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CURRENT STATUS ON NARROW $N\bar{N}$ STATES

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I. Introduction

This review represents an attempt to summarize the experimental status of narrow $B\bar{B}$ states as of mid-1979. In particular, this review concentrates on the current experimental situations and prospects regarding three "serious" contenders for the so-called baryonium states.

The name baryonium derives itself from the notion that there might exist a class of mesons coupling preferentially to $B\bar{B}$ final states. Baryoniums are interesting because they might be exotic, possibly being composed of four quarks. As will be discussed in Section II, the name baryonium may not be appropriate for the kind of exotic mesons theorists envisage. At the moment the only safe way to describe the exotics under discussion is to state that they are not the conventional mesons with a $q\bar{q}$ pair and a simple string connecting the two quarks. According to theorists, these exotic mesons may be composed of four quarks, two quarks or no quarks at all. In addition, according to a model, certain exotic four-quark mesons may be forbidden to decay into $B\bar{B}$ to first order.

Section III describes the experimental evidence for the three narrow $N\bar{N}$ states at 1935, 2020 and 2204 MeV, respectively. Although these narrow states have been thought to be reasonably secure (in particular, the 1935 MeV state), there appeared conflicting experimental results casting doubt on all these states. There are, however, a number of experiments with data on hand or about to take data which should decide the fate of these states; these prospects are dealt with in Section IV. Section V is reserved for conclusions.

The coverage in this review is limited in scope; in particular, possible narrow states below the $N\bar{N}$ threshold or the broad $N\bar{N}$ states are not dealt with here. The reader is referred to a number of existing review articles, both theoretical and experimental, on these and other related states as well as on the whole picture of exotic hadrons.(1-7)

II. Theoretical Concepts on baryoniums

A new family of mesons, possibly narrow, which should couple predominantly to baryon-antibaryon ($B\bar{B}$) channels, was first predicted by Rosner[8] in 1968 on the basis of duality concepts. The existence of a meson-exchange process for $B\bar{B}$ scattering, as shown in Fig. 1, implies that an s-channel resonance with the quark content of $qq\bar{q}\bar{q}$ ought to exist. The resonance is expected to couple mainly to $B\bar{B}$ channels, hence the name "baryonium."

An additional argument for supposing existence of such a state is afforded by the presence of forward differential peaks in the so-called forbidden-exchange reactions. For example, a forward peak is observed in the reaction

$$pn \to \Delta^-\Delta^{++}$$

at 6.98 GeV/c by G. Yekuteli, et al.[9] and also at a lower energy.[10] A natural expalanation for such a process is to postulate existence of an I = 2 meson state coupling to $B\bar{B}$ channels (see Fig. 2). Such a state would, of course, have to consist of $qq\bar{q}\bar{q}$ and couples to $B\bar{B}$; i.e. a baryonium state! As an additional example, one can cite "I = 3/2 meson" exchange processes observed in the reactions[11,12,13] $\bar{p}p \to \bar{\Sigma}^+(1385)\ \Sigma^-(1385)$, $\pi^-p \to K^+\Sigma^-(1385)$ and $K^-p \to \pi^+\Sigma^-(1385)$. All these reactions exhibit "forbidden" peaks.

Partly based on this circumstantial evidence for baryoniums plus certain experimentally observed candidates (to be discussed in the later sections), a number of theorists worked out mass spectra and quantum numbers for the presumed baryonium states. In the following, an experimentalist's survey of the relevant concepts and ideas is given, with emphasis on presenting various contrasting ideas instead of any detailed results.

One approach, due to Shapiro[14] and his collaborators and Dover[15] and others, is to start out with a one-boson exchange potential for NN scattering and relate it to the $N\bar{N}$ potential, leading to a rich spectrum of $N\bar{N}$ bound states both below and above the $N\bar{N}$ threshold. Although this approach proved fruitful, it is of course not a fundamental theory, as it relies on phenomenological, nonrelativistic NN potentials. Nevertheless, it is a valuable "interim" model, providing essential physical insights to the $N\bar{N}$ bound-state problem.

Relevant to the general multiquark theory of mesons but not necessarily to the baryonium picture only, one can cite two disparate approaches. The MIT bag model, due to R. Jaffe,[16] confines $qq\bar{q}\bar{q}$ quarks into a spherical cavity and they are allowed to interact with one another via gluon exchanges. According to his picture, the low-mass scalar mesons, ε(770) and δ(980) for example, are in fact four-quark states. If so, multiquark hadrons are not as rare as previously supposed, and existence of four-quark mesons above the $N\bar{N}$ threshold may not be so exotic after all! Another approach, due to Brayshaw,[17] supposes that, within the boundary of a meson of the basic $q\bar{q}$ pair, an excitation occurs creating an additional s-wave $q\bar{q}$ pair which then share with the original $q\bar{q}$ pair to form three-way virtual states of pseduo-scalar and vector mesons. In this picture, even the A_2-meson is exotic in the sense that it is an excited ρ-meson with an additional $q\bar{q}$ pair within the particle boundary. Naturally, such a four-quark model will produce states coupling to $B\bar{B}$ above threshold.

Turning now to theories of more immediate concern to baryoniums, one can cite two approaches. According to Rossi and Venziano,[18] what characterizes a baryonium is not so much the number of quarks within a state but the "string structure" binding the quarks. Thus, the usual $q\bar{q}$ mesons and qqq baryons have the simple string structures shown in Fig. 3a, while baryoniums have more complex string structure shown in Fig. 3b. Note that $q\bar{q}$-pair creation across dotted lines in Fig. 3b leads to creation of $B\bar{B}$ pairs. Note also that a baryonium may consist of just one $q\bar{q}$ pair or no valence quark at all (glueball).

Another phenomenological approach, due to Chan and others,[19] calls for a four-quark model in which the quark arrangement is $(qq)(\bar{q}\bar{q})$, as distinct from the picture of Jaffe in which the four-quark states are essentially a loosely bound "molecular" state of two $(q\bar{q})$ pairs. In the picture of Chan, et al., a qqq baryon is a bound state of a color-antitriplet diquark (qq) interacting with the "bachelor" quark. Consider now a $(qq)(\bar{q}\bar{q})$ state with the diquarks in the color-antitriplet states with the two diquark systems separated spatially from each other within the particle boundary (perhaps by angular-momentum barrier effects). Then, the state can readily decay into $N\bar{N}$ via a $q\bar{q}$ pair creation. However, if the diquarks happen to be in the color-sextet states, the parent state will not readily couple to $B\bar{B}$, preferring instead to cascade down to lower-mass states of the same color content. It is speculated that such a baryonium state would be very narrow in width, especially for high-mass excited states. As a manifestation of the color degree-of-freedom of quarks, it would be exciting indeed to discover such a state.

Carrying the color argument one step further, one can imagine a four-quark state with the quark structure of two $(q\bar{q})$ pairs, i.e. $(q\bar{q})(q\bar{q})$, with each $q\bar{q}$ pair in a color-octet state. This would prevent the $(q\bar{q})$ pairs from flying apart readily, leading to a relatively narrow baryonium state. Such an exotic state, likewise, may not have appreciable branching ratios into $B\bar{B}$.

At this stage of the theoretical developments, it would be premature to try to prefer one model over others, one obvious reason being that the experimental picture is still murky. Indeed, at the moment there is not a single narrow $B\bar{B}$ state, considered well established and its quantum numbers determined. Some of the more broad $N\bar{N}$ states, T(2190) and U(2350), could perhaps be identified with the baryoniums, but then they may also be simply the usual $q\bar{q}$-meson states.

III. Narrow $N\bar{N}$ states

This section is devoted to a discussion of three states: S(1935), $\bar{p}p$(2020) and $\bar{p}p$(2204). They are narrow (< 50 MeV) states above the $N\bar{N}$ threshold coupling mainly to $N\bar{N}$, so that they indeed are prime baryonium candidates.. The first one was seen in a number of experiments, whereas the second and the third were seen in a single experiment but with good statistical significance. However, recent experiments do not confirm these states, casting doubt on their existence.

A. S(1935)

This state was first reported in 1974 by A.S. Carroll, et al.[20] in a BNL experiment. It was a standard transmission-technique experiment with all scintillation-counter apparatus. The result is shown in Fig. 4, where both $\sigma_{total}(\bar{p}p)$ and $\sigma_{total}(\bar{p}d)$ are plotted as a function of the beam momentum. A peak centered around 1930 MeV is seen with a width of ∿10 MeV. The effect for $\bar{p}p$ systems is ∿10% with a cross section of ∿18 mb.

The state is also seen in two bubble-chamber experiments. The first one by Kalogeropoulos and Tzanakos[21] was an experiment of stopping antiprotons on deuterium in the BNL 30" chamber. They report two states, 1932 MeV and 1895 MeV, respectively (see Fig. 5). The second experiment is by V. Chaloupka, et al.[22] with stopping antiprotons on protons in the CERN 2m chamber. The effect is seen most clearly in σ_{el}, as shown in Fig. 6.

A more significant confirmation came in 1977 from a CERN counter experiment by W. Brückner, et al.[23] The $\bar{p}$ beam, identified by time-of-flight and Č counters, was individually measured by drift chambers. The liquid-hydrogen target was surrounded by scintillation hodoscopes and lead-glass counters. The result is shown in Fig. 7a, where a significant peak near 1940 MeV is seen in the reaction $\bar{p}p \to$ charged mesons, and also in the $\bar{p}p$ elastic scattering although with less statistical significance. Fig. 7b displays the inelastic σ after background subtraction which shows a peak centered around 1939 MeV with width less than 4 MeV.

A brief summary of the four experiments showing S(1935) is given in Table I. Some of the more recent results, within the last year or so, have shown no sign of the S(1935), casting serious doubt on its existence. Before these results became available, the S(1935) was considered a secure, well-established state, and few people thought it would need further confirmation.

The most significant of these negative-result experiments is that of R. Tripp, et al.[24] They have produced negative results in two separate experiments. The first one[25] measured $\sigma(\bar{p}p \rightarrow \bar{n}n)$ with no apparent structure in 1935 MeV, leading to a speculation that the 1935 structure is a superposition of I = 0 and I = 1 objects. However, they find that no 1930 peak is seen in their more recent experiment of backward elastic scattering, nor in the σ_{total} measurement using the same transmission technique as that used by A.S. Carroll, et al. The result of their σ_{total} measurement is shown in Fig. 8, where the dotted line corresponds to the peak expected if the S(1935) had the cross section as given by A.S. Carroll, et al.

An additional negative evidence is reported by G. Alberi, et al.[26] Their experiment is similar to that of Kalogeropoulos and Tzanakos,[21] but no structure is seen in eigher 1935 MeV region of 1897 MeV region (see Fig. 9). The experiment of Geneva-Lausanne collaboration[27] looked for states in $\bar{p}p$ and $\bar{p}p\pi$ systems produced peripherally with π^+ beam at 50 GeV/c. The statistics is impressive, but no 1935-MeV signal is seen.

However, a positive evidence for the S(1935) has been reported at the International Symposium on Photon and Lepton Interactions at High Energies (Fermilab, August 1979). The evidence comes from an experiment with the CERN Ω spectrometer, exposed to the tagged photon beams at 20 to 70 GeV/c. A narrow peak (width $\lesssim$ 20 MeV) centered around 1930 MeV is seen in the reaction $\gamma p \rightarrow \bar{p}p + X^+$, with the peak containing $\sim$25 events on a background of $\sim$25 events. This result is to be contrasted with that of an Orsay experiment finding an absence of the S(1935) peak in the reaction $e^+e^- \rightarrow \bar{p}p$. This indicates that the S(1935) appears not to couple to the γ. If the CERN result is later substantiated, their observation of the S may have thus resulted from the cascade decay of a higher-mass state coupling to the γ.

B. $\bar{p}p(2020)$ and $\bar{p}p(2204)$

These states have been reported by Benkheiri, et al.[28] in an experiment carried out with the CERN Ω spectrometer. The liquid-hydrogen target was exposed to two π^- beams, 9 and 12 GeV/c, respectively. The trigger required a fast forward proton identified by two Čerenkov counters. The reaction of interest is

$$\pi^- p \rightarrow \Delta^0 \text{ (or } N^{*0}) \; (\bar{p}p)$$
$$\hookrightarrow p\pi^-$$

where Δ^0 or N^{*0} is produced forward by baryon exchange and the $\bar{p}p$ system is produced with slow momentum in laboratory.

Their data, with visible sensitivities 1 to 2 ev/nb, show two clear and narrow peaks at 2020 and 2204 MeV, in addition to a hint of the 1935 MeV state (see Fig. 10). The masses and widths measured in this experiment are given in Table I.

The same states have also been reported by Gibbard, et al.,[29] with very limited statistics, in the reaction $e^- p \rightarrow e^- p(p\bar{p})$. It is a mystery, however, why the same states have not been seen in $\bar{p}p$ formation experiments. Note, in particular, the results of the experiment of R. Tripp, et al.,[24] which covered enough energy to have seen the 2020 MeV state (see Fig. 8). Turning now to a discussion of recent results from production experiments, one can cite a preliminary result from a Brookhaven MPS experiment, a BNL/Carnegie-Mellon/Southeastern Massachusetts collaboration.[30]

They looked at a reaction $\pi^+ p \rightarrow \Delta^{++}\bar{p}p$ at 10 GeV/c with the forward proton from the Δ decay detected in the laboratory. They see no evidence for either 2020 or 2204 states, whereas they should have seen 2 to 3 σ effects based on the cross sections of the CERN Ω experiment. In addition, the Geneva-Lausanne collaboration(27) reports no such states in the peripherally produced $\bar{p}p$ system with a π^+ beam at 50 GeV/c.

Further analysis of the Ω spectrometer data showing the two states at 2020 and 2204 MeV reveal that they are made via nucleon exchange with little, if at all, Δ exchange present.(31) It appears also that these states do not couple to two-body meson states such as $\pi\pi$ or $K\bar{K}$, while their couplings to $N\bar{N}$ are large (at least 30%). If so, how is it that they are produced <u>prominently</u> with a virtual proton but not by a real proton? Obviously, further confirming experiments are necessary before the states are to be accepted as established.

IV. Forthcoming Results

There are several BNL experiments with data on hand which should shed light on the S(1935) in the near future. Two $\bar{p}N$-formation experiments, a BNL/Department of Energy/Michigan State/Syracuse collaboration and a California/New Mexico/Temple collaboration, respectively, took data with the BNL low-energy separated $\bar{p}$ beams. Another experiment with data on hand, a BNL/Brandeis/Cincinnati/Florida State/Southeastern Massachusetts collaboration is a $\bar{p}p$-production experiment done with the BNL MPS. This experiment triggered on fast forward protons with a $\bar{p}$ beam at 5 GeV/c impinging on a hydrogen target. Their first goal is to look at the reaction $\bar{p}p \rightarrow \bar{p}p\pi^0$ where the $\bar{p}p$

system is produced forward by baryon exchange. In addition, there is a $\bar{p}N$ formation experiment which took data with the SLAC Hybrid Facility. This experiment triggered on fast forward $\pi^{\pm}$'s, $K^{\pm}$'s or protons with $\bar{p}$ beams at 6.1 and 8.9 GeV/c.

Another BNL experiment, a BNL/Case Western Reserve collaboration, expects to take data in late 1979 or early 1980 in a search for the S meson in the total and elastic $\bar{p}p$ cross sections. A unique feature of this experiment is that both the incoming $\bar{p}$ beams and the outgoing particles will be measured with drift chambers, so that each event can be individually reconstructed. Results from this experiment are eagerly awaited.

There are several recent experiments which bear on the $\bar{p}p(2020)$ and $\bar{p}p(2204)$ as well. In addition to the aforementioned SLAC experiment, there are three BNL MPS experiments with data on hand. One of these is the BNL/Carnegie-Mellon/Southeastern Massachusetts collaboration with data on the reaction $\pi^{+}p \rightarrow \Delta^{++}\bar{p}p$ at 10 GeV/c, as mentioned in the previous section. Another MPS experiment is that with a $\bar{p}$ beam at 5 GeV/c discussed earlier in this section.

An additional MPS experiment with data already on hand, a BNL/Brandeis/CCNY/University of Massachusetts/Southeastern Massachusetts Collaboration, is nearly identical to the original CERN Ω-spectrometer experiment. Whereas the CERN experiment took data with π^{-} beams at 9 and 12 GeV/c, the MPS experiment took data at 12 and 16 GeV/c, triggering on fast forward protons as the CERN experiment did. The statistical sensitivity of the MPS experiment is expected to be at least five times better than that of the CERN experiment. Preliminary results from the experiment should become available by early 1980.

In addition, there is a new CERN Ω-spectrometer experiment with a π^+ beam at 20 GeV/c which was taking data in summer, 1979. Their reaction of interest is $\pi^+ p \rightarrow \Delta^{++} \bar{p}p$, where Δ^{++} is produced forward by baryon exchange. The sensitivity of this new CERN experiment is expected to be about $\sim$15 times larger than that of the original CERN experiment.

In any event, it is clear that new and hopefully clarifying information should become available within a year regarding the narrow $\bar{p}p$ states in the region between threshold and 3.0 GeV.

V. Conclusions

It does not happen very often in high energy physics that a hitherto well-established resonance such as the S(1935) is thrown into a class of doubtful states by more recent, supposedly careful experiments. In addition, the two remaining narrow states at 2020 and 2204 MeV have so far been seen with good statistics in only a single experiment. It can be even said that there exists at the moment no serious candidate for baryoniums. Fortunately, there are a number of experiments whose results are in the offing in the near future, with potentially decisive informations on these states. It is hoped that the experimental confusion will ease within a year.

In any case, it is hard to believe that nature is so strict with its fundamental building blocks that only the two-quark and three-quark hadrons should exist; as a matter of fact, it is a mystery why four-quark states are as rare as they appear to be. With the experiments that are bound to come with better statistical sensitivities, exotic states will be found, one hopes, leading to a better understanding of the dynamics of the fundamental building blocks of nature.

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Table I. Narrow $N\bar{N}$ States

M (MeV)	Γ (MeV)	Reactions	References
1932 ± 2	9^{+4}_{-3}	$\sigma_T(\bar{p}p)$, $\sigma_T(\bar{p}d)$	Carroll, et al. (20)
$1932^{+2.4}_{-0.4}$	4.5 ± 4	$\sigma_T(\bar{p}n)$	Kalogeropoulos, et al. (21)
1936 ± 1	9^{+4}_{-3}	$\sigma_T(\bar{p}p)$, $\sigma_{el}(\bar{p}p)$	Chaloupka, et al. (22)
1939 ± 3	$\lesssim 4$	$\sigma_{el}(\bar{p}p)$, $\sigma_{in}(\bar{p}p)$	Brückner, et al. (23)
2020 ± 3	24 ± 12	$\pi^- p \to \Delta^0(\text{or } N^{*0})\bar{p}p$	Benkheiri, et al. (28)
2204 ± 5	16^{+20}_{-16}	$\pi^- p \to \Delta^0(\text{or } N^{*0})\bar{p}p$	Benkheiri, et al. (28)

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Figure Captions

Fig. 1. $B\bar{B}$ scattering diagram with a meson exchange in the t-channel. The dotted line shows a 4-quark meson state which should exist from duality.

Fig. 2. I = 2 t-channel exchange diagram for the reaction $pn \to \Delta^- \Delta^{++}$.

Fig. 3a. Quark contents for mesons and baryons.

Fig. 3b. Possible string structures for baryoniums.
Dotted lines show the points where $q\bar{q}$ creations can occur leading to $B\bar{B}$ decays.

Fig. 4. Observation of S(1935) in $\sigma_T(\bar{p}p)$ and $\sigma_T(\bar{p}d)$ by A. S. Carroll, et al. (Ref. 20).

Fig. 5. $\bar{p}n$ annihilation cross section vs. $Q = M_x - 2\,m_p$ by T. E. Kalogeropoulos and G. S. Tzanakos (Ref. 21).
(a), (b) and (c) correspond to the spectator-proton momenta greater than 200 MeV/c and stopping, 100-200 and 100-150 MeV/c, respectively.

Fig. 6. $\bar{p}p$ cross sections by V. Chaloupka, et al. (Ref. 22): total, inelastic, elastic and charge-exchange (0-prong) cross sections, respectively.

Fig. 7a. $\bar{p}p$ cross sections by W. Brückner, et al. (Ref. 23).

Fig. 7b. Background-subtracted $\sigma(\bar{p}p \to$ charged mesons) near the S(1935) as a function of beam momentum.

Fig. 8. $\bar{p}p$ total cross section of R. Tripp, et al. (Ref. 24) as a function of beam momentum.

Figure Captions

Fig. 9. $\bar{p}n$ total cross section of G. Alberi, et al. (Ref. 26) as a function of $Q = M_x - 2\,m_p$ for the spectator-proton momentum in the range 100-200 MeV/c. Dotted line corresponds to the parameters given in Ref. 21.

Fig. 10. $\bar{p}p$ effective mass ($\cos\theta_J < 0$) for the reaction $\pi^- p \to \Delta^0 \bar{p}p$ at 9 and 12 GeV/c, as measured by P. Benkheiri, et al. (Ref. 28).

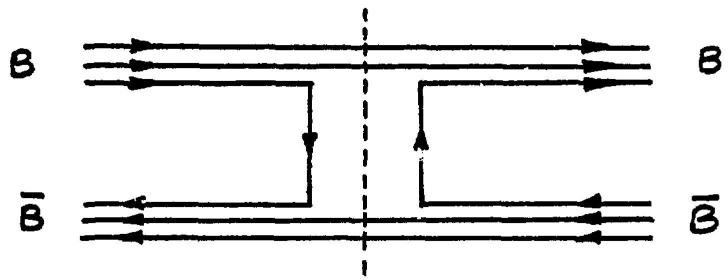


Fig. 1

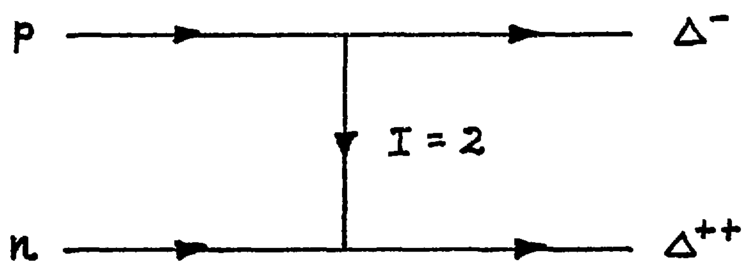


Fig. 2

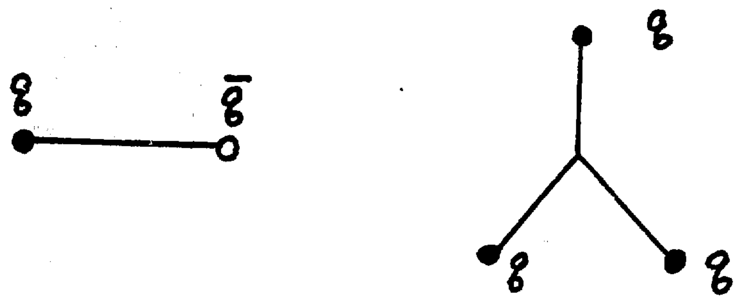


Fig. 3a

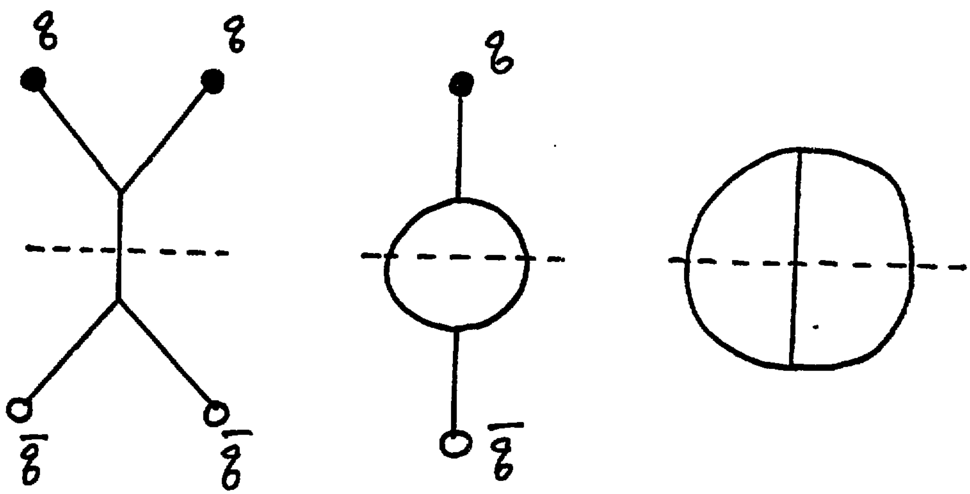
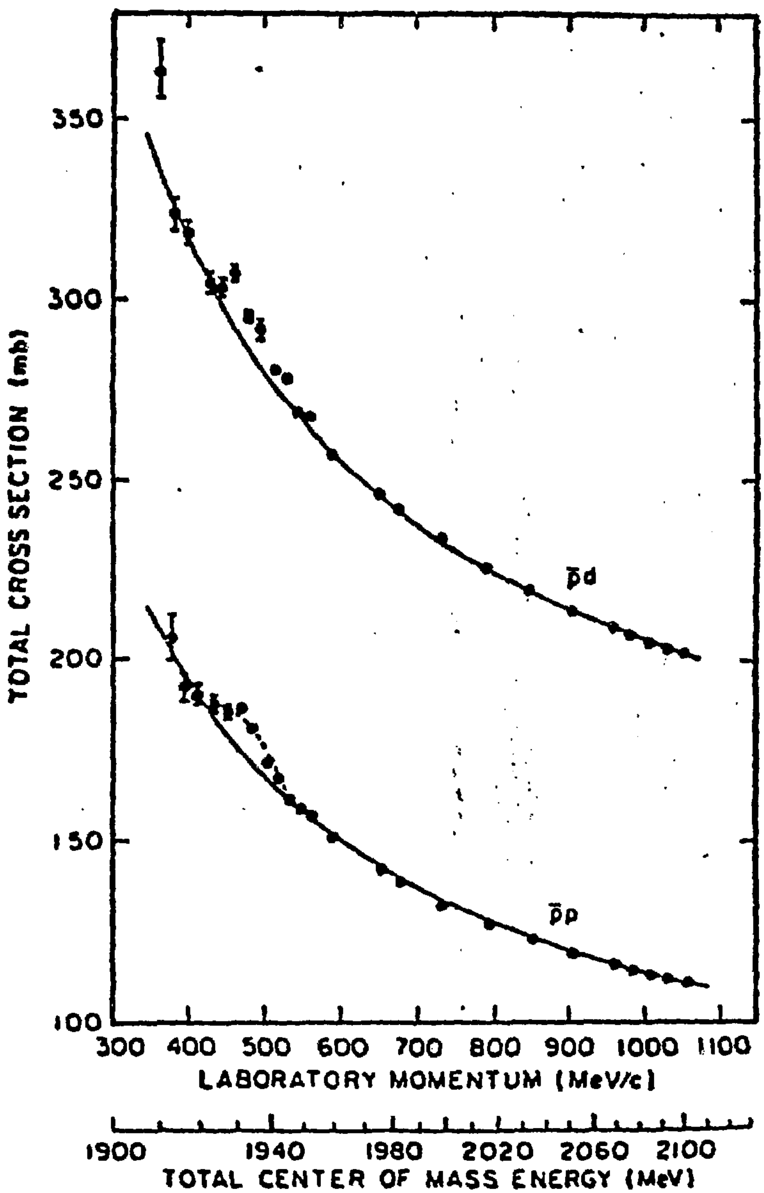


Fig. 3b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300
250
200
150
100
TOTAL CROSS SECTION (mb)
p̄d
p̄p
300 400 500 600 700 800 900 1000 1100
LABORATORY MOMENTUM (MeV/c)
1900 1940 1980 2020 2060 2100
TOTAL CENTER OF MASS ENERGY (MeV)

Fig. 4

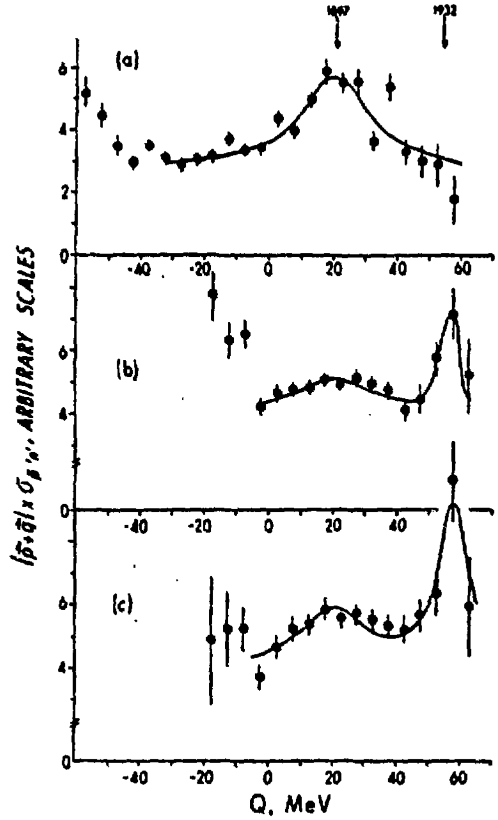


Fig. 5

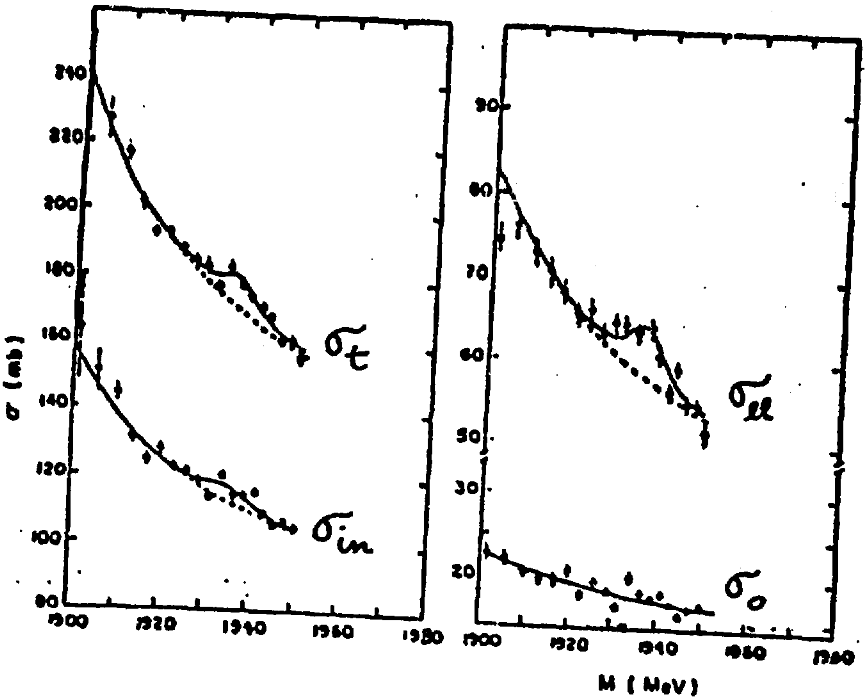


Fig. 6

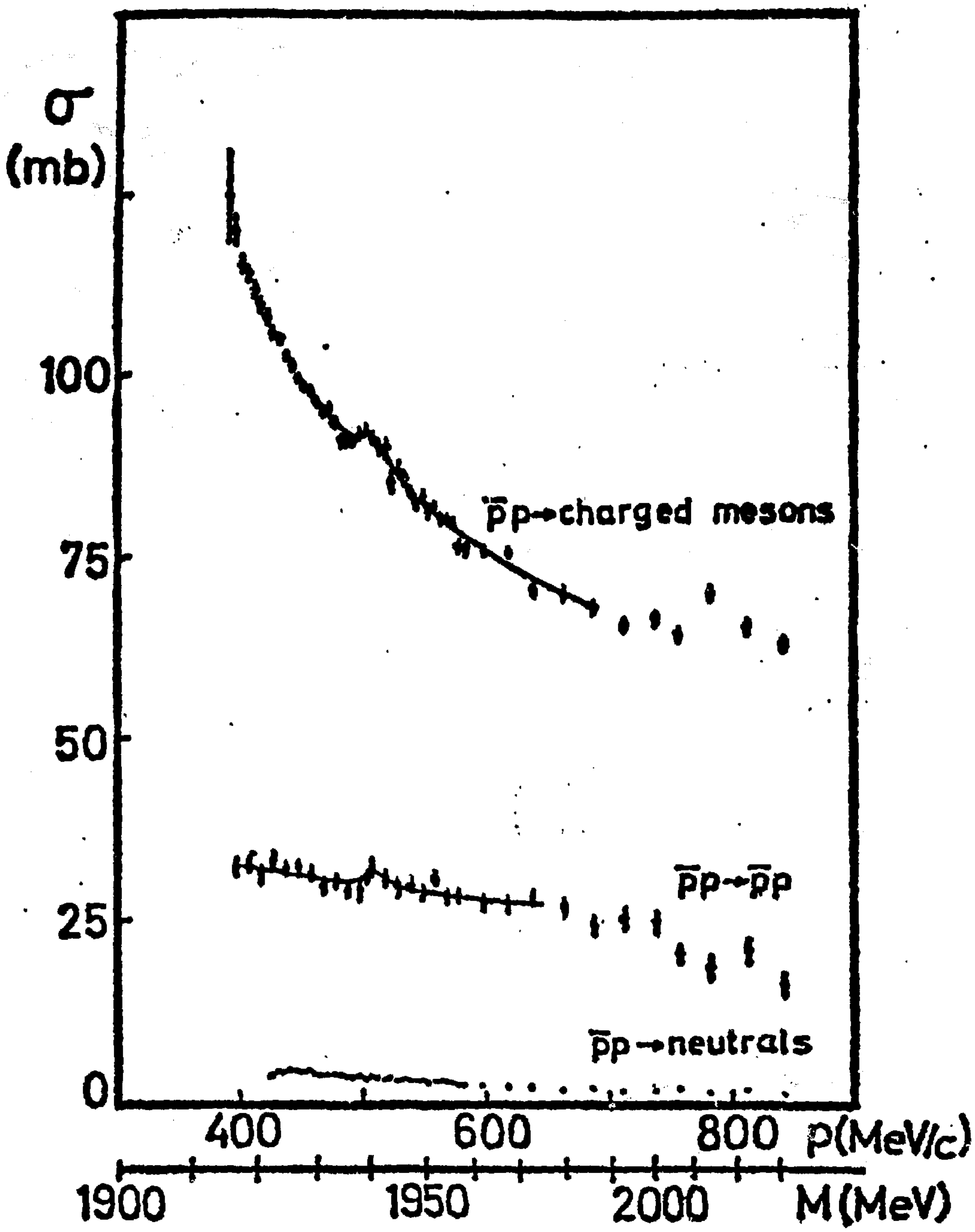

σ
(mb)
100
75
50
25
0
p̄p→charged mesons
p̄p→p̄p
p̄p→neutrals
400
600
800
p(MeV/c)
1900
1950
2000
M(MeV)

Fig. 7a

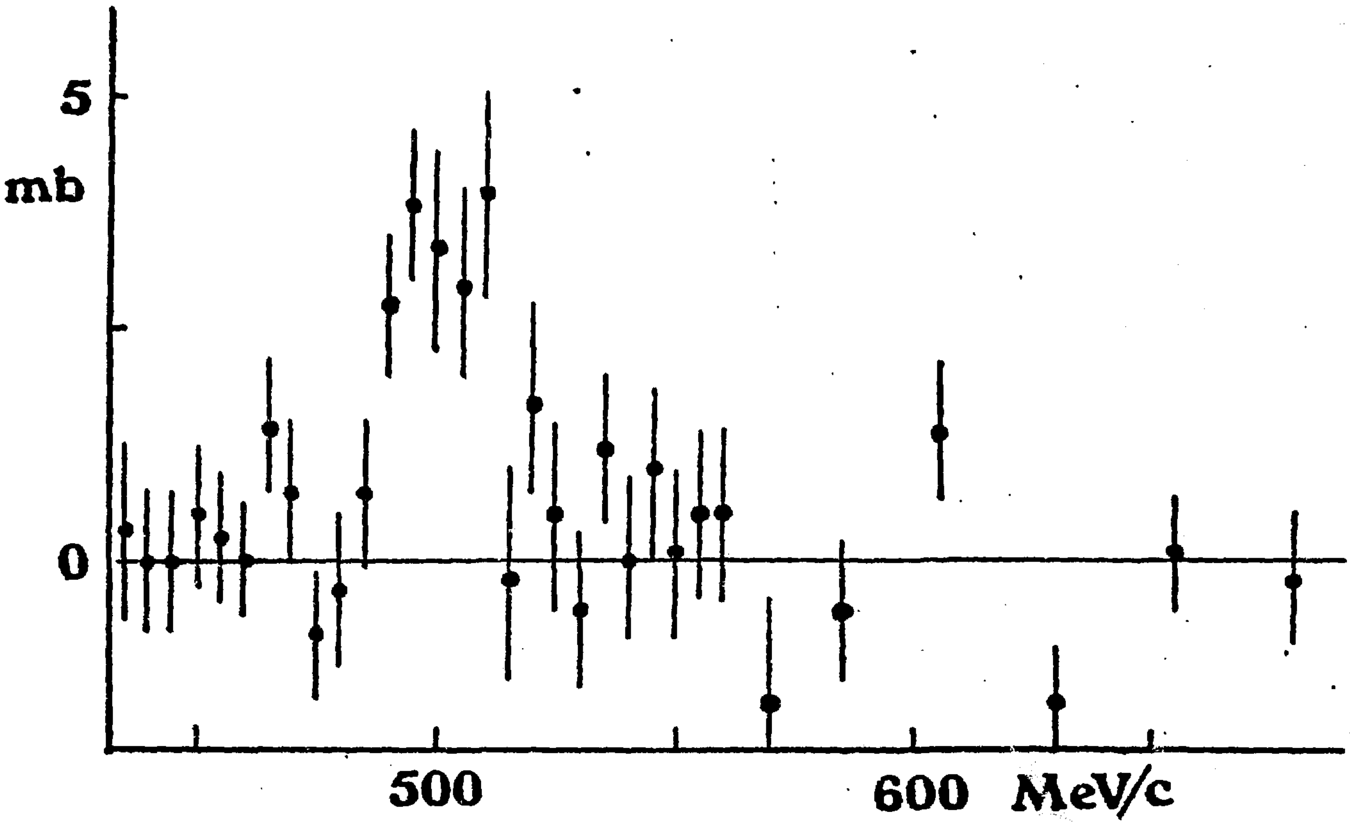


Fig. 7b Resonance region of inelastic cross section after subtraction of the smooth background

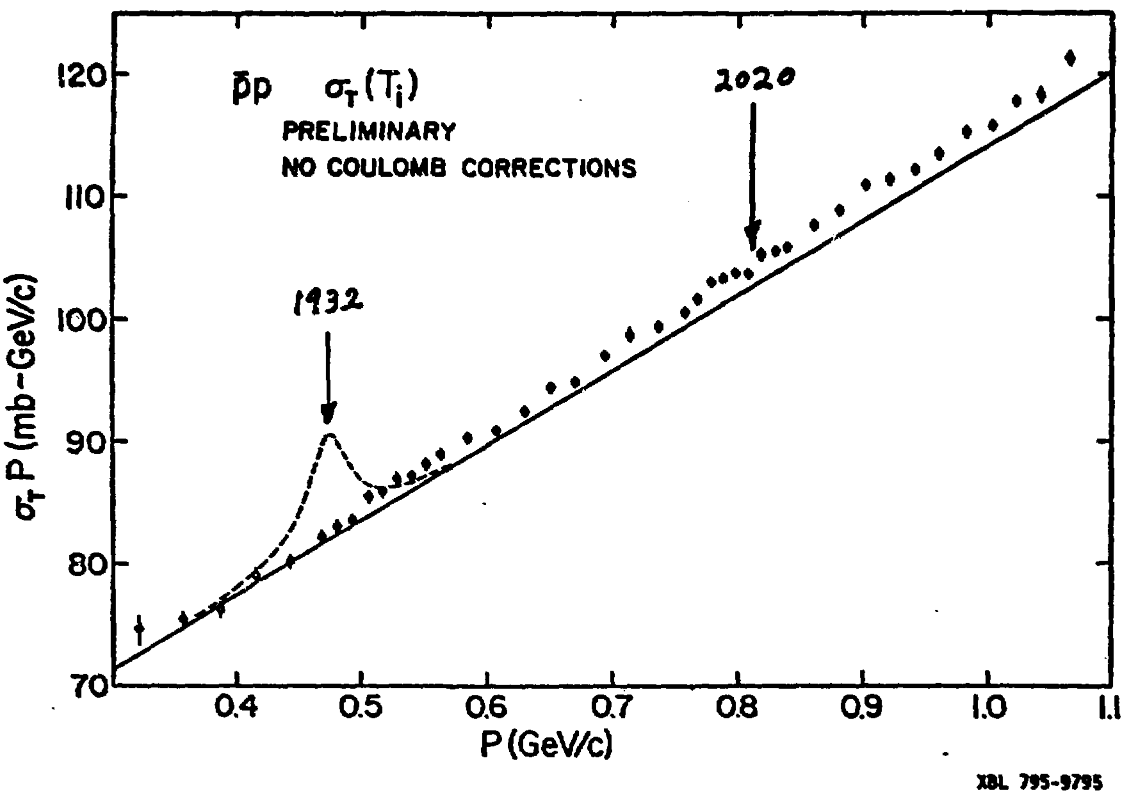
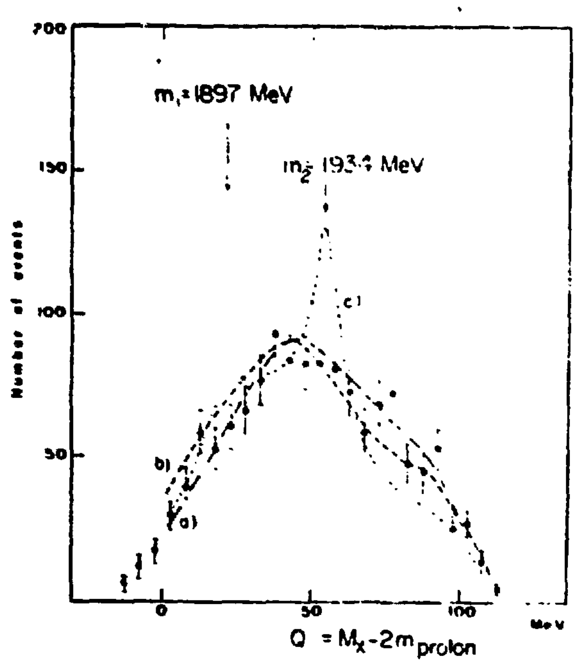
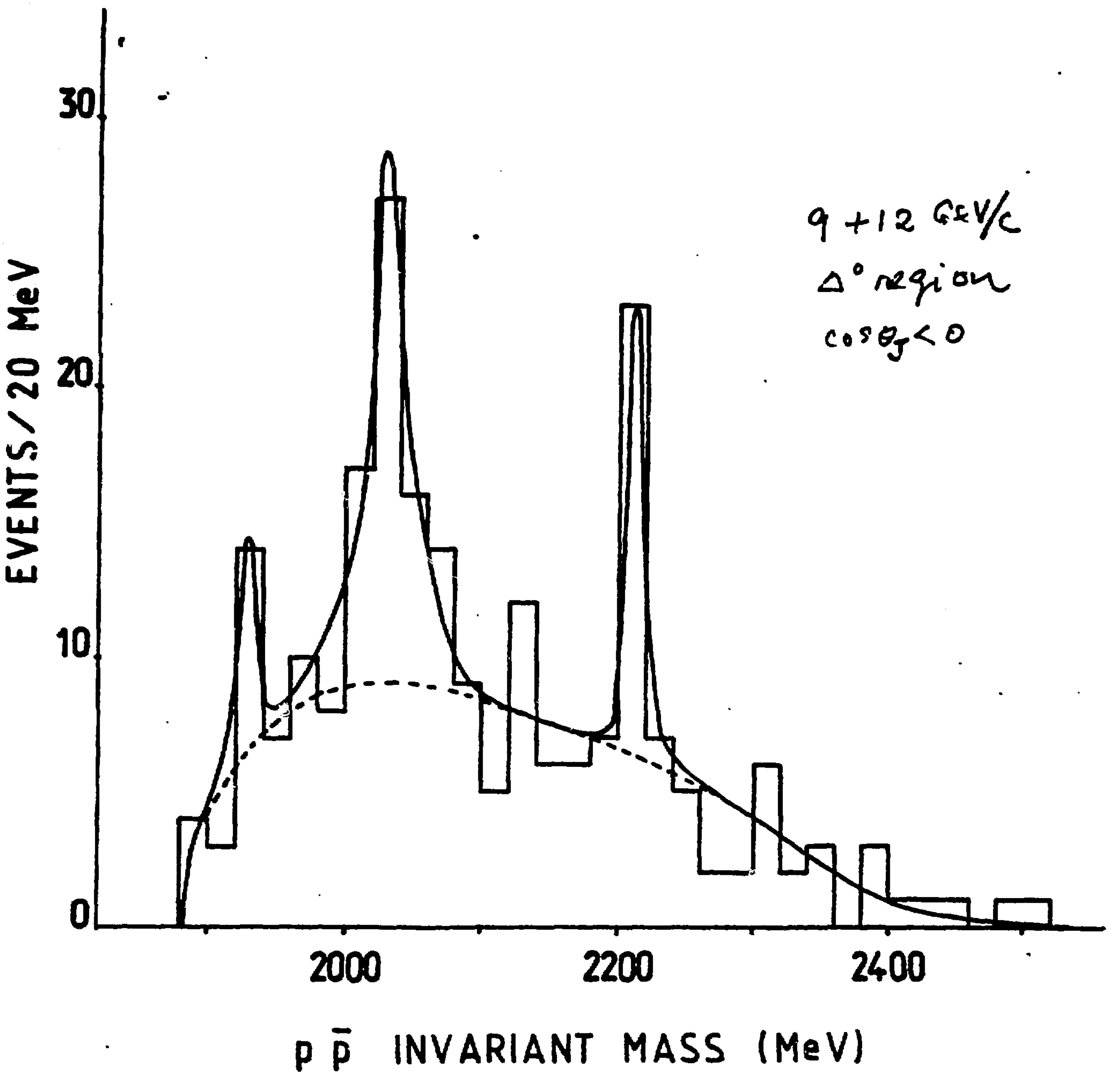

120
110
100
90
80
70
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
p̄p σT(Ti)
PRELIMINARY
NO COULOMB CORRECTIONS
2020
1932
σT P (mb-GeV/c)
P (GeV/c)
XBL 795-9795

Fig. 8



200
150
100
50
Number of events
m_1 = 1897 MeV
m_2 = 1934 MeV
c)
b)
(a)
0
50
100
MeV
Q = M_x - 2m_{proton}

Fig. 9



EVENTS / 20 MeV
30
20
10
0
2000
2200
2400
p p̄ INVARIANT MASS (MeV)
9 + 12 GeV/c
Δ° region
cos θJ < 0

Fig. 10