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THE TOTAL CROSS SECTION FOR $e^+e^- \rightarrow$ HADRONS AND ITS ASSOCIATED SPECTROSCOPY AT SPEAR*

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The feverish activity of the past couple of years in hadron-hadron, photon-hadron, lepton-hadron, and lepton-lepton collisions has resulted in numerous mysteries and stimulated many new ideas. This great confluence of different branches of physics has been the result of important discoveries in all of them and promises to make this conference an exciting event. From the cross-fertilization of ideas, new directions have resulted or existing information has been complemented.

As an example of this confluence, let me discuss briefly the relation between the cross section for $e^+e^- \to$ hadrons and $pp \to e^+e^-$ hadrons. Figure 1a shows a schematic for $e^+e^- \to$ hadrons through an unspecified intermediate state. The use of unitarity and time reversal results in the celebrated Breit-Wigner formula for a resonance

$$\sigma(e^+e^- \to \text{hadrons}) = \frac{\pi(2J+1)}{w^2} \frac{\Gamma_e}{(m-w)^2 + \frac{\Gamma^2}{4}} \sum_f \Gamma_f \quad , \tag{1}$$

where J is the spin of the intermediate state, w is the center-of-mass energy, Γ is the total width of the resonance, Γ_e is the partial width to electrons, and Γ_f are the partial widths to the states f. Figure 1b shows the analogous diagram for the formation and subsequent decay of a resonance into e^+e^- pairs in pp collisions. The resonance formation is the sum of a certain set of states a and b. (Such a simplification is the result of a prejudice that it is hard to get three or more "particles" together to make a reaction.) Thus this case is the sum over a proper subset of the states f available to e^+e^- annihilation. There is, therefore, an intimate relation between the two kinds of experiments. Because of the different set of states available to pp collisions one may be able to learn new physics by comparison with e^+e^- annihilation. For example, $\psi(3095)$ is copiously produced in hadron-hadron collisions while $\psi(3684)$ is not.[1,2]

Figure 2 shows the status, as of the Lepton-Photon Symposium in August 1975, of the world's knowledge of the ratio $R = \sigma_{hadron}/(\sigma_\mu = \frac{4\pi\alpha^2}{3s})$ vs center-of-mass energy.[3] This ratio is particularly convenient because it uses as a natural scale σ_μ, the simple QED cross section for production of μ pairs. In the region 0.7 to 1.0 GeV one sees the production of the "old standard" vector mesons, ρ, ω, and ϕ. A few years ago it was believed that these were the only characteristic masses which could enter into a theoretical interpretation of R, and thus it was expected that R = constant "far above" these resonances. Thus it was that the relatively constant value of R between 2 and 3 GeV was successfully "postdicted". The existence of the two enormous, narrow resonances, $\psi(3095)$ and $\psi(3684)$, completely disrupts such thinking. Furthermore, the complicated structure in R in the region of 4 GeV is interesting in its own right, but the temptation to relate it to the ψ's is great. As of the symposium, a number of questions existed concerning the detailed shape of R vs w:

1. Are there other brothers of the ψ's nearby?
2. Is there a real bump at 3.95 GeV? Such a suggestion rests largely upon a couple of low points at 3.99 GeV.
3. There appears to be a very sharp rise, within 30 MeV, of R between 4.00 and 4.03 GeV. Such a rise suggests a resonance.
4. There is a suggestion of a bump at 4.1 GeV, based upon poor statistics.
5. The existence of a resonance-like structure at 4.41 GeV was clearly established, but an anomalously low point at 4.39 GeV raises questions on the complexity of such a state.
6. Since the symposium we have heard the suggestion of a new resonance[4] at 5.97 GeV, called Υ, decaying into e^+e^- and produced in hadron-hadron collisions.

A large part of the SLAC-LBL Collaboration's[5] emphasis in data taking has centered on answering these questions. [A number of other questions surrounding $\psi(3095)$ and $\psi(3684)$ decays will be discussed by G. Goldhaber in the next talk.]

This experiment has been discussed often enough that a detailed description is not necessary. For the purpose of the present discussion, suffice it to say that at least two charged particles having momenta $\gtrsim 200$ MeV/c into the 65% solid angle of the detector are required to trigger the spark chambers, etc. Additional cuts are made to separate hadron production from QED processes.[6] Backgrounds are generally only a few percent. Such a trigger has a manifest bias: (1) There is a set of charged particle events which escape the trigger and the cuts. Monte Carlo methods are used to estimate such losses, and the model dependence of such estimates is the ultimate limit of systematic errors. (2) There is a class of final states consisting entirely of neutrals of which we have no experimental knowledge. If one believes that the hadron production proceeds through one photon annihilation, however, those quantum numbers severely limit this class of undetected events. The most obvious case is a final state consisting entirely of π^0's; this is forbidden by C invariance. Crude estimates of totally neutral final states consistent with an intermediate photon show that only a couple of percent of the total cross section is missing.

In searching for narrow resonances, the energy spread of the machine is an important parameter: the r.m.s. dispersion is ~ 1 MeV at $w = 3$ GeV, and ~ 4 MeV at $w = 6$ GeV. Therefore, if one searches for a resonance much narrower than the energy resolution, only the total area under the resonance is important. Using Eq. (1), one finds

$$\int \sigma_h \, dw = \frac{2\pi^2(2J+1)}{m^2} \Gamma_e \frac{\Gamma_h}{\Gamma} , \tag{2}$$

where Γ_h is the partial width to hadrons. Thus our direct sensitivity is to $\Gamma_e B_h$, where $B_h = \Gamma_h/\Gamma$; since one expects $B_e \ll 1$ then $B_h \simeq 1$ and our sensitivity is mainly to Γ_e. Alternatively, when the resonance is wide enough to be resolved the peak resonance cross section is

$$\sigma_h(\text{peak}) = \frac{4\pi(2J+1)}{m^2} \frac{\Gamma_e \Gamma_h}{\Gamma^2} , \qquad (3)$$

so the sensitivity is to $B_e B_h$, or essentially B_e if $B_h \approx 1$.

We have previously published[7] the results of a fine scan in which the machine energy was changed in small increments at regular intervals. Fig. 3 shows the result of such work. Generally speaking, one expects 1-2 hadron events/point. As a result we have learned there are no more large, narrow resonances having $\Gamma_e \gtrsim \frac{1}{10} \Gamma_e(\psi)$. We have acquired a large amount of new data in such a scan mode, with substantially greater integrated luminosity at each point.

For such a search near the $\psi(3684)$ data were accumulated in 2.3 MeV intervals and sufficient luminosity at each point was accumulated so that one expects ~ 5 hadron events/point. No narrow peaks were found. For convenience of display, these preliminary data are shown in Figure 4 in 10 MeV bins. Excepting the $\psi(3684)$, which goes off scale, there are no unambiguous new resonances, but there are regions at 3.63, 3.77, and 3.85 GeV which attract attention of those seeking bumps. These are all roughly two standard deviations from our smooth expectations. The only conservative approach we can take is to present 90% confidence upper limits on the branching ratio to electrons[8] for such conjectured states; these are of the order of $1.5 - 3.0 \times 10^{-5}$. To put these numbers into perspective, recall that the $\psi(4414)$ state has $B_e = 1.3 \times 10^{-5}$.

Although we took a lot of data in the 4 GeV region, a number of the original questions remain. Figure 5 shows the present state of our information; the points labeled with "x" are the new data. A fine scan from 3.994 to 4.036 GeV with integrated luminosity equivalent to about 20 hadronic events per 2.3 MeV step gives us two pieces of information: the low points at ~ 3.99 GeV have reproduced, and the sharp rise suggested in the previous data was confirmed. As a result the possibility of a bump at 3.95 GeV is somewhat clearer, although it is still only a little more than two standard deviations from being just part of the general rise. The main evidence for such a bump depends upon the low points at 3.99 GeV. The rapid rise in R from 3.99 to 4.03 GeV is quite interesting because it suggests another state. The rise is much too rapid for the opening of a new continuum channel. One would very much like to see the falling edge of such a state, but the data are not yet adequate for this. The region around 4.03 GeV is clearly complex and needs more study. In this experiment of seemingly boundlessly increasing complexity of information, it is of some comfort to know that the low point at 4.39 GeV in the original data did not reproduce. Thus it appears that the 4.41 GeV bump is relatively simple.

The whole region from 3.8 to 4.3 GeV is open to considerable conjecture. The optimist can imagine as many as five possible bumps in R using the high points at 4.12 GeV; the pessimist could draw a smooth curve with a wide bump centered at about 4.1 GeV. I suspect that the truth is somewhere between these extremes. The possible richness of structure in this region is on the one hand exhilarating and on the other hand depressing: Is there a whole new spectroscopy to be uncovered, and how are such states related to the ψ? Have we rediscovered the world of nuclear physics having perplexing complexity?

There is at least some disappointment/consolation in the general character of the total cross section above 5.65 GeV. In order to investigate the Υ resonance produced in hadron-hadron collisions and seen to decay into e^+e^- we acquired a large amount of data between 5.65 and 6.64 GeV in $\sim$ 4 MeV steps. The accumulated luminosity is equivalent to the observation of about 60 hadrons/point. The steps are wider than the low energy scan because the spread in beam energy is larger. No narrow peaks were found, and the data in 10 MeV bins are shown in Fig. 6. Given such results, we can only calculate upper limits for either Γ_e or B_e of any proposed resonance as a function of energy. These limits are shown in Fig. 7 in three cases.[8] If the resonance is too narrow to be resolved, then our sensitivity is to Γ_e; on the other hand, if the resonance is wide, then B_e is the better indicator of our sensitivity. Two such cases are shown, $\Gamma = 10$ and $\Gamma = 50$ MeV. Because of the narrow range of energies scanned, larger widths become ambiguous. To put these numbers into perspective, one should note that $\Gamma_e \lesssim 150$ eV is rather stringent; the conventional vector mesons, ρ, ω, ϕ, ψ, ψ', have $\Gamma_e \sim$ several keV. On the other hand, the $\psi(4414)$ has $\Gamma_e = 440$ eV, so such a small partial width to electrons is not unthinkable. Likewise, to put the limit $B_e \lesssim 10^{-5}$ into perspective, one can use the data presented, along with the announcement of the $\Upsilon(5970)$,on the product of the production cross section times branching ratio to electrons, $(\sigma \cdot B_e)_\Upsilon = 5 \times 10^{-4} (\sigma \cdot B_e)_\psi$. Since we know $B_e \approx .07$ for the ψ, we can conclude that $\sigma_\Upsilon \gtrsim 3.5\ \sigma_\psi$. This result is rather surprising. A few words of caution are in order in interpreting these results. First, we have assumed spin one. If spin 0 were used instead, these limits on Γ_e or B_e would be three times larger and correspondingly weaker. The consequence is important. Spin zero mesons coupling to lepton pairs are very rare; an example is $\eta \to \mu^+\mu^-$, which has a branching ratio of 2.2×10^{-5}. The other major assumption is that we are not missing some important part of the total cross section for $e^+e^- \to$ hadrons. It could happen, for example, that there is an anomalous selection of all neutral final states for such a resonance; in such a case our sensitivity is badly degraded. Estimates of such a case are obviously very model-dependent. Lastly, it may be that if some other simple decay mode, for example two-body or quasi-two-body, could be identified, the sensitivity might be improved. (Cf. discussion of relation between $e^+e^- \to$ hadrons and $pp \to e^+e^-x$.)

We have also made such a scan from 6.95 to 7.45 GeV with ~ 150 hadron events/4 MeV step. The results analogous to the Υ search are shown in Figs. 8 and 9. Again no narrow peaks were found and appropriate upper limits[8] are applicable.

Nearly every experiment done in the past two years has been used in one way or another as a search for charm; we are no exception. This is an enterprise much like a treasure hunt; if you find the treasure, you are a hero; if not, you are nobody. Putting upper limits on the nonexistence of such a treasure is not very informative, because the interpretation is model-dependent. Just about the only distinguishing property of an unknown particle is its mass, so making invariant mass plots is a natural attempt. We have used our multihadron data at all energies to search for peaks in the invariant mass plots for these channels: (a) $n\pi^{\pm}$ ($n = 2,3,\ldots,6$), (b) $K^{\pm}n\pi^{\pm}$ ($n = 1,2$), $K^{\pm}$ not identified, (c) $K_S n\pi^{\pm}$ ($n = 1, 2,\ldots,5$), where K_S is identified through $K_S \to \pi^+\pi^-$, and (d) $K_S K^{\pm}$ (K_S and $K^{\pm}$ as in other cases). Nothing significant was found. In high multiplicity events the number of combinations one must try tends to dilute the strength of such tests. One really needs to find some distinguishing characteristics to reduce the background. Another possible tool for a charm search is to make use of the assumption that the decay of charmed particles will involve weak interactions, and therefore will involve a parity violation. This suggestion involves searching for a pseudoscalar of the form of the triple product of three momenta, with appropriate ordering to prevent washing out the effect.[9] Unfortunately, even under the most optimistic assumptions such terms are expected to be $\sim 5\%$, so that our limit of a few % is not very restrictive. (This limit is largely due to systematics.)

Another part of the standard folklore is that crossing the charm threshold should result in a larger relative fraction of K's among the particles of the final state. Figure 10 shows the relative fractions of charged particles identified by time of flight in ranges of momenta as a function of center-of-mass energy. If one examines these spectra the only obvious conclusion is that ψ has a lower fraction of K's. All other changes are gradual. An obviously interesting related study is the relative fraction of K^0's; this turns out to be substantially more difficult because of the small number of spark chambers; such work is under way but not ready for public consumption.

In conclusion we have learned some things, raised new issues, and left others unchanged. We have no evidence for relatives of the ψ and ψ' from 3.55 to 3.90 GeV, but we cannot exclude some "small ones" having branching ratios to electrons $\lesssim 3 \times 10^{-5}$. The region from 3.80 to 4.60 is very complex where even the most pessimistic must admit the existence of at least two substantial bumps. The optimist feels free to imagine as many as five bumps in that region. The latter interpretation is more fun for experimenters, and it is probably closer to the truth. The rapid rise between 3.99 and 4.03 GeV must be taken seriously and strongly suggests a new state. There is an intimate connection between experiments on $e^+e^- \rightarrow$ hadrons and hadrons $\rightarrow e^+e^-$ hadrons; taking our failure to find the Υ at face value implies raising more questions. Finally we, like Coronado, have not managed to find the riches of the seven cities of Cíbola (charm); will we also seek Quivara?

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FIGURE CAPTIONS

1. Relation between (a) $e^+e^- \rightarrow$ hadrons and (b) $pp \rightarrow e^+e^-$ hadrons.
2. R vs center-of-mass energy (data as of August 1975).
3. Relative hadron cross section vs center-of-mass energy.
4. R vs center-of-mass energy near $\psi(3684)$.
5. R vs center-of-mass energy. Data denoted by "x" are new since August 1975.
6. R vs center-of-mass energy from 5.6 to 6.5 GeV.
7. Upper limits on (a) Γ_e or (b,c) B_e for coupling of resonances to electron pairs vs center-of-mass energy.
8. R vs center-of-mass energy from 6.9 to 7.5 GeV.
9. Upper limits on (a) Γ_e or (b,c) B_e for coupling of resonances to electron pairs vs center-of-mass energy.
10. Relative fraction of prongs identified as charged K's in ranges of momenta vs center-of-mass energy.

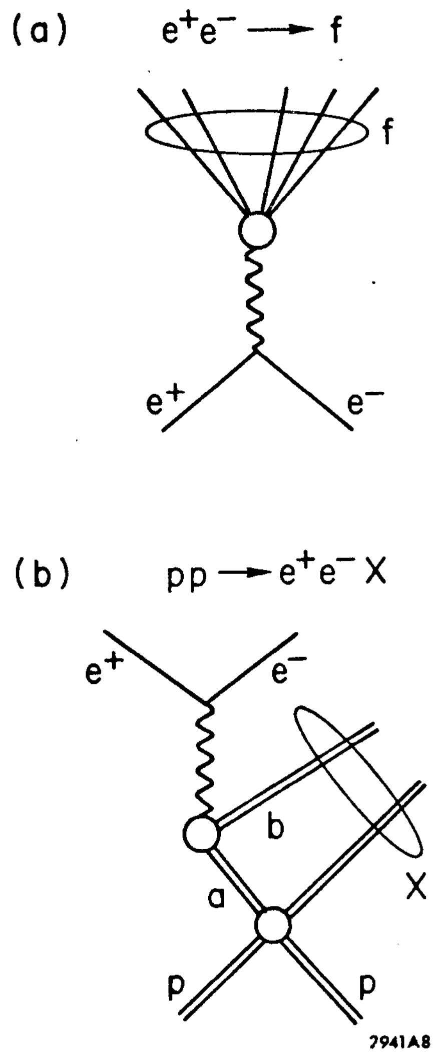

FIGURE 1
Relation between (a) $e^+e^- \to$ hadrons and (b) $pp \to e^+e^-$ hadrons.

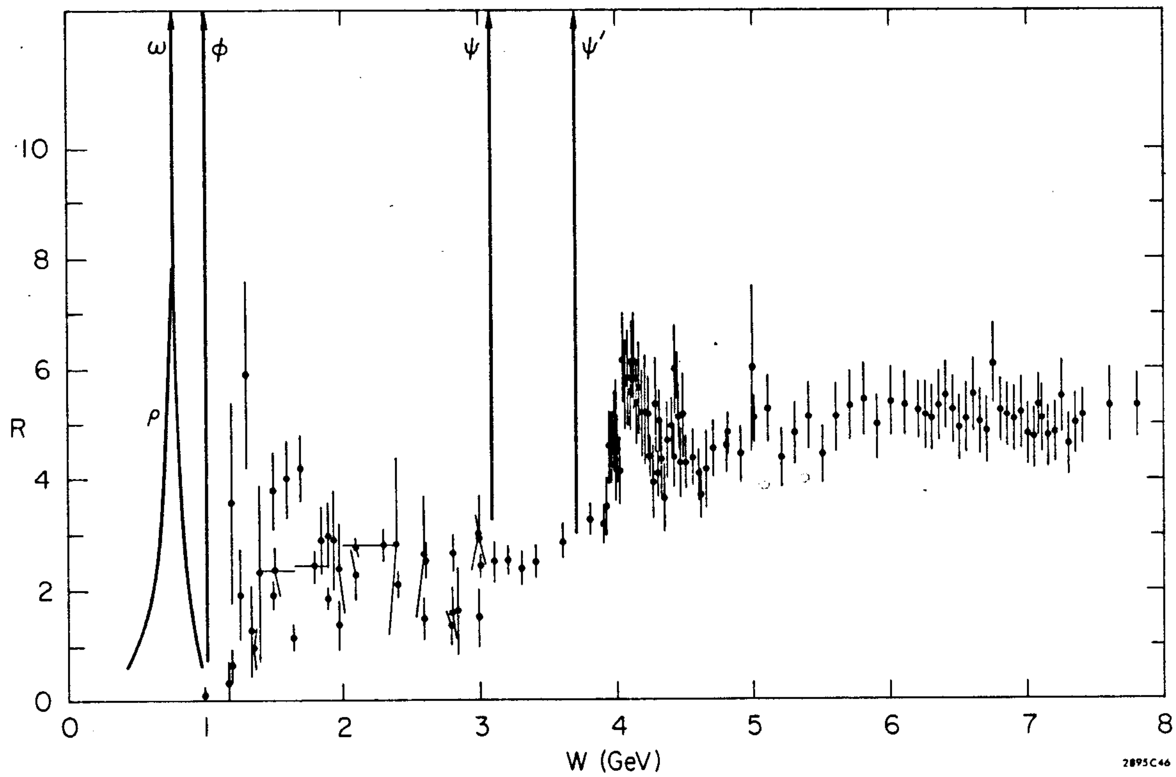

FIGURE 2
R vs center-of-mass energy (data as of August 1975).

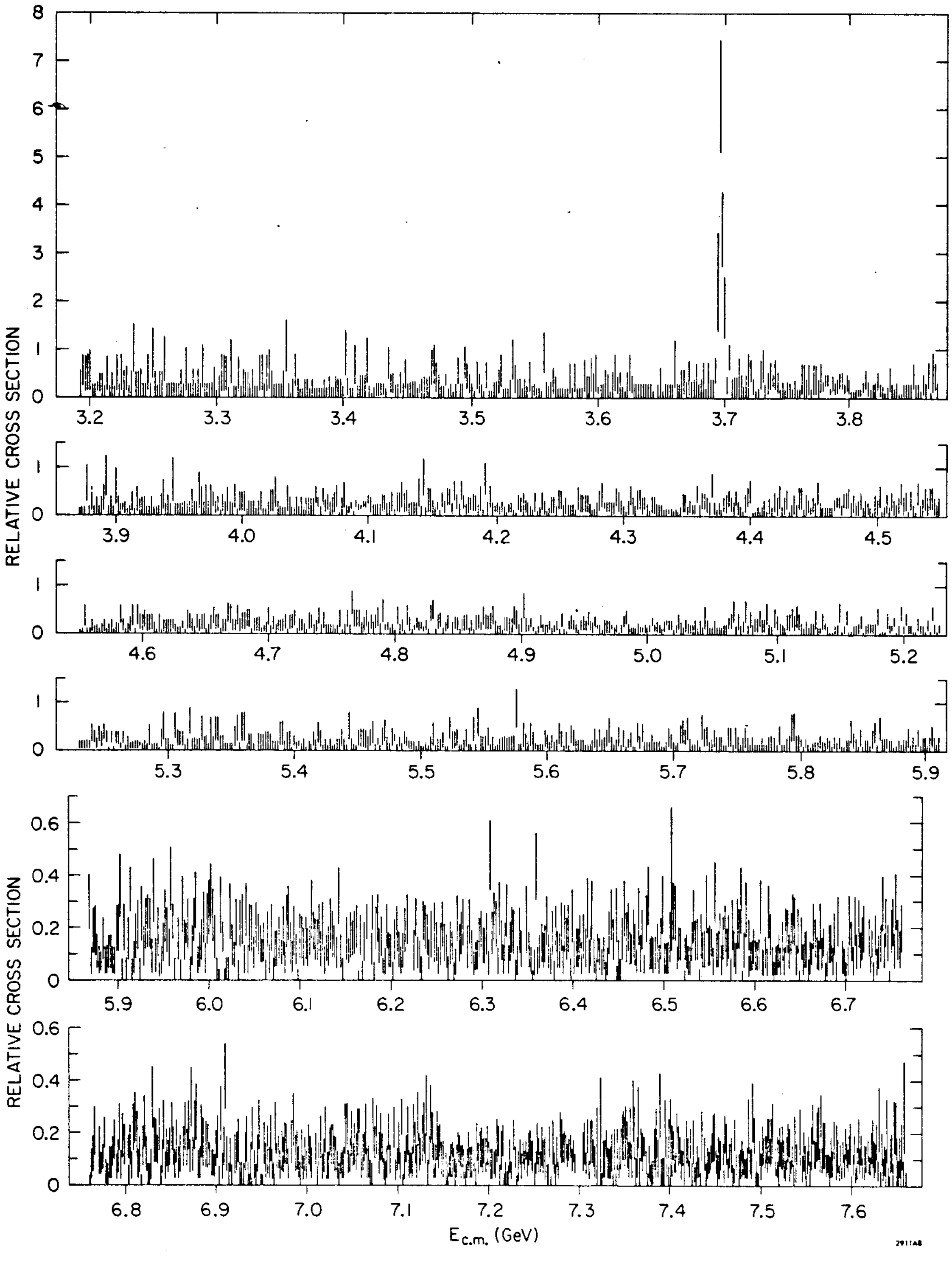

FIGURE 3
Relative hadron cross section vs center-of-mass energy.

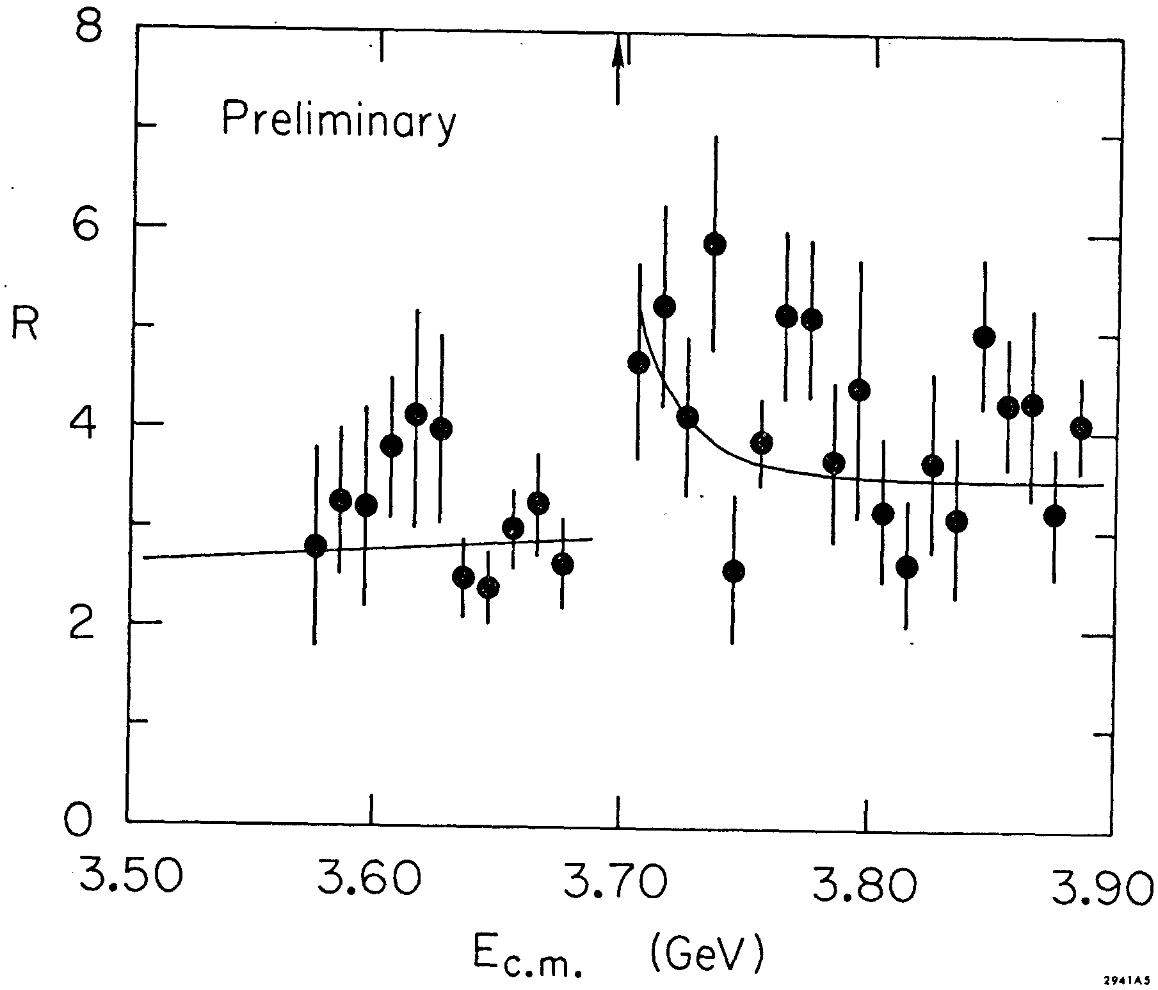

FIGURE 4
R vs center-of-mass energy near $\psi(3684)$.

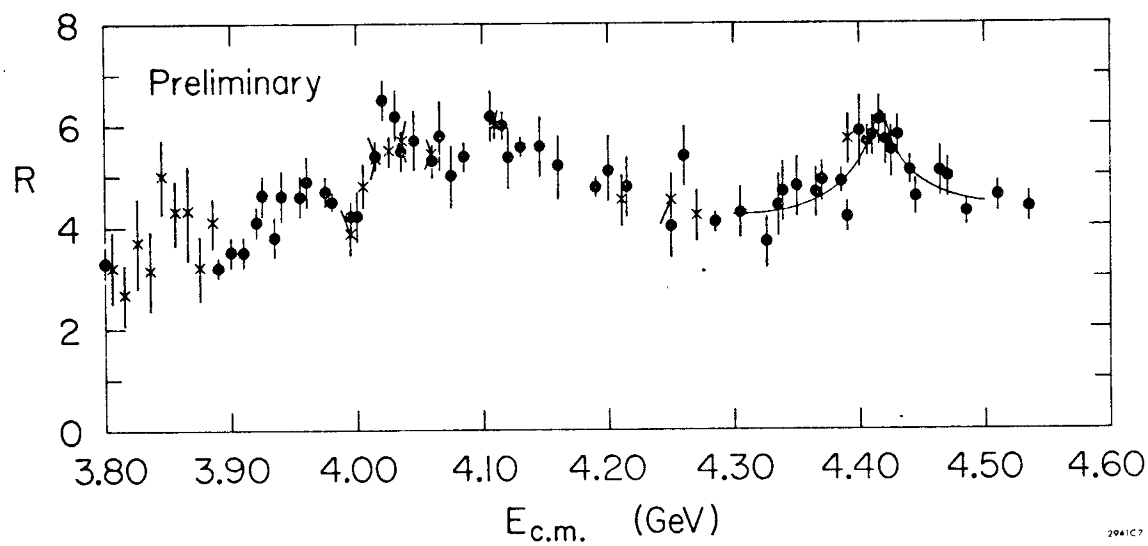

FIGURE 5

R vs center-of-mass energy. Data denoted by "x" are new since August 1975.

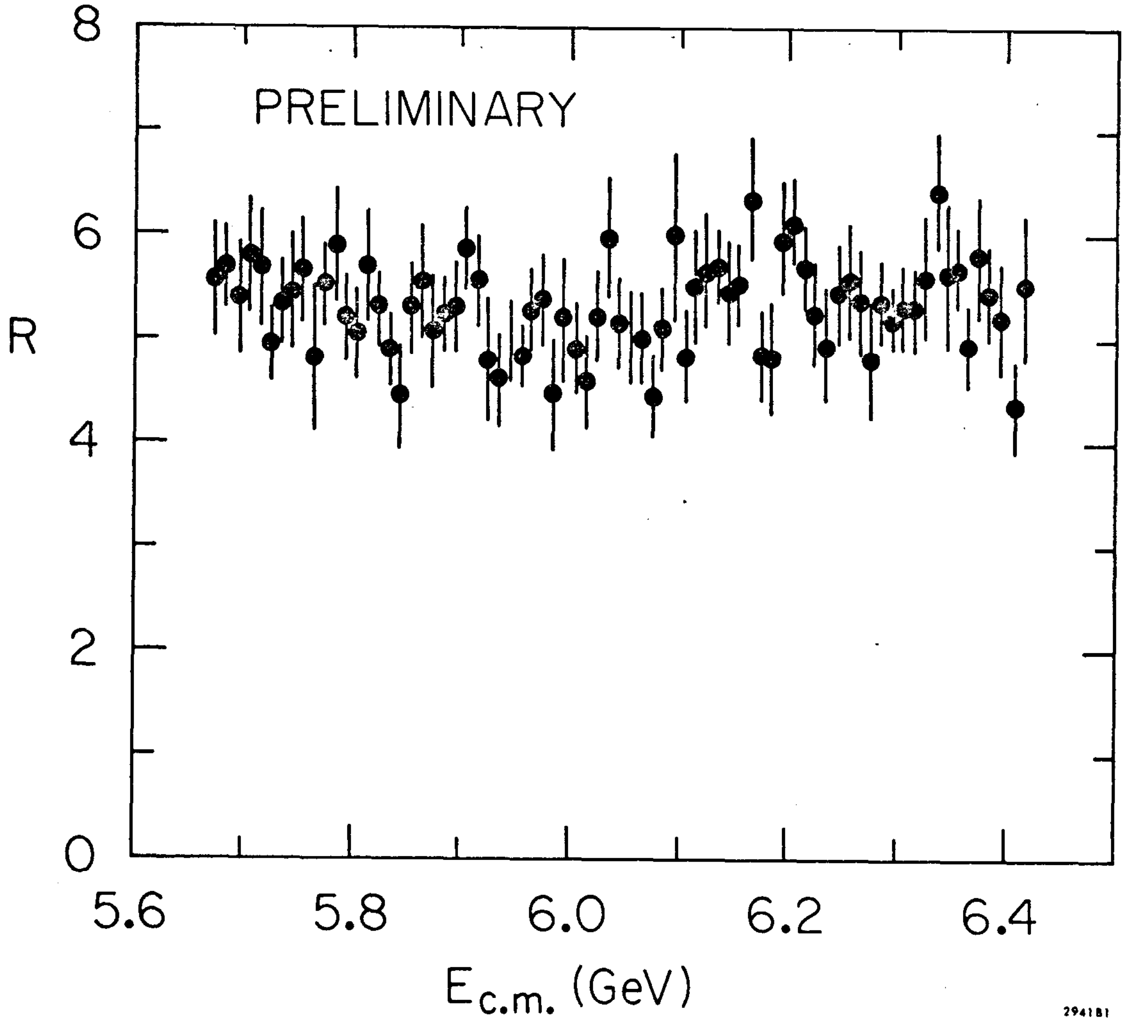

FIGURE 6
R vs center-of-mass energy from 5.6 to 6.5 GeV

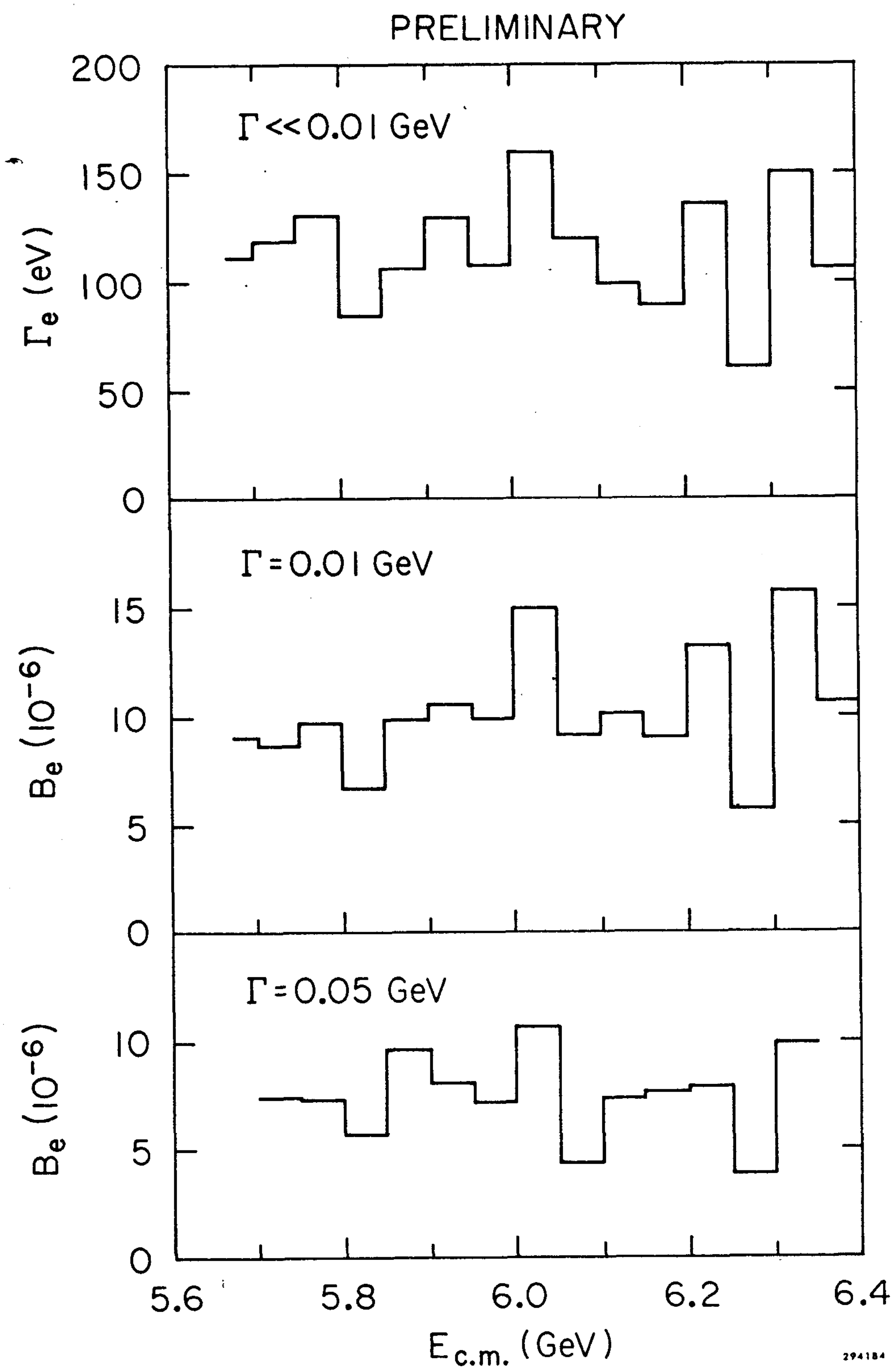

FIGURE 7

Upper limits on (a) Γ_e or (b,c) B_e for coupling of resonances to electron pairs vs center-of-mass energy.

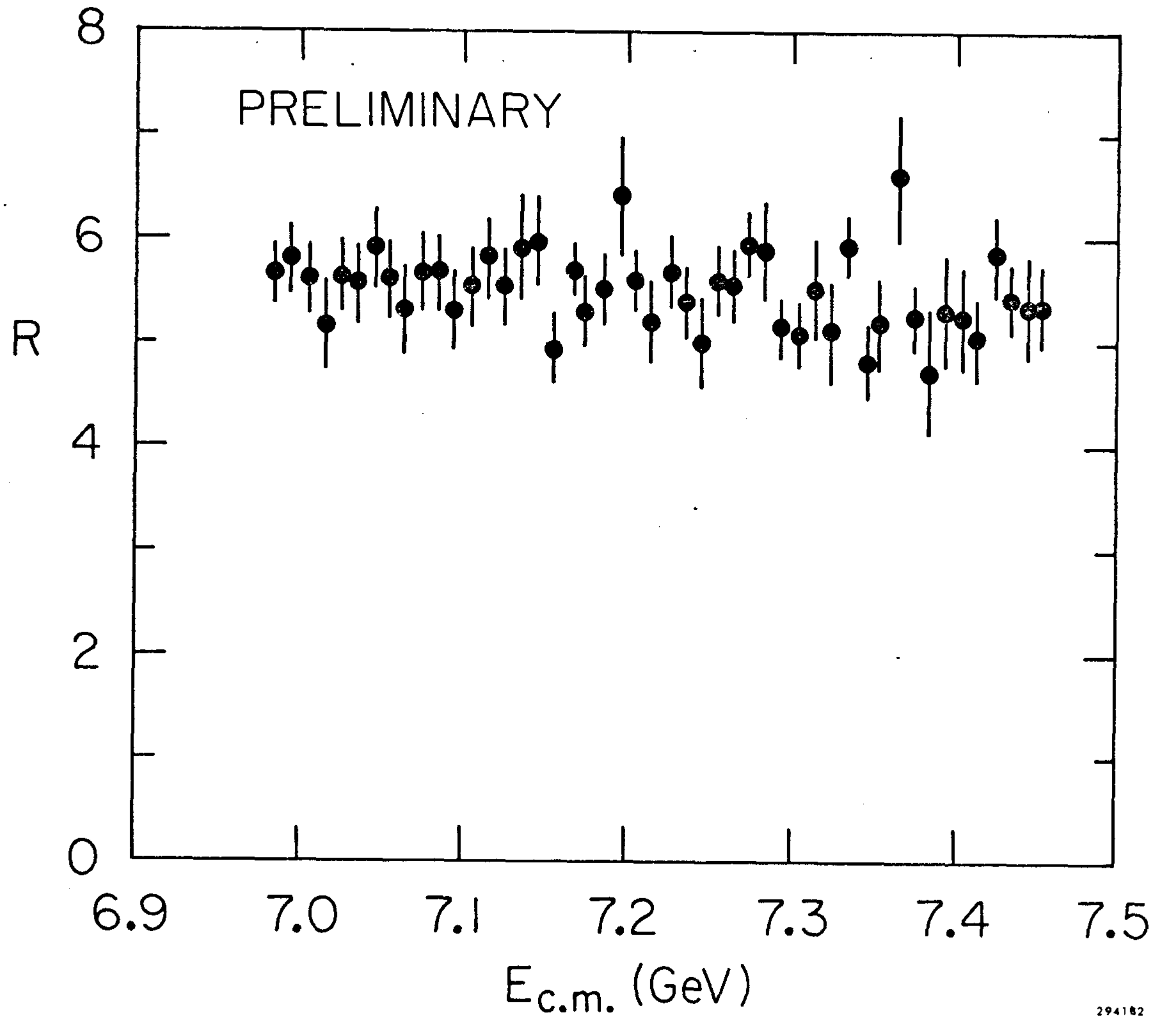

FIGURE 8
R vs center-of-mass energy from 6.9 to 7.5 GeV.

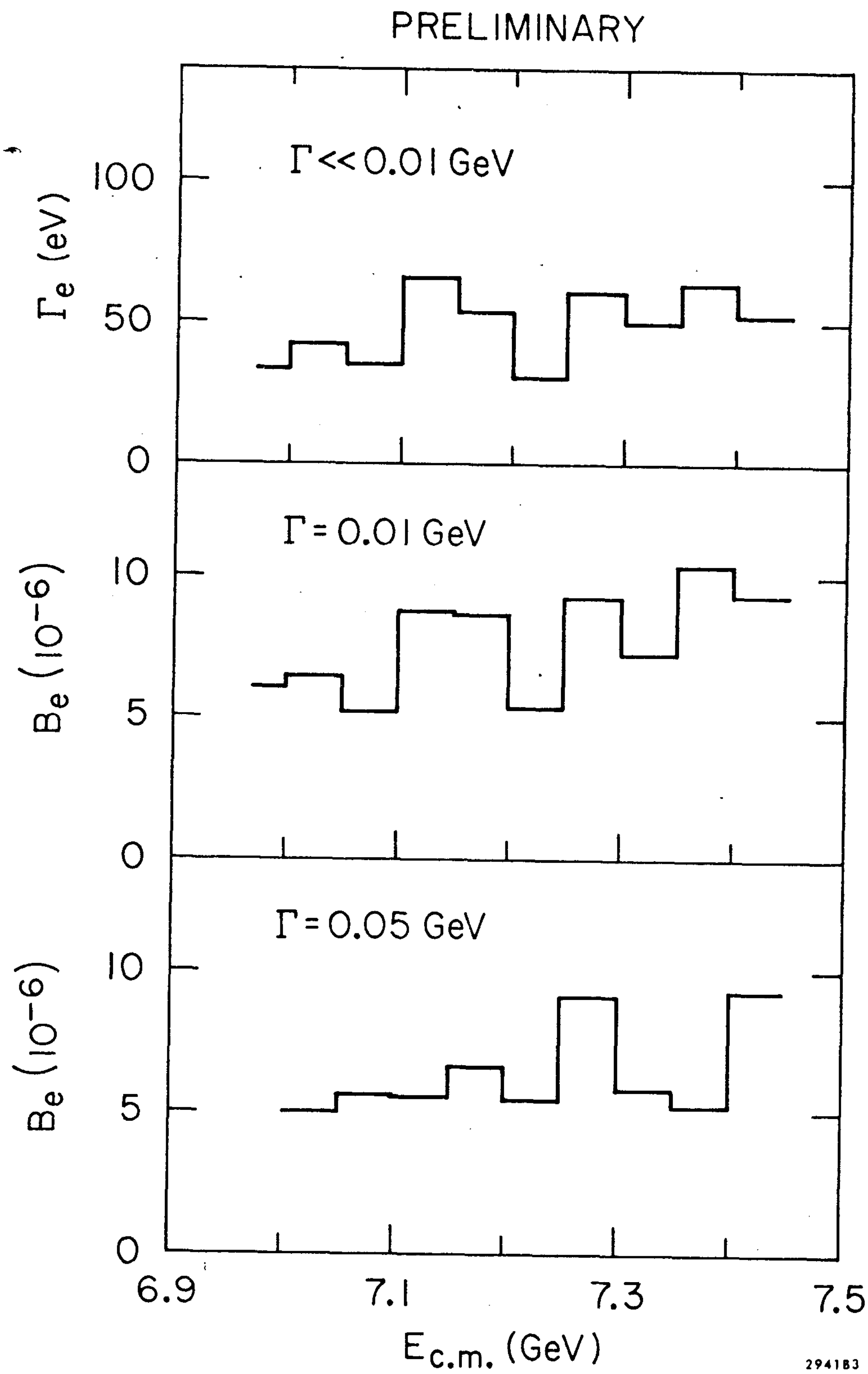

FIGURE 9

Upper limits on (a) Γ_e or (b,c) B_e for coupling of resonances to electron pairs vs center-of-mass energy.

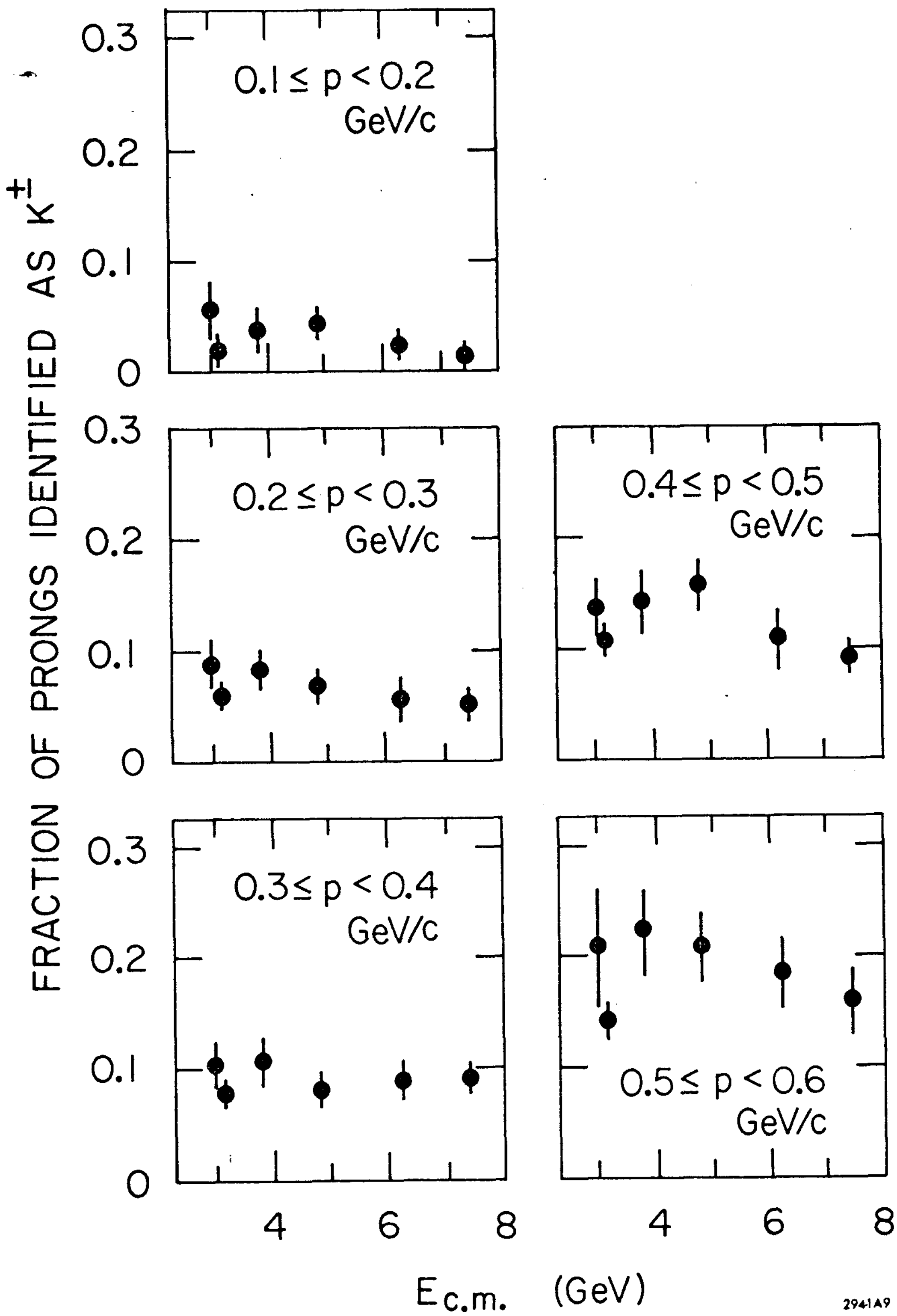

FIGURE 10
Relative fraction of prongs identified as charged K's in ranges of momenta vs center-of-mass energy.