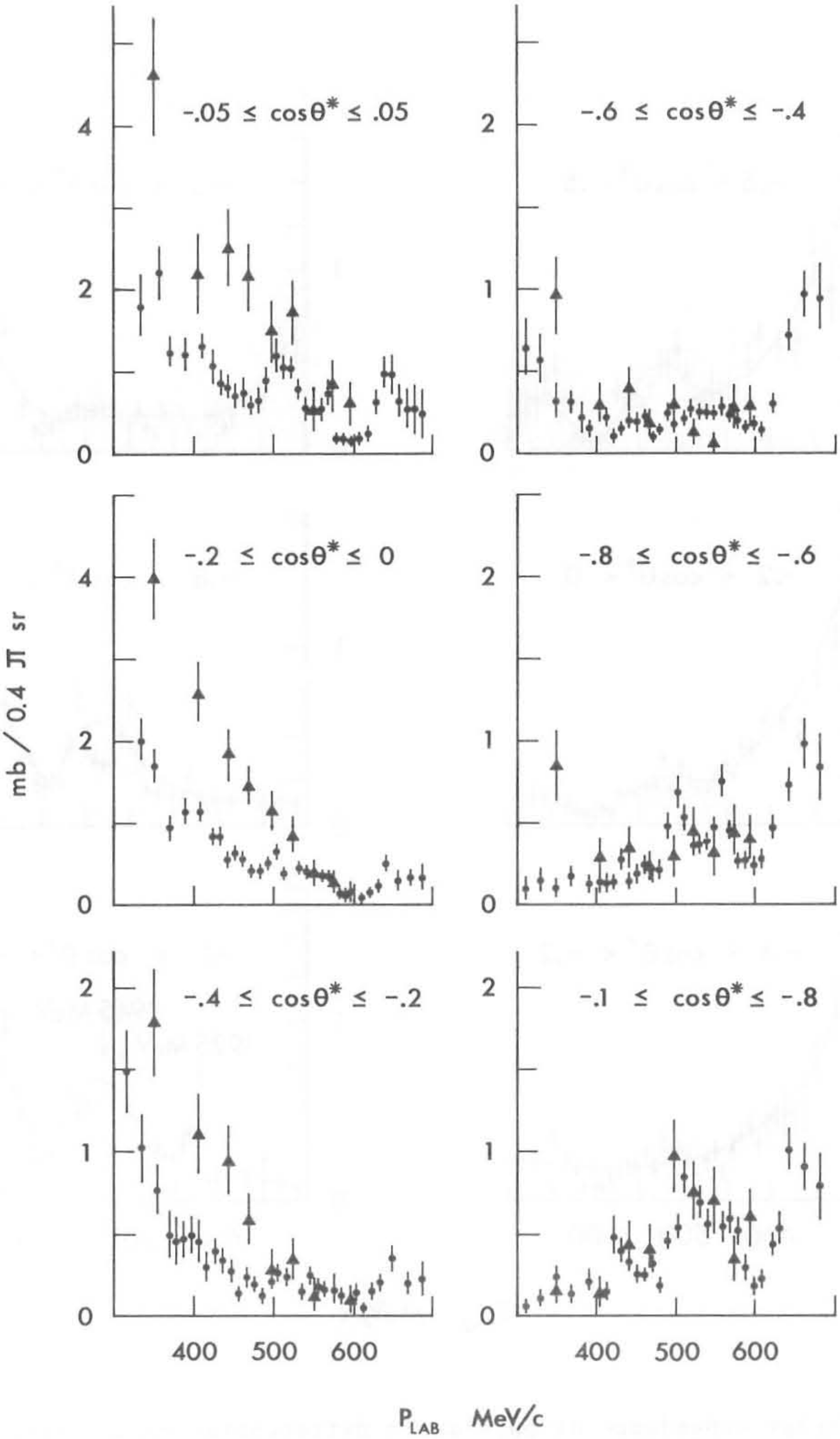

Fig. 11 - Energy dependence of $\bar{p}p$ elastic differential cross section for various $\cos\theta^*$ cuts: comparison between Cline (1968)♦and Conforto (1968)▲ data (Castelli 1969).

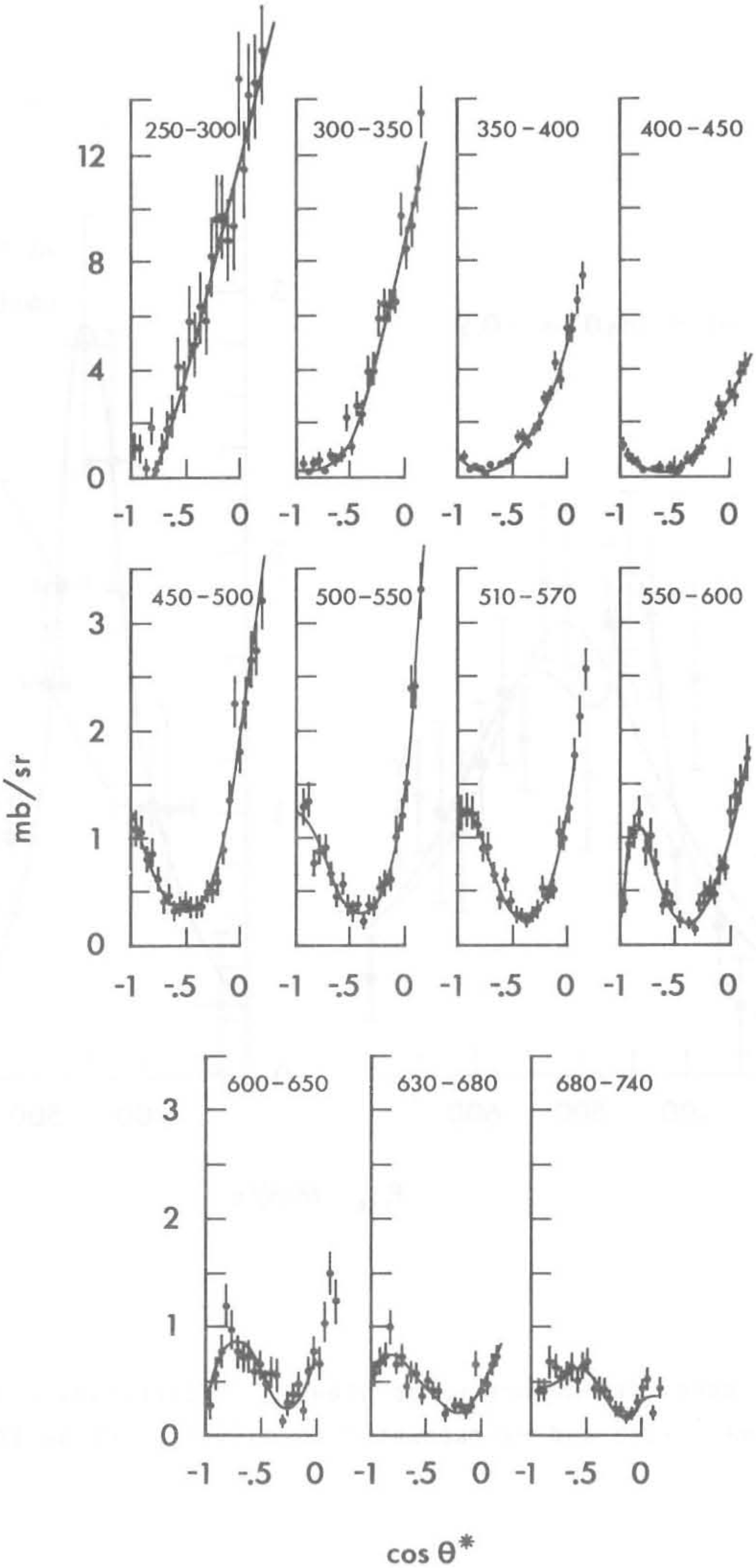

Fig. 12 - $\bar{p}p$ elastic differential cross sections for various intervals of p_{lab} in MeV/c (Cline 1970).

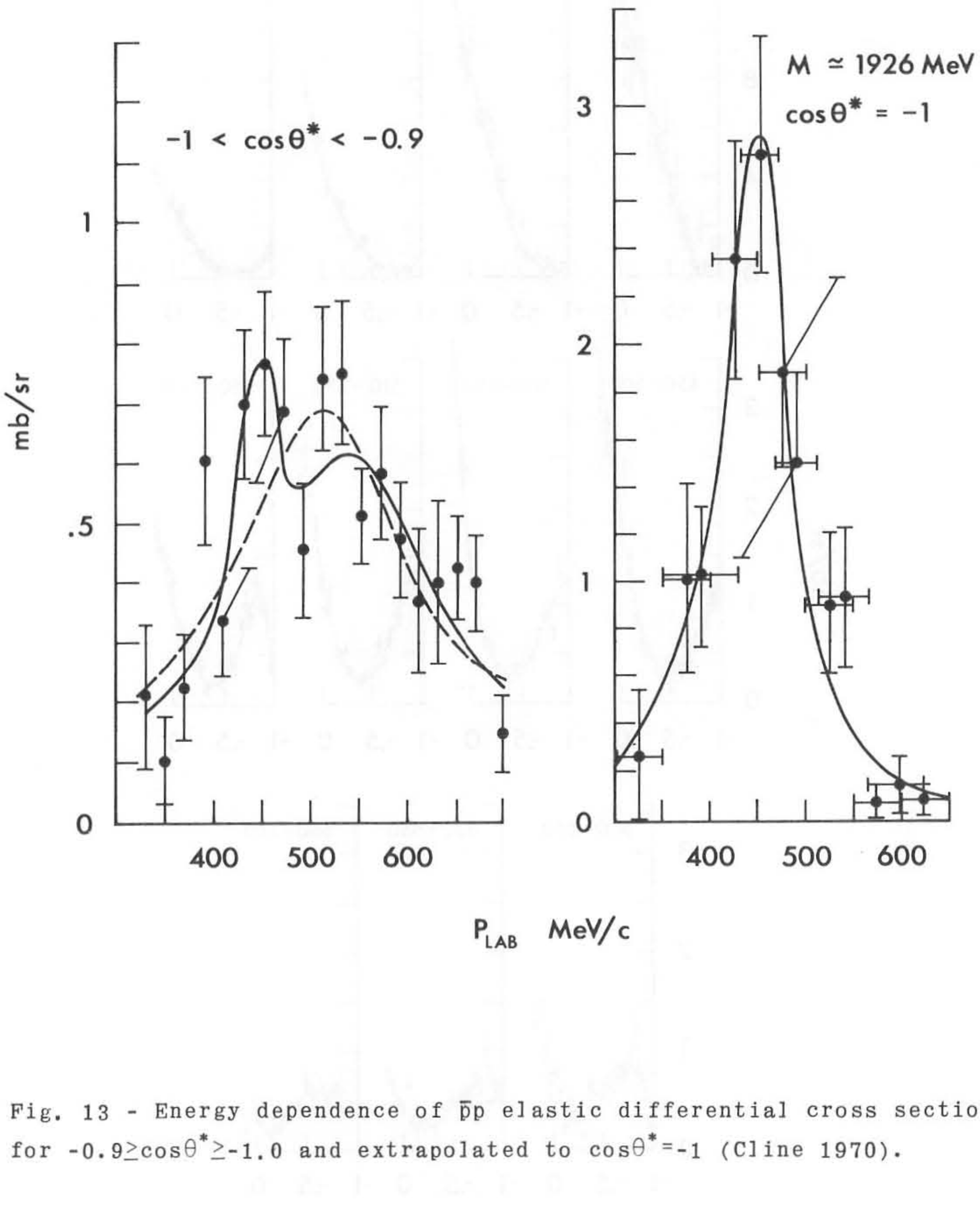

Fig. 13 - Energy dependence of $\bar{p}p$ elastic differential cross section for $-0.9 \geq \cos\theta^* \geq -1.0$ and extrapolated to $\cos\theta^* = -1$ (Cline 1970).

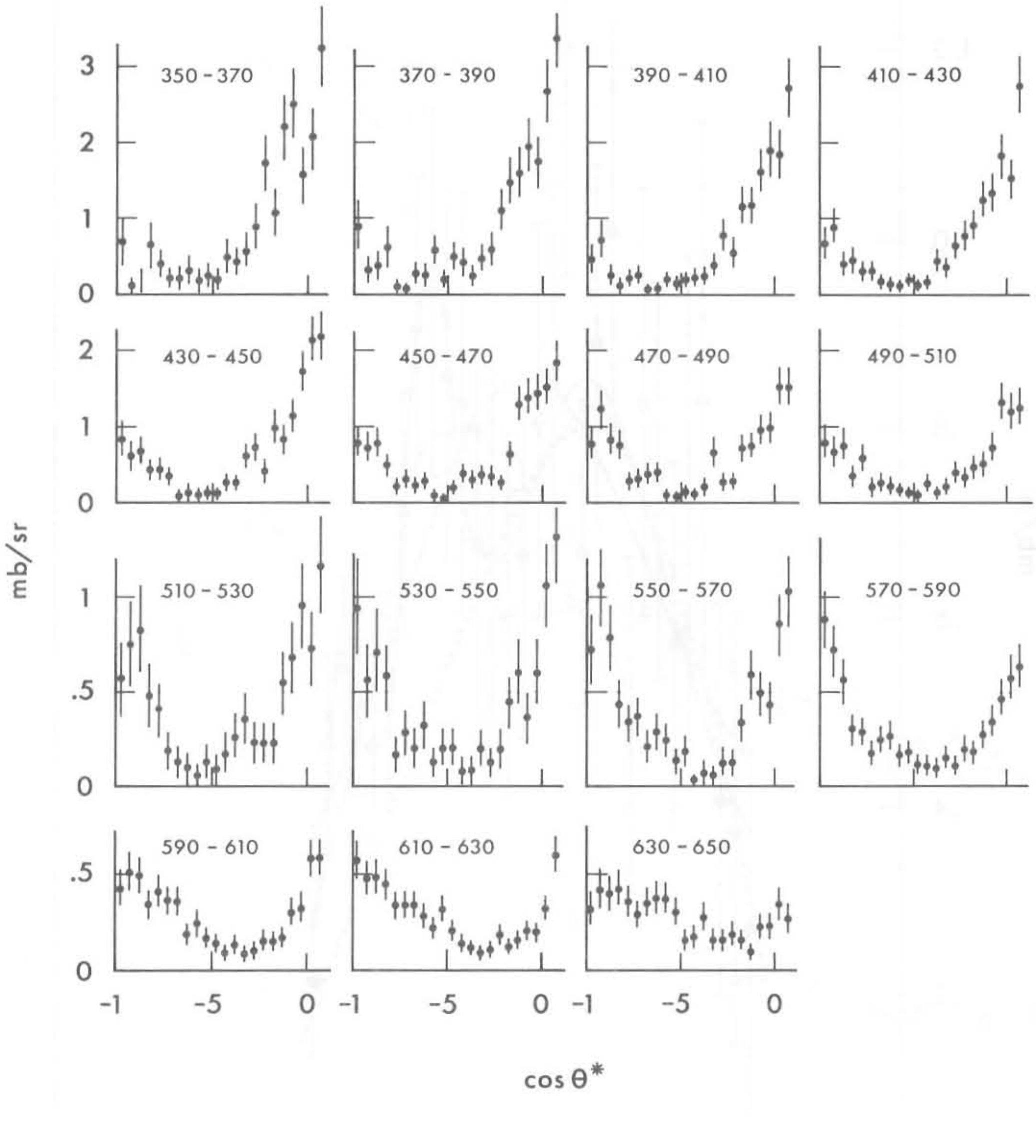

Fig. 14 - $\bar{p}p$ elastic differential cross sections for various intervals of p_{lab} in MeV/c (d'Andlau 1971).

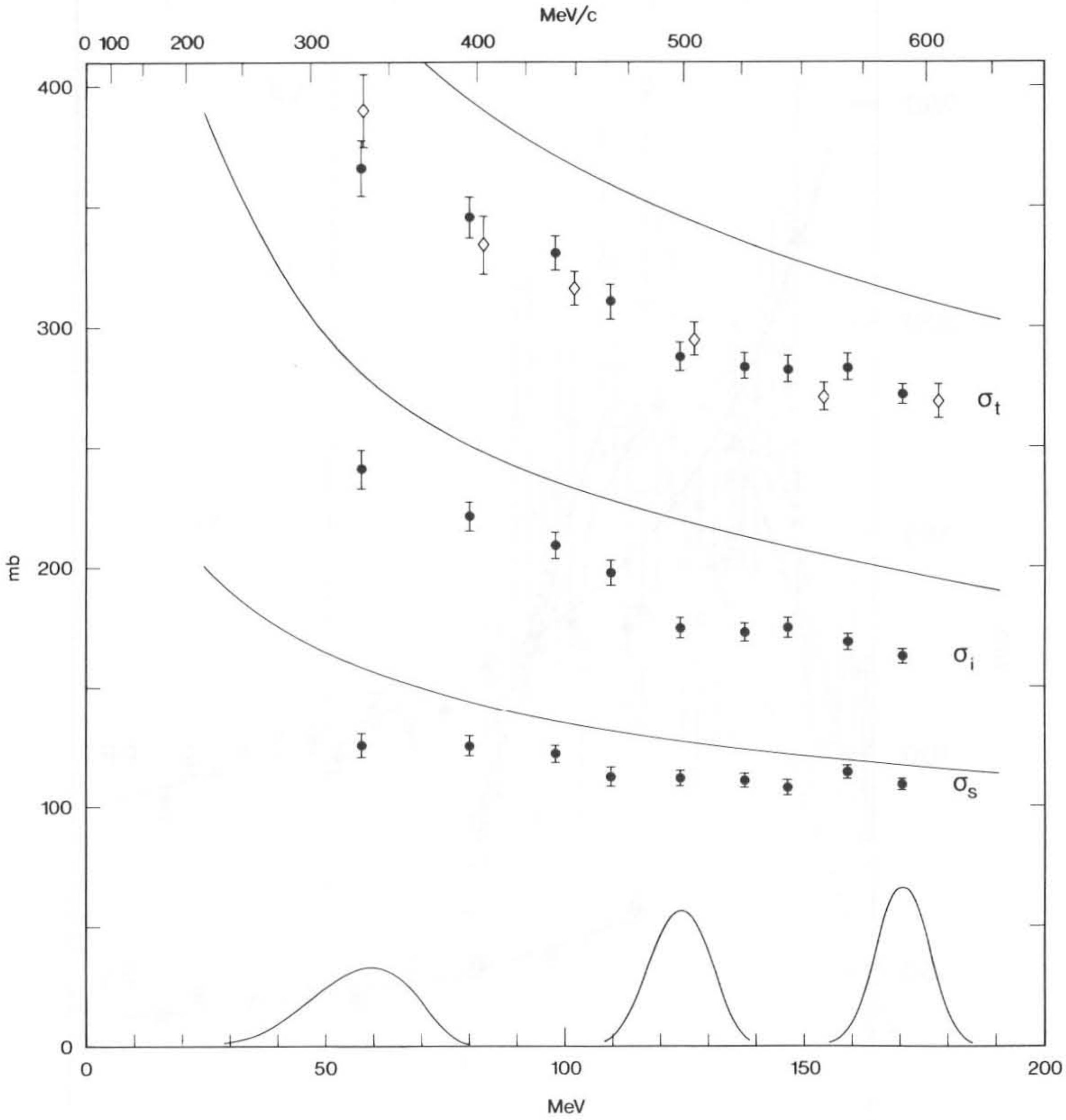

Fig. 17 - $\bar{p}d$ total, inelastic and scattering cross sections (Bizzarri 1973); (◇ Burrows 1970), (● Bizzarri 1973). The curves are the $\bar{p}p$ theoretical computation of Phillips (1967) multiplied by two.

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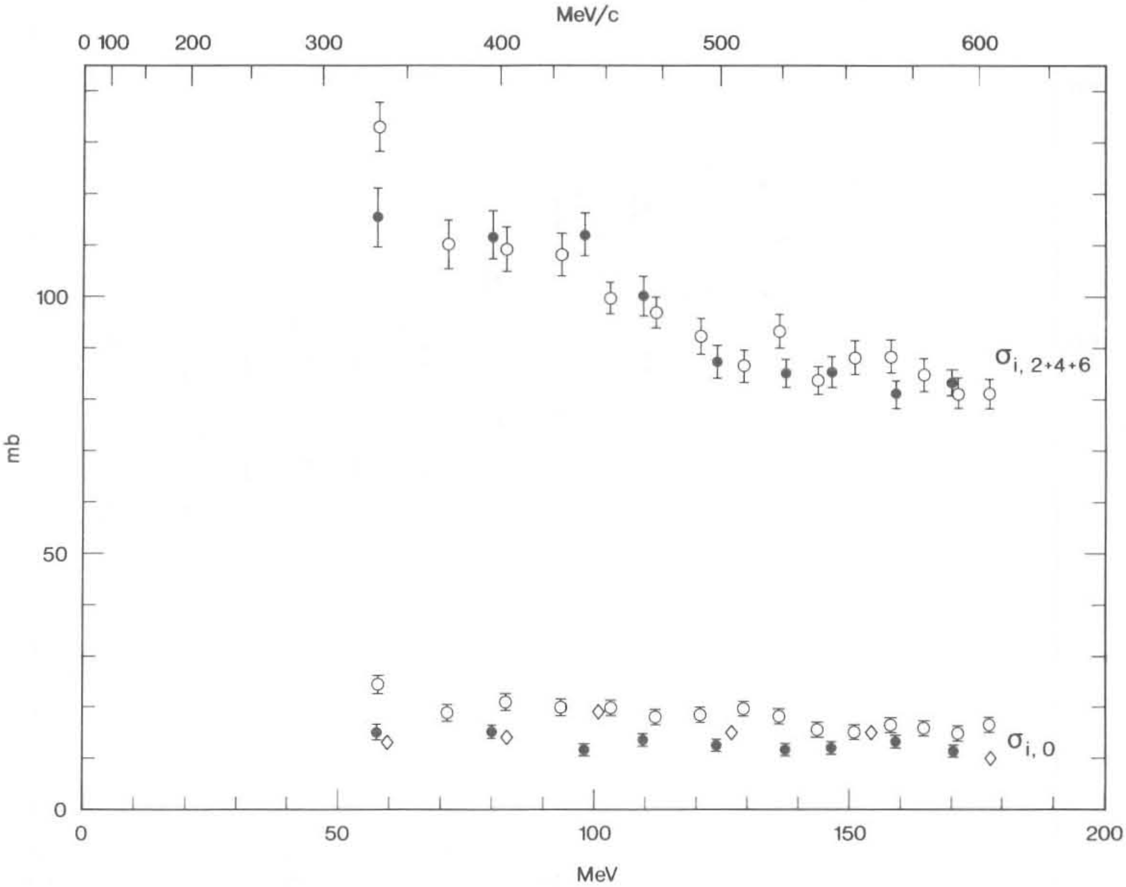

Fig. 18 - $\bar{p}p$ charged and zero prong cross sections (Bizzarri 1973) in hydrogen (○ Amaldi 1966) and in deuterium (◇ Burrows 1970, ● Bizzarri 1973).

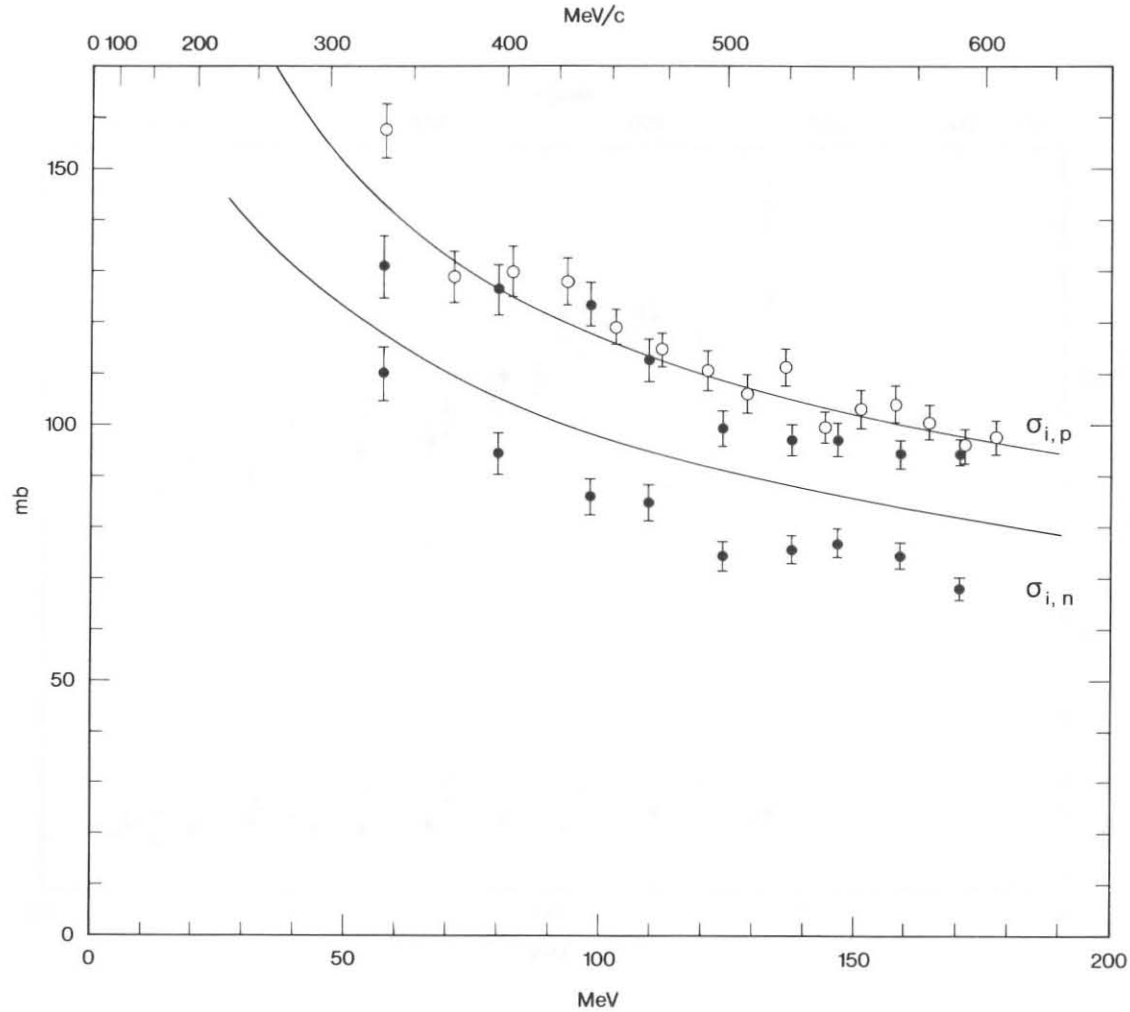

Fig. 19 - $\bar{p}p$ and $\bar{p}n$ inelastic cross sections (Bizzarri 1973) in hydrogen (ϕ Amaldi 1966) and in deuterium (● Bizzarri 1973). The curves are theoretical calculations by Bryan (1968).

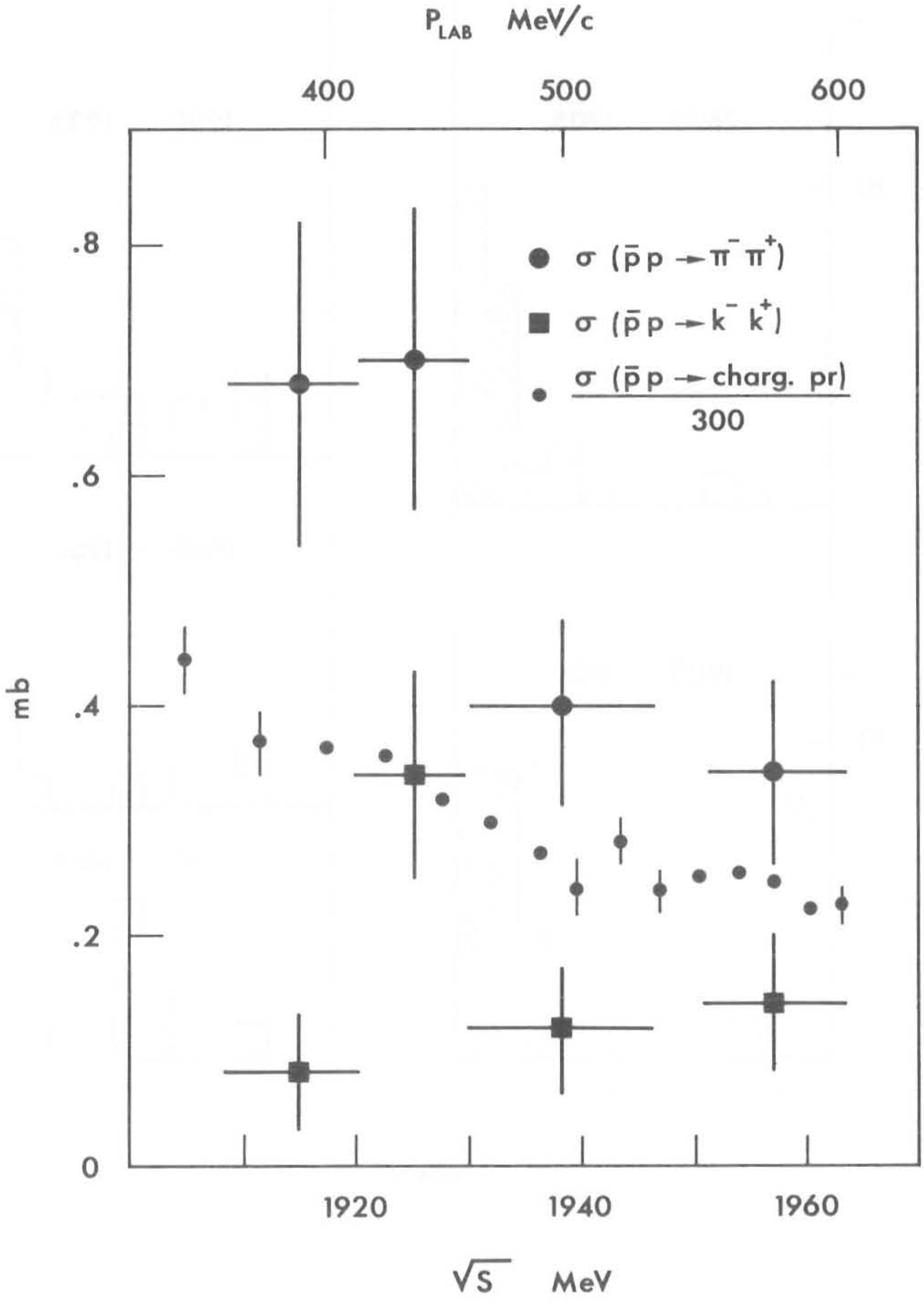

Fig. 20 - Total cross-sections of $\bar{p}p - \pi^-\pi^+$ and $\bar{p}p-K^-K^+$: (Bizzarri 1969).

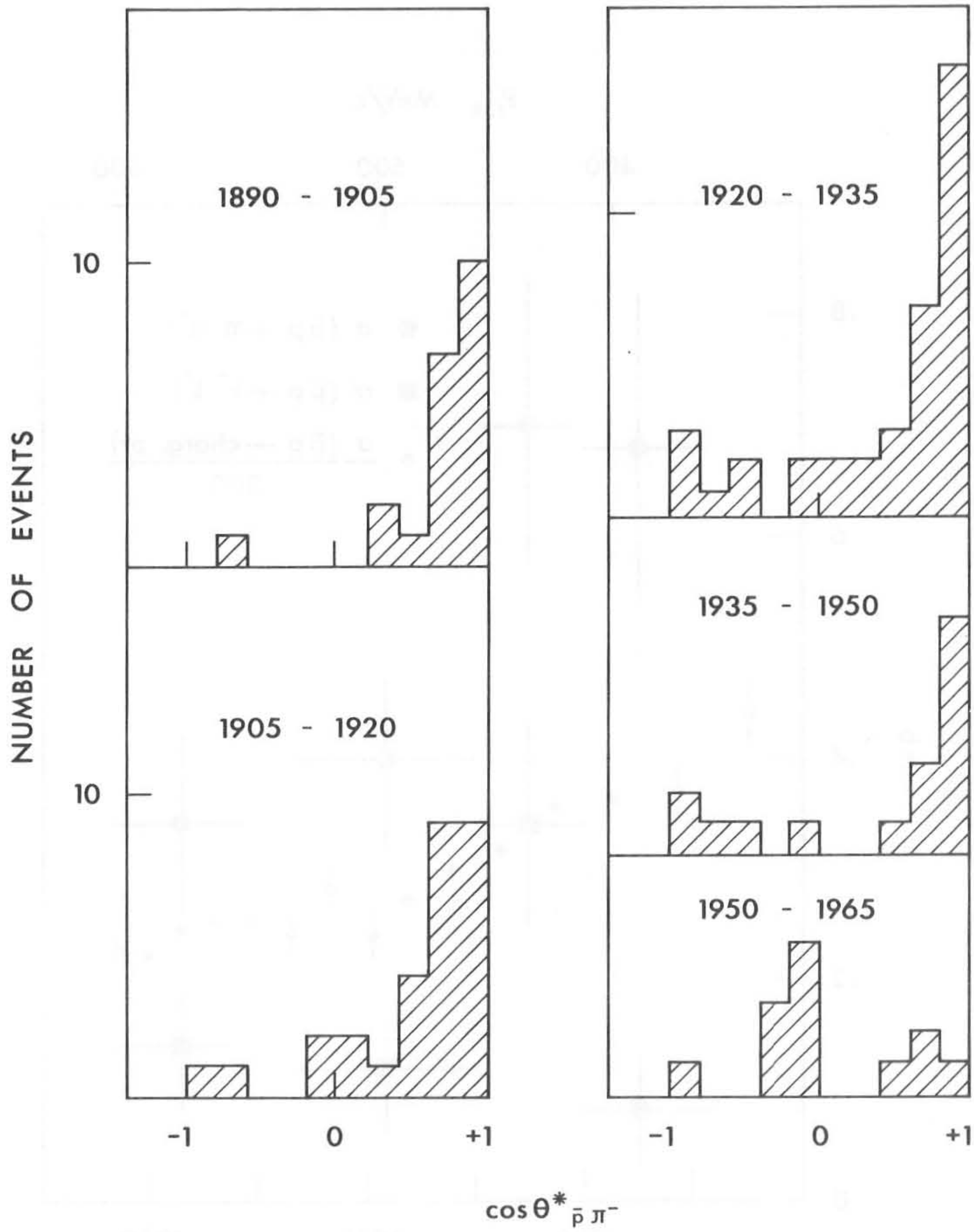

Fig. 21 - $\bar{p}p - \pi^-\pi^+$ angular distributions for various intervals of $\sqrt{s}$ in MeV. (Bizzarri 1969).

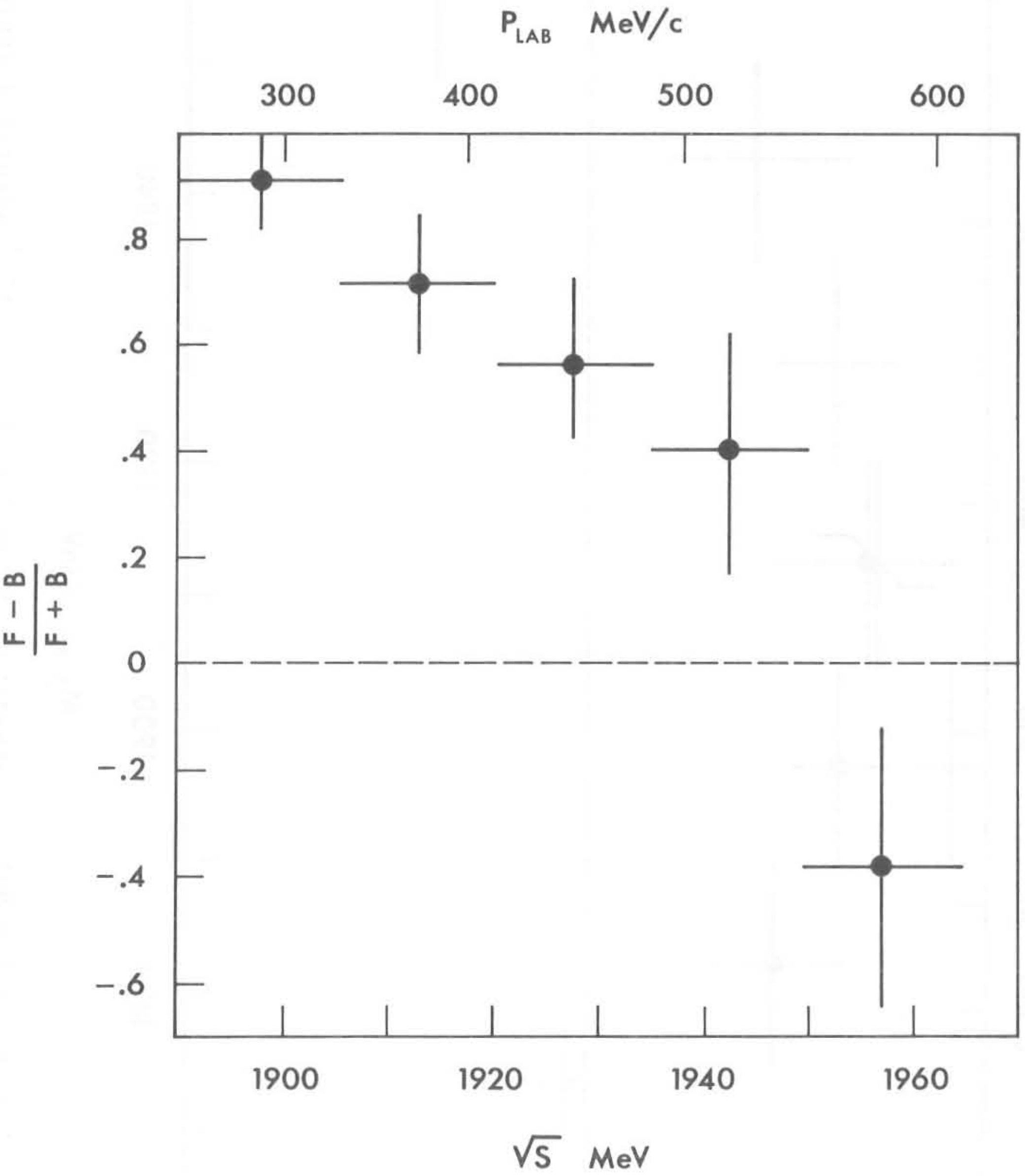

Fig. 22 - Asymmetry ratio for the $\bar{p}p - \pi^-\pi^+$ angular distribution. (Bizzarri 1969).

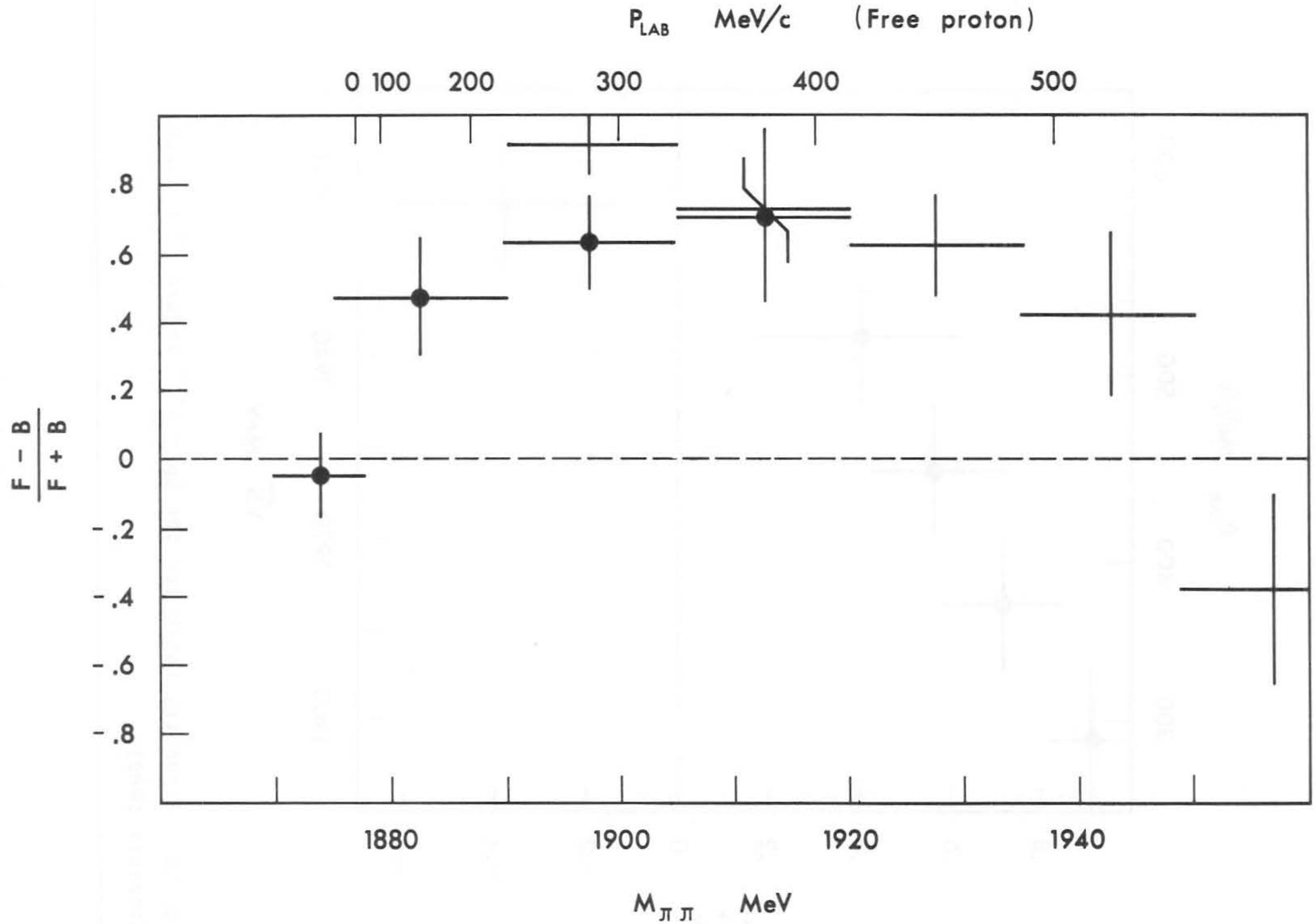

Fig. 23 - $\bar{p}d - \pi^+\pi^-(n)$ below 400 MeV/c. Assymmetry ratio for the $\bar{p}p - \pi^-\pi^+$ angular distribution (Dickinson 1970); for comparison from Bizzarri (1969).

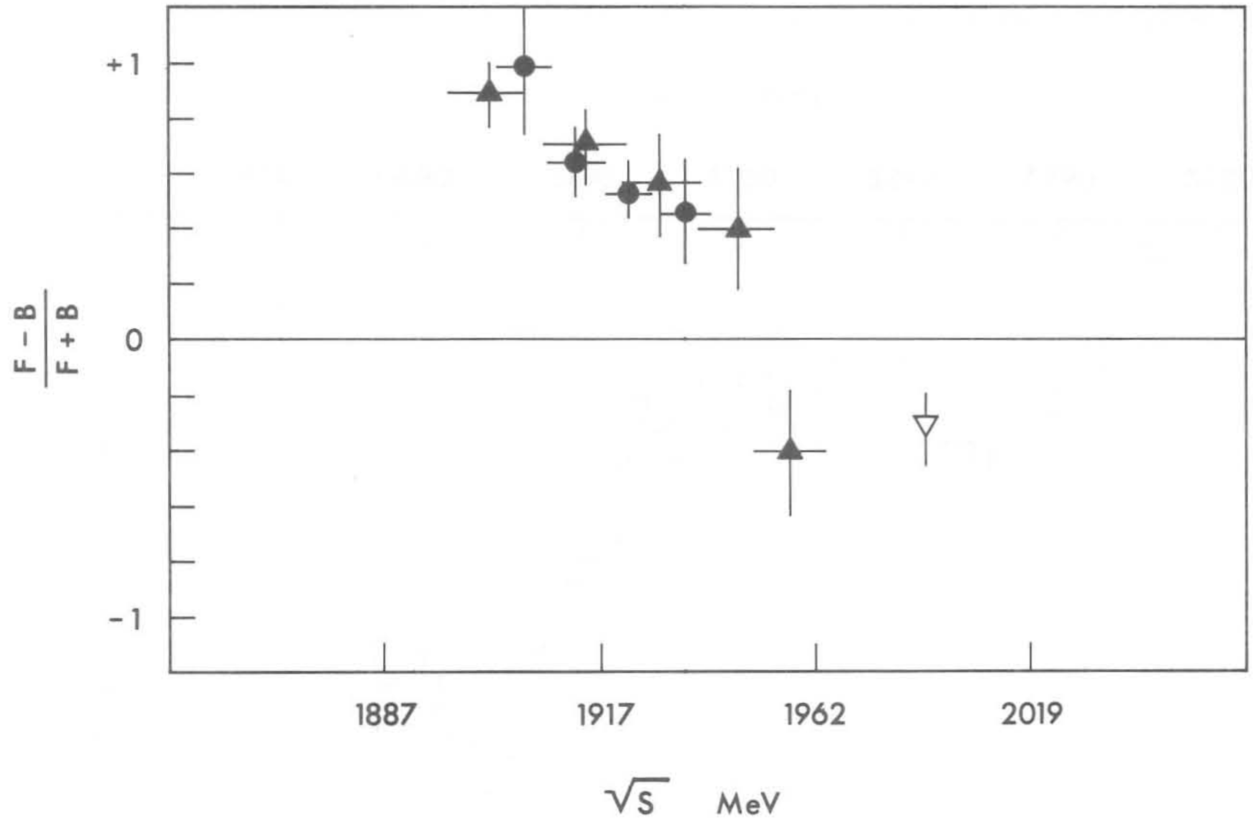

Fig. 24 - Compilation of asymmetry ratio for the $\bar{p}p - \pi^-\pi^+$ angular distribution (Cline 1971b). ● Cline (1971b), ▲ Bizzarri (1969), ▽ Montanet (1969).

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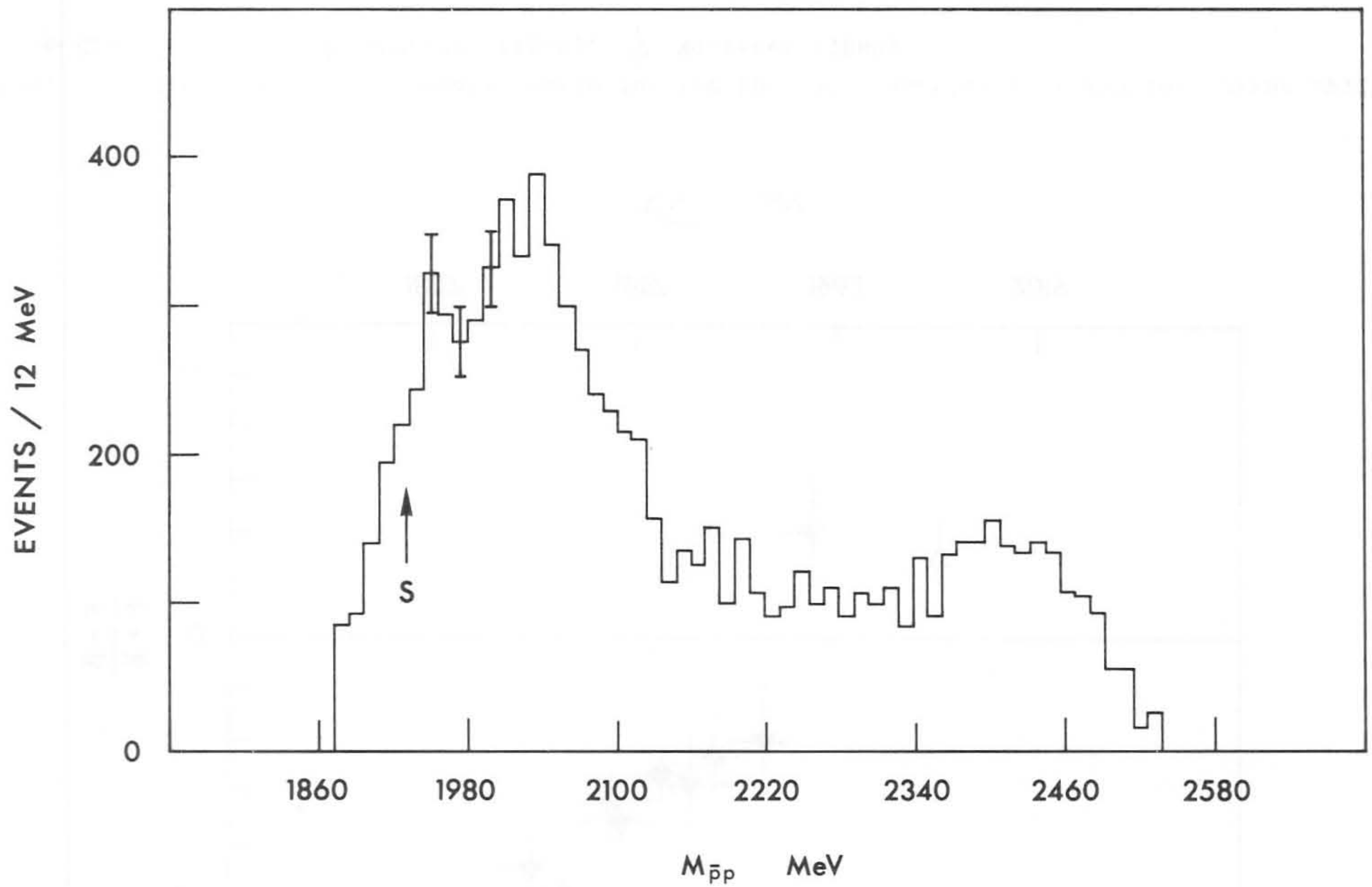

Fig. 25 - $\pi^- p \rightarrow \bar{p}pn$ at 6 GeV/c. Spectrum of $\bar{p}p$ effective mass (Ayres 1972).

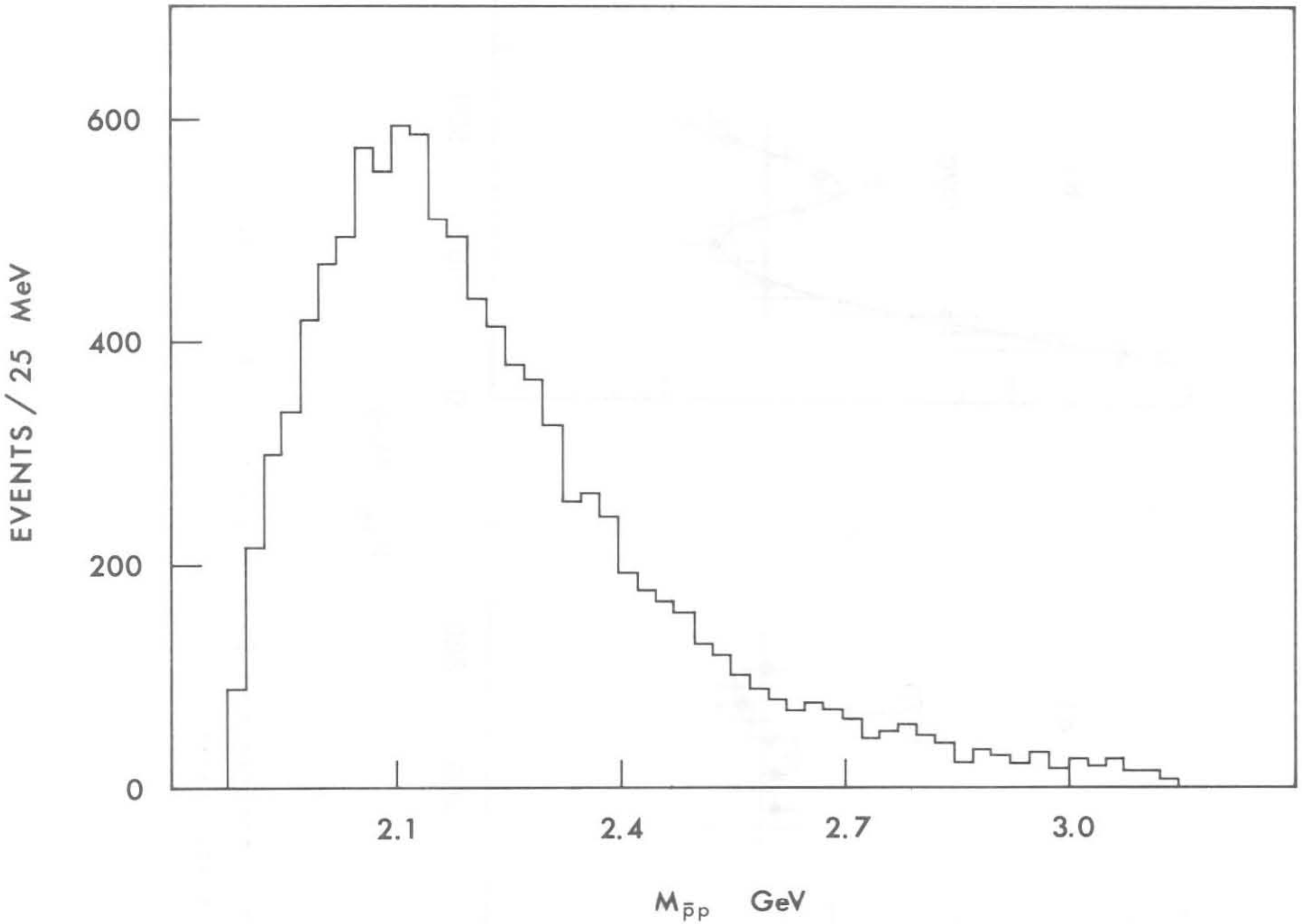

Fig. 26 - $\pi^- p \rightarrow \bar{p}pn$ at 19 GeV/c. Spectrum of $\bar{p}p$ effective mass (Grayer 1972).

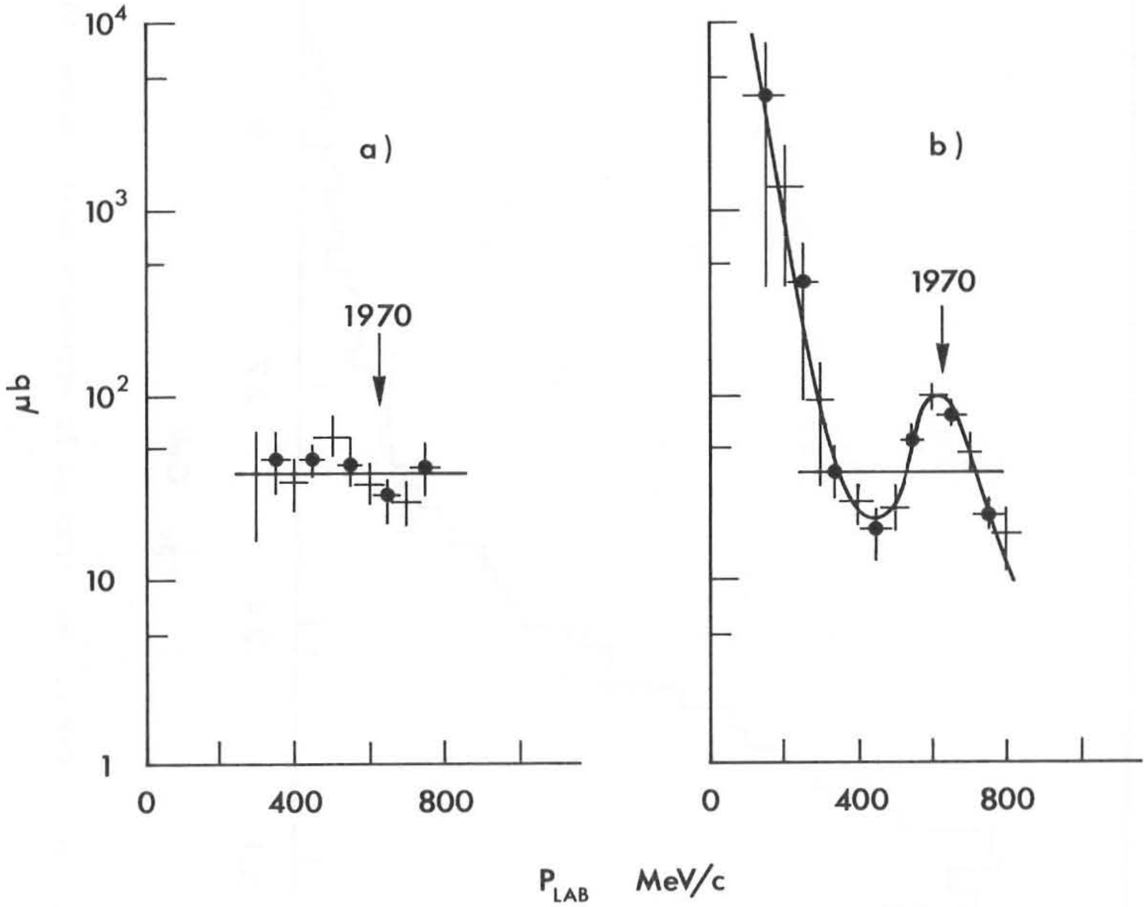

Fig. 27 - Comparison of $\bar{p}p - K^0_S K^0_L$ results of a) Carson (1972) and b) Benvenuti (1971).

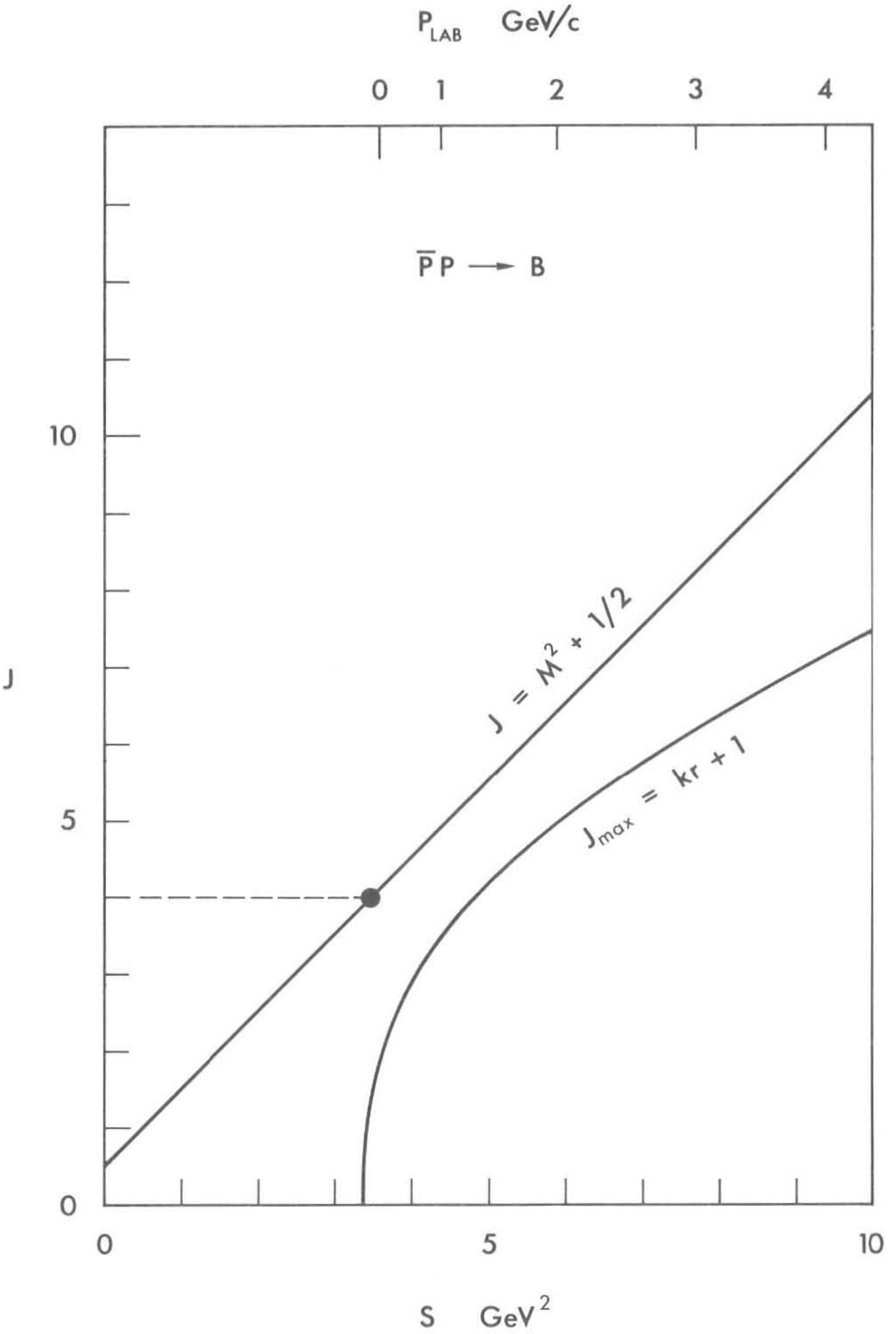

Fig. 28 - The leading boson trajectory and the J_{max}=Kr+1 curve in order to illustrate the centrifugal barrier effects.