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BARYON-ANTIBARYON THRESHOLD RESONANCES*

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ABSTRACT

Experimental and theoretical arguments are presented to support the conjecture of a high density of levels (resonances), with quantum numbers shared by baryon-antibaryon channels, in the neighborhood of the thresholds for such channels. These levels, generated by long-range pion exchange, are of a nature familiar in classical nuclear physics but usually ignored in particle physics. Their possible relevance to a variety of high energy phenomena is discussed, including the rising tendency of high energy hadronic total cross sections and the anomalously large e^+e^- annihilation.

I. INTRODUCTION

This paper discusses the role of baryon-antibaryon ($B\bar{B}$) threshold phenomena in high energy physics, a role that has not been widely appreciated and analyzed. We shall use resonance terminology in our discussion , but the physical ideas could also be expressed through notions such as "long-range attractive forces" or "final state interactions." Our central observation is that special circumstances influence a baryon-antibaryon pair at low kinetic energy, circumstances not present near most two-particle thresholds. A variety of consequent effects may be expected in high energy experiments.

The order in which we here discuss different aspects of $B\bar{B}$ threshold physics is not dictated by logic; there is no clear central point at which to begin an analysis. We have chosen to follow, more or less, the temporal sequence of our own thinking, which received its initial impetus from the large production of antiprotons observed at the ISR. In an effort to relate this observation to the multiperipheral mechanism we were led to contemplate baryon-antibaryon thresholds, and only then did we realize that for a long time there has existed evidence for anomalously large nucleon-antinucleon interaction at low kinetic energy.

II. PERIPHERAL ANTIPROTON PRODUCTION IN pp COLLISIONS

The inclusive production of antiprotons in pp collisions is a minor effect below center-of-mass energies around 12 GeV, but thereafter commences a strong rise.[1] Such a "delayed threshold" has been explained by Gaisser and Tan through the doubly peripheral mechanism of Fig. 1 as due to the kinematic difficulty of achieving

small momentum transfers when a central cluster of mass at least 2 GeV must be produced.[2] When the total energy finally becomes adequate to this kinematic task, the rate of observed rise implies a potent baryon-antibaryon producing vertex. The required strength may be estimated through an ABFST-type multiperipheral model, where momentum transfers are associated with π exhange.[3] If s_{max} is the maximum squared cluster mass produced along the multiperipheral chain it is easily inferred from the arguments of Ref. 4 that

$$\frac{1}{\sigma^{tot}_{pp}} \frac{d}{d\,\ell n\, s} \sigma^{\bar{B}(incl.)}_{pp} \underset{s \gtrsim 150\ GeV^2}{\approx} \frac{\int^{s_{max}} \sigma^{B\bar{B}}_{\pi\pi}(s') \frac{ds'}{s'}}{\int^{s_{max}} \sigma^{e\ell}_{\pi\pi}(s') \frac{ds'}{s'}}, \qquad (1)$$

so long as $s_{max} \ll 150\ GeV^2$. In both numerator and denominator of the right-hand side of (1) an average should be taken over pion isospin combinations.

Since any produced antibaryon will eventually decay to an antiproton or an antineutron, the observed antiproton inclusive cross section should be roughly half the total antibaryon inclusive cross section; the left-hand side of (1) on such a basis has been measured to be approximately 0.1. Why do we suggest that such a number be regarded as "large"? The denominator of (1) for $I = 1$ can be estimated from the dominant ρ contribution to be roughly

$$\frac{\pi\Gamma_\rho}{m_\rho} \sigma^{I=1}_{\pi\pi}(max) \approx 150\ mb.$$

Thus, if the $\pi\pi \to B\bar{B}$ $I = 1$ cross section were constant between the lowest $B\bar{B}$ threshold at $4m_p^2$ and the upper limit s_{max}, Eq. (1) implies

$$\sigma^{B\bar{B}}_{\pi\pi} \approx \frac{15\ mb}{\log(s_{max}/4m_p^2)} . \qquad (2)$$

Even were s_{max} as large as 30 GeV^2 we would need $\sigma^{B\bar{B}}_{\pi\pi}$ to be 7 mb -- a substantial magnitude compared to the usual guess of 15 mb for the <u>total</u> $\pi\pi$ cross section in this energy range.[5]

In fact the $B\bar{B}$-threshold increase in the $\pi\pi$ cross section will almost certainly be greater than the preceding estimate, as has been emphasized by Einhorn and Nussinov.[6] The concept of "final state interaction," together with the observed fact that the $p\bar{p}$ annihilation cross section for $4m_p^2 < s \lesssim 30\ GeV^2$ is larger (by about a factor two) than the elastic $p\bar{p}$ cross section, suggests that processes of the type shown in Fig. 1 will be accompanied by a comparable or larger number of events where instead of a $B\bar{B}$ pair there appears a cluster of mesons of the same total mass. A corresponding component in the $\pi\pi$ cross section is evidently to be anticipated.

Figure 2 shows results of a measurement of the special reaction $\pi^+\pi^- \to p\bar{p}$,[7] whose cross section is seen to have a maximum of height 0.3 mb, located at 2.1 GeV, and width about 0.5 GeV. The contribution of this single reaction to the numerator of (1) is only a few percent of the requisite total, so we are anticipating additional production of many different baryon-antibaryon pairs, such as $\Delta\bar{\Delta}$. This important point will recur in our discussion.

The conjectured increase in the $\pi\pi$ cross section[8] could be characterized as a threshold effect but, if as large as proposed above,

encourages our speaking of "resonances" in the $B\bar{B}$ threshold region. Many different resonances of different quantum numbers (we shall estimate the number in the following section) are required to accomplish the large integrated $\pi\pi$ cross-section increase, and Breit-Wigner formulas turn out to be inappropriate, but the terminology of resonances nevertheless has advantages. In particular, we thereby recognize the inappropriateness of special attention to communicating channels such as $\pi\pi$ for which the individual partial widths are tiny. The central question is why clusters of resonances should be concentrated near the thresholds of $B\bar{B}$ channels.

Alternatively we could speak of $B\bar{B}$ "final-state enhancement" at low kinetic energy. The question in such terms is why the $B\bar{B}$ threshold region is enhanced relatively more than that of meson-meson channels such as $K\bar{K}$ or $\rho\bar{\rho}$. The answer, we suggest, lies in the relatively long-range attractive force between a baryon and an antibaryon of low relative velocity, due to exchange of pions. Such an interaction, because of the peculiar quantum numbers of the pion, does not operate between most meson systems.

III. CLASSICAL NUCLEAR PHYSICS DESCRIPTION OF THE BARYON-ANTIBARYON SYSTEM

Shortly after the discovery of large proton-antiproton cross sections at (lab) kinetic energies $\lesssim 200$ MeV, it was realized that the Yukawa force due to pion exchange was capable of explaining the magnitude involved.[9] The pion-mediated force is sufficiently attractive for certain $B\bar{B}$ spin orientations that a substantial proportion of low velocity $B\bar{B}$ pairs with large impact parameter are deflected toward each other into the region of high attraction and (possibly)

annihilation. Without the long-range pion attraction the low energy $p\bar{p}$ cross section would be much smaller than is observed. At high kinetic energies the pion exchange mechanism decreases in importance, because of the zero pion spin, and the $p\bar{p}$ cross section gradually subsides to a "normal" magnitude.

The foregoing semi-classical picture may be re-expressed in terms of individual partial waves of the low-energy $N\bar{N}$ system. Table I enumerates those states in which according to Ref. 9 the

TABLE I

I^G	0^+	0^-	1^+	1^-
J^P	$(0^+, 1^+, 2^+, 0^-)$	$(1^-, 3^-)$	$(1^-, 1^+)$	$(0^+, 1^+, 2^+, 0^-)$

long-range force is sufficiently strongly attractive at 100 MeV kinetic energy (c.m. system) that the unitarity limit for the partial cross section is likely to be approached. These are states for which the orbital angular momentum of the $N\bar{N}$ channel is 0, 1 or 2, most of the total cross section arising from $\ell > 0$. Now whenever a partial-wave unitarity limit for an elastic amplitude is approached near the threshold for the channel in question, there is likely to be an S-matrix pole somewhere near the threshold.[10] We thus may speak of "resonances" near the baryon-antibaryon threshold with the quantum numbers given in Table I.

As illustrated in Appendix A these are not Breit-Wigner resonances, the positions of the poles not being immediately adjacent to the physical region, and there are so many resonances that it is

unprofitable to emphasize any particular one in isolation from the group. Such situations are familiar in classical nuclear physics, and it is apparent that the phenomenon under discussion is more economically approached through classical nuclear ideas rather than through the recently developed concepts that have dominated "particle physics." Particle-physics tends to emphasize those aspects of nuclear states (resonances) that are unrelated to individual channel thresholds. Nuclear physics, being confined (by definition) to low kinetic energy, is dominated by threshold considerations.

If we were to invoke Breit-Wigner partial-width terminology, despite the non-Breit-Wigner location of the pole, one would say that of the many channels coupled to one of the resonances in Table I, the $B\bar{B}$ channel has by far the largest partial width, although the ratio of low energy $p\bar{p}$ annihilation to elastic scattering indicates that the sum of (multi) meson widths is somewhat larger than the $B\bar{B}$ width. It is the relative largeness of the latter, together with the rough pole location, that makes meaningful the designation "threshold resonance." The $B\bar{B}$ channel bears a special relationship to this resonance, just as the np channel bears a special relationship to the deuteron.

The foregoing arguments suggest that unstable baryon-antibaryon states (such as $\Delta\bar{\Delta}$) of low kinetic energy will also be enhanced by pion exchange, so the collection of $B\bar{B}$ threshold resonances may be vast and extend over a wide interval of total energy. It is difficult to estimate this interval with confidence, but if pion exchange is the key, a plausible requirement is that the participating unstable baryon (antibaryon) have a width that is not much larger than the

pion rest mass. (Otherwise its lifetime would be too short for the notion of a pion-mediated "force" to be meaningful.) Should the main contributing baryons (antibaryons) belong to the relatively low-lying octet and decuplet, the interval spanned by these thresholds lies between 1.9 and 3.3 GeV. If, as observed for $p\bar{p}$ (Fig. 2) the resonances associated with each $B\bar{B}$ threshold span an interval of a few hundred MeV, we would estimate the total interval of resonance masses to extend up to about 4 GeV.

IV. POSSIBLE HIGH-ENERGY MANIFESTATIONS OF $B\bar{B}$ THRESHOLD RESONANCES

Assuming the existence of a collection of $B\bar{B}$-associated resonances, what impact might they have on phenomena at extremely high energies? The original motivation for our investigation was the multiperipheral relationship to a large probability for producing antiprotons in pp collisions when $s \gtrsim 150\ \mathrm{GeV}^2$. The same mechanism has led others to the conjecture that the 10% rise in the total pp cross section observed for $150\ \mathrm{GeV}^2 \lesssim s \lesssim 3000\ \mathrm{GeV}^2$ is connected with the "peripheral threshold" for antibaryon production.[2,11] The point of view of the present paper implies a slight restatement of this conjecture in terms of a peripheral threshold for "$B\bar{B}$-associated" resonances, these resonances having a substantial but not overwhelming tendency to decay into $B\bar{B}$ pairs. An equivalent view, without speaking of resonances, has been expounded in Ref. 12.

The expected predominance of multi-meson combinations over $B\bar{B}$ pairs in the decay of the resonances will make difficult an effort to confirm a special $B\bar{B}$ role in the pp total cross section increase. A study should nevertheless be made to see if there exists a tendency for produced $B\bar{B}$ pairs to have low relative velocity.

Persuasive evidence may come from $\pi\pi$ elastic and total cross section extrapolation measurements at NAL. Should a major cross section increase be found for $\pi\pi$ masses above 2 GeV, it will be difficult to avoid a resonance interpretation. Should it further be confirmed that in the region of large $\pi\pi$ total cross section a substantial fraction of the excess events lead to baryon production, one will be on secure ground in associating the resonances with $B\bar{B}$ channels.

It might appear tempting to associate the $B\bar{B}$ threshold resonances with the surprisingly large cross sections observed for $e^+e^- \to$ hadrons at energies above 2 GeV.[13] If one prefers to avoid speaking of resonances, one may, as indicated in Fig. 3, say that whenever a $B\bar{B}$ pair is produced (by whatever mechanism) there is a prolonged final-state interaction due to pion exchange that enhances the probability. The $B\bar{B}$ pair may subsequently annihilate and never be observed, but its temporary existence in the presence of pion-exchange forces may be responsible for an amplification of "normal" probabilities. Whether one does or does not speak of resonances, the intermediate photon guarantees that only 1^- states of the $B\bar{B}$ channel can be produced, but the collection of attractive nucleon-antinucleon configurations of Table I suggests a plentiful supply of 1^- combinations.

There already exists experimental evidence against a dominant role for $B\bar{B}$ threshold resonances in e^+e^- annihilation at center-of-mass energies between 2 and 5 GeV: there is no unusual probability for producing antiprotons. The observed antiproton rate is on the order of 1% of the π^- rate, and is consistent with a simple equilibrium (Boltzmann) distribution.[14] The point perhaps is that the

long-range character of pion exchange only distinguishes $B\bar{B}$ channels from a multitude of meson-meson channels for orbital angular momentum greater than 0, whereas the photon with $J^P = 1^-$ may couple predominantly to $\ell = 0$.

V. SUMMARY AND CONCLUSION

Because of its low mass the pion generates an unusually long-range interaction when it can be exchanged between two particles, but only at small relative velocity of the two particles is the force fully effective. This combination of circumstances systematically enhances baryon-antibaryon channels close to their thresholds,[15] and one may speak of $B\bar{B}$ threshold resonances. The nucleon-antinucleon threshold region, which should be fairly representative, has an estimated total of 12 different partial waves that approach the unitarity limit; i.e. there are roughly 12 different threshold resonances. The $N\bar{N}$ partial width of each resonance is approximately one third of the total width, the partial widths for all other individual channels being much smaller.

A sum over all $B\bar{B}$ threshold-resonance partial widths for the $\pi\pi$ channel has been estimated from the measured $\bar{p}$ inclusive production at the ISR, using a multiperipheral model. Our estimate for this sum corresponds to a large increase in $\pi\pi$ elastic and total cross sections for energies above 2 GeV. Since the contribution to the sum from the $N\bar{N}$ threshold is only a few percent of the total, many different $B\bar{B}$ thresholds must be important, the interval of important resonances probably extending to 4 GeV and perhaps higher.

Implications of the $B\bar{B}$ threshold resonances for high energy experiments are extensive, and we have touched briefly on connections

with certain special hadronic cross sections as well as with e^+e^- annihilation. The most decisive experimental domain appears to be $\pi\pi$ total and elastic cross sections between 2 and 4 GeV.

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FOOTNOTES AND REFERENCES

* This work was supported in part by the U. S. Atomic Energy Commission.

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15. Baryon-baryon channels are also enhanced, but for reasons explained in Ref. 9 the enhancement is less effective.

APPENDIX

The Location of a $B\bar{B}$ Threshold-Resonance Pole

We here use a scattering length expansion to exhibit the location of a threshold resonance pole coupled to a $B\bar{B}$ channel of zero orbital angular momentum, such as would occur when the channel is $N\bar{N}$ and the quantum numbers are $J^P = 0^-$, $I^G = 1^-, 0^+$ or $J^P = 1^-$, $I^G = 1^+, 0^-$. We shall ignore $N\bar{N}$ spin on the grounds that the centrifugal barrier close to threshold suppresses transitions between $\ell = 0$ and $\ell = 2$. Although there are four different $\ell = 0$ states we can treat each separately.

Close to threshold an elastic S-wave $B\bar{B}$ phase shift will have the behavior

$$k \cot \delta \approx \alpha \tag{A.1}$$

where the complex constant

$$\alpha = \alpha_R - i\,\alpha_I \tag{A.2}$$

has a negative imaginary part. Corresponding to (A.1) we have

$$S = e^{2i\delta} = \frac{\alpha_R - i(\alpha_I - k)}{\alpha_R - i(\alpha_I + k)}, \tag{A.3}$$

showing that $\alpha_I \geqslant 0$ guarantees $|S| \leqslant 1$. The pole is evidently located at $k = -\alpha_I - i\alpha_R$. It is straightforward to compute the $\ell = 0$ partial cross sections:

$$\sigma_{e\ell} = \frac{4\pi}{\alpha_R^2 + (\alpha_I + k)^2}, \tag{A.4}$$

$$\sigma_{in} = \frac{4\pi}{k} \frac{\alpha_I}{\alpha_R^2 + (\alpha_I + k)^2}, \tag{A.5}$$

$$\sigma_{tot} = \frac{4\pi}{k} \frac{\alpha_I + k}{\alpha_R^2 + (\alpha_I + k)^2}. \tag{A.6}$$

Now it is plausible that at $k \approx m_\pi$, the lowest momentum for which measurements are available, the elastic $p\bar{p}$ cross section is dominated by its $\ell = 0$ components. The observed 80 mb = $4m_\pi^{-2}$ is an average over the four different $\ell = 0$ states, but let us assume that at least one state has an elastic cross section near this value. Then for this state

$$\alpha_R^2 + (\alpha_I + m_\pi)^2 \approx \pi m_\pi^2, \tag{A.7}$$

ao $(\alpha_R^2 + \alpha_I^2)^{\frac{1}{2}} < 1.7\, m_\pi$. The distance of the pole from threshold in the k complex plane is thus of the order of m_π, as might have been expected from the arguments in the main text of the article.

The observed inelastic $p\bar{p}$ cross section of 200 mb ($10\, m_\pi^{-2}$) at $k \approx m_\pi$ will contain important contributions from $\ell > 0$ because centrifugal repulsion acts only in the incident channel. More precisely

$$\sigma_{e\ell}^{\ell} \propto k^{4\ell}, \tag{A.8}$$

but

$$\sigma_{in}^{\ell} \propto k^{2\ell-1}. \tag{A.9}$$

The maximum possible $\ell = 0$ inelastic cross section at $k = m_\pi$, in fact, is only 63 mb. It seems plausible, given the large observed annihilation cross section that we choose the ratio of α_I to α_R so as to maximize the $\ell = 0$ contribution subject to (A.7). That means choosing $\alpha_I \approx 0.77\, m_\pi$ with $\alpha_R \ll \alpha_I$. We then achieve about 60 mb for $\sigma_{in}^{\ell=0}$.

What does it mean in the complex energy plane for the pole to be located at $k_{pole} \approx -0.77\, m_\pi$? Since the energy is $2(k^2 + m_N^2)^{\frac{1}{2}}$, we have

$$E_{pole} \approx 2m_N + \frac{k_{pole}^2}{m_N}, \tag{A.10}$$

only about 12 MeV above threshold. The pole does not lie in (or immediately adjacent to) the physical region, but is to be reached by encircling the threshold branch point, as shown in Fig. 4. The collection of threshold states listed in Table I correspond to $\ell = 0, 1, 2$ and it is easy to show that they all lie on the lower side of the $B\bar{B}$ cut, although one expects the pole position to rise with increasing ℓ.

Note that the pole cannot be reached from the physical region by a simple negative imaginary displacement, as is the case for poles describable by the Breit-Wigner formula. To reach the pole one must first retreat to the $B\bar{B}$ threshold and then return on the lower side of the physical cut. The width of the peak in the cross section associated with the pole is correspondingly not simply proportional to the imaginary part of the pole position. It would nevertheless be true, if channels other than $N\bar{N}$ were considered, that the residue of the

pole would be factorizable. In such a sense we are able to speak of "partial widths" even though the sum of the partial widths is not the width of a peak in energy.

FIGURE CAPTIONS

Fig. 1. The doubly peripheral mechanism for antibaryon production in pp collisions. The symbol B stands for either stable or unstable baryons.

Fig. 2. The cross section for $\pi^+\pi^- \to p\bar{p}$ according to Ref. 7.

Fig. 3. Diagram representing $B\bar{B}$ enhancement due to pion exchange, following e^+e^- annihilation.

Fig. 4. Location of a $B\bar{B}$ threshold resonance pole in the complex energy plane.

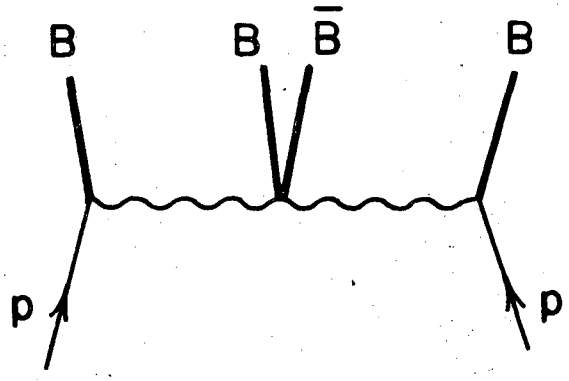

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Fig. 1

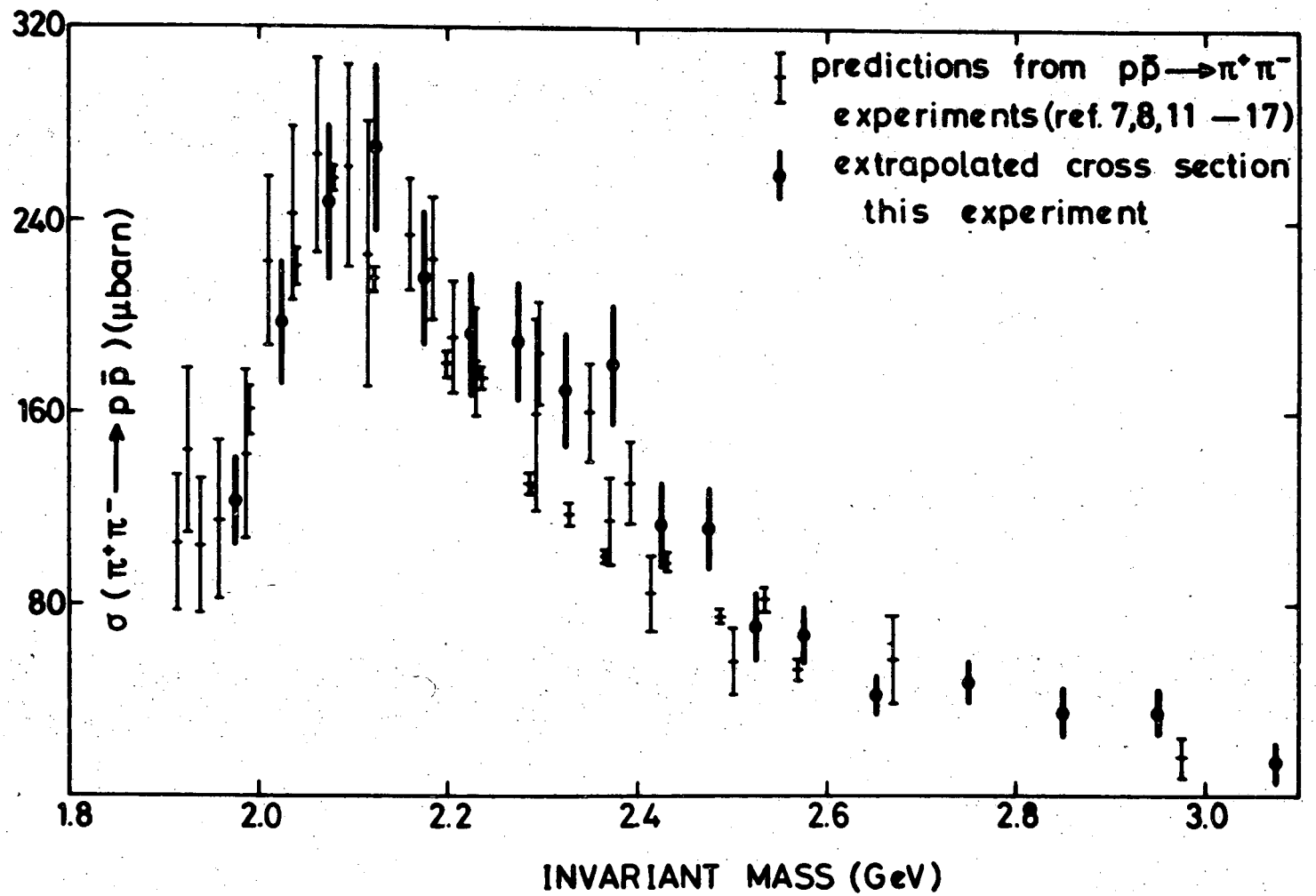

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Fig. 2

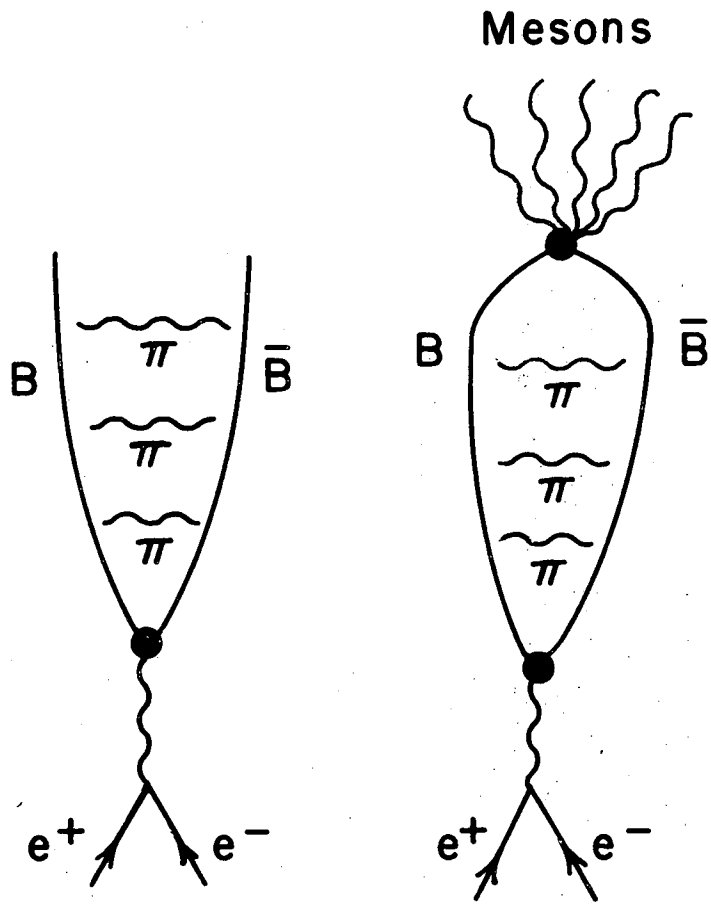

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Fig. 3

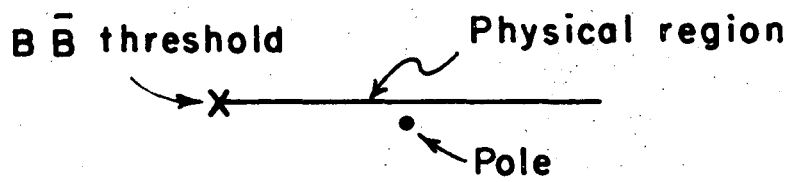

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Fig. 4

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