NEW EXPERIMENTAL RESULTS ON THE PHOTOPRODUCTION OF MESONS

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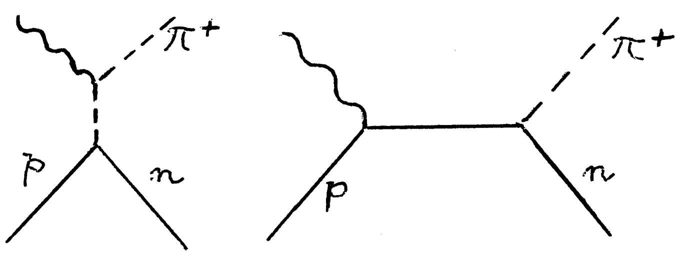
In this paper I shall present a number of selected topics about photoproduction at energies above a few GeV. Much of this material is contained in presentations which were given at the Heidelberg Conference[1], and at the Stanford Conference[1].

1. Photoproduction of Pseudoscalar Mesons

Fig. 1 shows the differential cross section[2] for the reaction

(1) $$\gamma p \rightarrow n\pi^{+}$$

at a number of different photon energies. The authors have plotted the quantity $(S - M^2)^2 \; d\sigma/dt$ vs. $\sqrt{-t}$. (S = (total CM energy)^2, t = (four-momentum transfer)^2). It is seen that except possibly at the highest energies (11 GeV and 16 GeV), the cross section depends on the primary energy roughly as $1/(S-M^2)^2$. The differential cross section continues to rise towards small momentum transfers. Such a behavior cannot be explained by a model using solely the exchange of a single boson (regeized or not regeized)[3]. A model of that kind would predict a dip in the differential cross section near zero degrees. Therefore more complicated models must be tried. The simplest possibility is to use the following two Born terms:



The amplitude representing the sum of these two terms satisfies gauge invariance. The curve resulting from this model (without the anomalous magnetic moment part of the nucleon pole term) is shown in Fig. 1. The agreement with experiment is poor, it can be somewhat improved by introducing absorptive corrections[4]. The data can be fitted by models containing more adjustable parameters, e. g. with the coherent droplet model[5] or with conspiring Regge trajectories [6]. It is probably too early to say something concerning the success of these attempts.

Fig. 2 shows the differential cross section [7] for the reaction

(2) $$\gamma p \rightarrow p\pi^{o}$$

at a number of different photon energies.

Restrictions coming from conservation laws and the smallness of certain coupling constants make it very likely, that the main contribution to Reaction (2) comes from the exchange of the ω-meson. A Regge pole fit to the data was made [8] using an ω-trajectory running parallel to the ρ -trajectory. In addition the model contains as a background term B-(1^{+}) exchange. The resulting curves (see Fig. 2) give a satisfactory fit to the data above 2 GeV, including the dip in the differential cross section near t = -O.5 GeV^{2}.

Fig. 3 shows the backward differential cross section $d\sigma/d\Omega$ for Reaction (2) (i. e. at 180^{o} in the CMS) as a function of photon energy[9]. Excitation of the nuclear resonances with isospin I = 3/2 is clearly seen, whereas there is no clear evidence for the resonances with I = 1/2.

Fig. 4 shows the differential cross section for the reaction

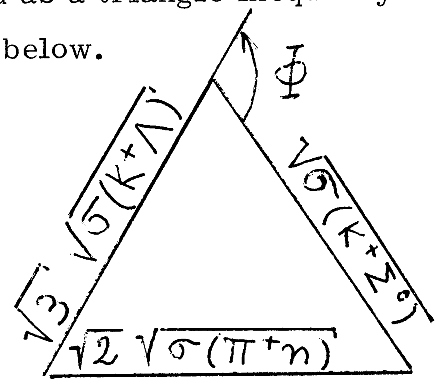
(3) $$\gamma p \rightarrow \Lambda K^{+}$$

at a number of different photon energies. Like Reaction (1), the cross section depends on primary energy very roughly like $1/S^2$. However, in contrast to Reaction (1), the differential cross section exhibits a dip in the forward direction.

Assuming SU_3 invariance and U - spin zero for the photon, one obtains a relation between the amplitudes of Reactions (1), (3) and

(4) $$\gamma p \rightarrow \Sigma^o K^+$$

These reactions were measured [10] for high energies and a range of t-values. The relation between the three amplitudes can be expressed as a triangle inequality between the cross sections as indicated below.



The inequality is satisfied, if $-1 \leq \cos \Phi \leq 1$. Figure 5 shows $\cos \Phi$ as a function of momentum transfer t for various photon energies. For large values of $|t|$ the data are consistent with SU_3 in variance. However, they violate SU_3 for small values of $|t|$. A possible reason might be the importance of meson-exchange processes contributing to the cross section at forward angles. The mass differences between the possible exchanged mesons could account for the SU_3 breaking.

2. Photoproduction of Rho-Mesons

Fig. 6 shows the cross section [11] for the reaction

(5) $$\gamma p \rightarrow p \rho^o$$

as a function of photon energy.

Above 2 GeV the cross section is practically constant with energy, suggesting a diffraction mechanism for Reaction (5). A fit to the cross section as a function of the photon energy k for k > 2 GeV gave

$$\sigma(k) = (19 \pm 3) \cdot k^{-0.12 \pm 0.16}$$

(all numbers in μb and GeV)

It has been pointed out [12], that one can measure the total ρ -nucleon cross section, by observing the absorption of mesons inside nuclear matter in an experiment on the forward production of ρ-mesons on heavy nuclei. Fig. 7 shows the forward ρ production cross-section [13] for a number of photon energies and a range of nuclei with different mass numbers A. The energy and A-dependence found is in good agreement with the result of theory [12] for a ρ -nucleon cross section of 31 mb. One obtains

$$\sigma_{tot}(\rho\,\text{nucleon}) = 31.0 \pm 2.5 \text{ mb.}$$

This can be compared with the prediction obtained from the Quark model:

$$\sigma^{Q}_{tot}(\rho p) = \frac{1}{2}\left(\sigma_T(\pi^+ p) + \sigma_T(\pi^- p)\right) \approx 28 \text{ mb.}$$

An analogous experiment was carried out [14] for φ-meson production on heavy nuclei. The result is (preliminary)

$$\sigma_{tot}(\varphi\,\text{nucleon}) = 13.3 \pm 2.7 \text{ mb}$$

This is in remarkable agreement with the Quark model prediction

$$\sigma^{Q}_{tot}(\varphi p) = 2\sigma_T(K^+ p) + \sigma_T(\pi^- p) - 2\sigma_T(\pi^+ p) = 11.5 \pm 1.5 \text{ mb}$$

3. Vector Dominance Model (VDM)

I shall not go into the theoretical foundation of the VDM. For most practical applications in photoproduction one starts from the equation[15)]

$$(1)\quad \sigma(\gamma + A \rightarrow B) \approx \sum \frac{\alpha}{4} \left(\frac{\gamma_V^2}{4\pi}\right)^{-1} \sigma_{Tr}(V + A \rightarrow B) + \text{interference terms}$$

A is any hadron, B any final state, V symbolizes one of the three vector mesons ρ, ω, φ, γ_V describes a direct vector meson - photon coupling. Equation (1) gives a relation between photoproduction and processes involving transversely polarised vector mesons. As we shall see, the coupling of the ρ-meson to the photon is much stronger than of the ω or φ meson, so for a rough first guess it is sometimes sufficient to consider only the ρ-meson contribution in the sum.

The ρ-photon coupling γ_ρ has been measured by observing the leptonic decay of the ρ-meson and by storage-ring experiments[16)]. The best value is[15)]

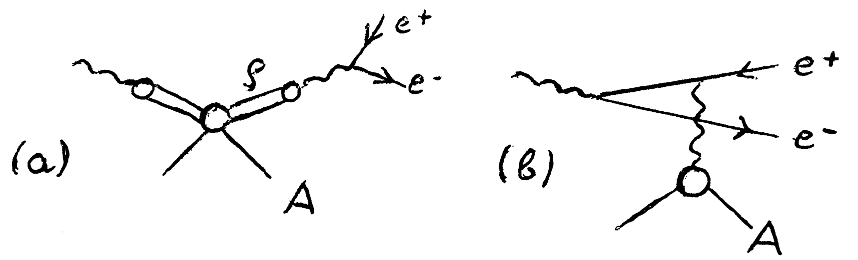
$$\left(\frac{\gamma_\rho^2}{4\pi}\right) = 0.47 \pm 0.12$$

Therefore $\left(\frac{\gamma_\rho^2}{4\pi}\right)^{-1} \cdot \frac{\alpha}{4} \approx 1/260$

I shall now mention seven applications of this model:

a) Phase anglė of rho production:

It has been shown[17)], that the phase of the ρ-meson production amplitude on heavy nuclei is indeed purely imaginary, as would be expected in this model, which describes ρ-production at high energies in terms of elastic ρ-meson nucleus diffraction scattering (diagram a)



In the experiment[17] the ρ was observed by its e^+e^--decay. This amplitude interferes therefore with the Bethe-Heitler-graph for electromagnetic pair production (one of the two BH-graphs is shown in diagram (b). Observation of the interference term between diagram (a) and the BH-diagrams, whose phase is known, establishes the phase angle φ for the ρ-production amplitude. The result is

$$\varphi = 15^o \pm 25^o$$

The phase convention is so that $\varphi = 0$ means a purely diffractive amplitude.

b) Dipion mass distribution from rho decay:

It was pointed out[18], that the ρ-meson propagator appearing in the diagram for ρ-photoproduction shown above (a) modifies the $\pi^+\pi^-$ in variant mass distribution $f(M_{\pi\pi})$ from ρ-decay. Instead of a Breit-Wigner distribution (BW), one obtains

$$(2) \qquad f(M_{\pi\pi}) = BW(M_{\pi\pi}) \,/\, M_{\pi\pi}^{\;4}$$

The $M_{\pi\pi}^{\;-4}$ term is responsible for a distortion and a mass shift in the $\pi\pi$ mass distribution, which was observed by experiments for rho production on hydrogen[11] and quantitatively confirmed for rho production on heavy nuclei[19].

c) Rho production on hydrogen:

According to Equ. (1) we have

$$(3) \qquad d\sigma/dt\,(\gamma p \rightarrow \rho p)\big|_{t=0} \approx 1/260\;\; d\sigma/dt\,(\rho p \rightarrow \rho p)\big|_{t=0}$$

At high energies one can express the forward differential ρ p-cross section by the optical theorem:

$$d\sigma/dt(\rho p \rightarrow \rho p)\big|_{t=0} = \sigma_T^{\,2}(\rho p) \,/\, 16\,\pi$$

Inserting experimentally measured values[11] into the left hand side of Equ. (3), and the Quark model cross section into the right hand side, one obtains for Equ. (3):

l.h.s. : 140 $\pm$ 20 μb/GeV^2

r.h.s. : 150 μb/GeV^2

Equ. 3 was also checked on heavy nuclei and good agreement found[19]

d) Comparison of ρ, ω and φ photoproduction:
Fig. 8 shows[11,20] the cross section for the reaction

(6) $\gamma p \rightarrow p\,\omega$

as a function of the photon energy. The cross section shows a variation with photon energy k. One can fit the cross section as a function of k for k > 2 GeV as the sum of two terms: one term having the energy dependence as found by Morrison[21] for two-particle reactions going via S = 0 meson exchange ($Ak^{-1.6}$), and a second term being practically constant with energy, which should give the diffractive part of the cross section σ_{diff}:

$$\sigma(k) = A \cdot k^{-1.6} + \sigma_{diff}$$

One obtains

$$\sigma_{diff} = 1.7 \pm 0.9\ \mu b$$

The cross section [11] for the reaction

(2) $\gamma p \rightarrow p\,\varphi$

is within the rather large errors constant as a function of energy. A summary of the three cross sections is shown in the Table.

Table

Vector meson cross sections (at about 4 GeV)

$\gamma p \rightarrow$	cross section (experimental[20])	VDModel μb
$p\rho$	16.6 $\pm$ 2.5 μb	16.6 *
$p\omega$(diffraction)	1.7 $\pm$ 0.9 μb	1.2
$p\varphi$	0.45 $\pm$ 0.13 μb	0.33

* input

For the application of the VDM to predict the ρ, ω and φ cross sections according to Equ. (1) one needs the photon-vector meson coupling γ_ρ, γ_ω and γ_φ. Their value must at present be taken from theory. We use[22)]

$$\gamma_\rho^{-2} : \gamma_\omega^{-2} : \gamma_\varphi^{-2} = 9 : 0.65 : 1.33$$

Using the Quark model to obtain the vector-meson-proton cross sections and assuming the same shape for the differential cross section of all three reactions (5), (6), (7), one obtains the predictions shown in the table, column VD Model. The agreement with experiment is reasonable. However, if the measured slope of the differential cross section for Reaction (7) is taken into account for the comparison, the VDM prediction for Reaction (7) comes out too large by a factor $\approx$ 2.

e) Multiple Meson Production[23)]:

According to Equ. (1) and neglecting the ω and φ contributions, we have

$$\sigma(\gamma p \rightarrow p\pi^+\pi^+\pi^-\pi^-) \approx 1/260 \ \sigma(\rho^o p \rightarrow p\pi^+\pi^+\pi^-\pi^-)$$

The cross section $\sigma(\rho^o p \rightarrow p\pi^+\pi^+\pi^-\pi^-)$ can be connected with the measurable cross section $\sigma(\pi^\pm p \rightarrow \text{nucleon} + 4\pi)$ by the Quark model and the statistical model[23)]. Fig. 9 shows the cross section for the reaction

$$(8) \quad \gamma p \rightarrow p\pi^+\pi^+\pi^-\pi^-$$

for various energies, as compared with the predictions coming from π - p collisions. There is excellent agreement between the photoproduction data and the predictions coming from hadron collisions.

f) Rho vs. π^+ Production[24]:

According to Equ. (1), we have

$$\sigma(\gamma p \rightarrow n\pi^+) \approx \frac{1}{260} \sigma(\rho_{transv.} p \rightarrow n\pi^+)$$

The cross section on the left hand side has been measured (see section 1). The cross section on the right hand side cannot be measured directly. However, by detailed balance it can be obtained from the cross section $\sigma(\pi^+ n \rightarrow \rho^o p)$, which is by isospin in variance equal to the cross section $\sigma(\pi^- p \rightarrow \rho^o n)$, which can be measured.

One has thus established[24] a relation between the cross sections for $\gamma p \rightarrow n\pi^+$ and $\pi^- p \rightarrow n\rho^o$. An experimental check is difficult because one must take only the cross section for transversely polarized rho mesons in the reaction $\pi^- p \rightarrow n\rho^o$. The relation between the two reactions seems to be satisfied[25] within better than a factor of 1.5. It is not yet clear, if the two reactions behave exactly alike at very small momentum transfers.

g) Total cross section for photoproduction of hadrons on the proton at high energies can be predicted from Equ. (1). If one neglects the contributions from the ω and φ, one gets

$$\sigma_{tot}(\gamma p) \approx 1/260\, \sigma_{tot}(\rho p) \approx 110\ \mu b.$$

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Figure Captions

Fig. 1 Differential cross section for the reaction $\gamma p \rightarrow n\pi^+$ for small values of $|t|$, together with predictions from a Regge pole model without conspiracy and a model using the electric Born terms (from ref. 2) data: SLAC ref. 2, DESY ref. 2a.

Fig. 2 Differential cross section for the reaction $\gamma p \rightarrow p\pi^o$, together with predictions from a Regge pole model (see text) (from ref. 7), data : CEA ref. 7a, Bonn - DESY ref. 7.

Fig. 3 Differential cross section $d\sigma/d\Omega$ at 180^o in the CMS for the reaction $\gamma p \rightarrow p\pi^o$ as a function of the photon energy (from ref. 9).

Fig. 4 Differential cross section for the reaction $\gamma p \rightarrow \Lambda K^+$ (preliminary results) (from ref. 10).

Fig. 5 Values of $\cos\phi$ obtained from the triangle in equality implied by SU_3 for the cross sections $\gamma p \rightarrow \Lambda K^+$, $\gamma p \rightarrow \Sigma^o K^+$, $\gamma p \rightarrow n\pi^+$ (from ref. 10)

Fig. 6 Total cross section for the reaction $\gamma p \rightarrow p\rho^o$ as a function of the photon energy: ┼ : results from ref. 11a, ○, △, ●: results from ref. 11, obtained by different methods (taken from ref. 11).

Fig. 7 Dependence of the differential forward cross section of rho production on the atomic number A of the target nucleus. Results shown are for average ρ momenta of p = 2.7, 3.5, 4.5 GeV/c, the curves are best fits according to the model ref. 12 (from ref. 13).

Fig. 8 Total cross section for the reaction $\gamma p \rightarrow p\omega$ as a function of the photon energy: results from ref. 11, results from ref. 20 (taken from ref. 11)

Fig. 9 Total cross section for the reaction $\gamma p \rightarrow p\pi^{+}\pi^{+}\pi^{-}\pi^{-}$ as a function of the photon energy. : : data from ref. 11. : Prediction from the vector dominance + quark model ref. 23 (from ref. 11).

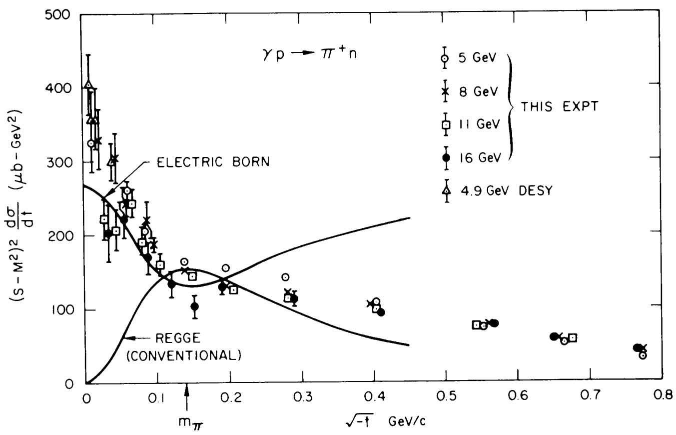


Fig. 1

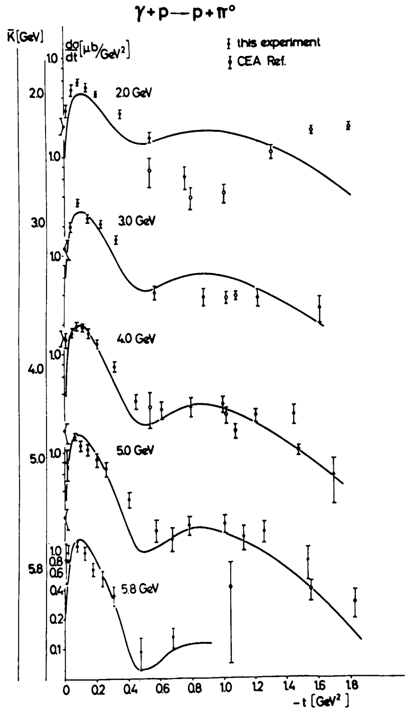
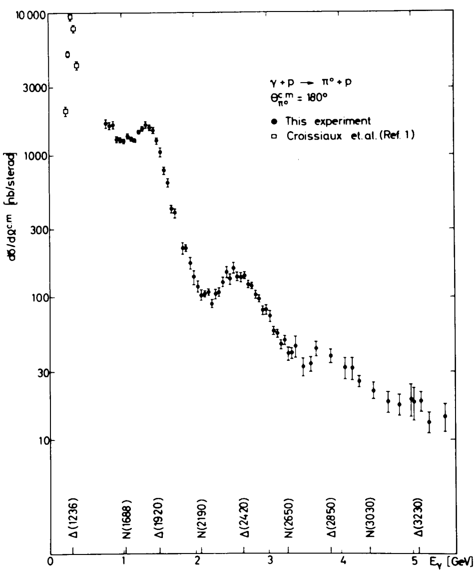


Fig. 2



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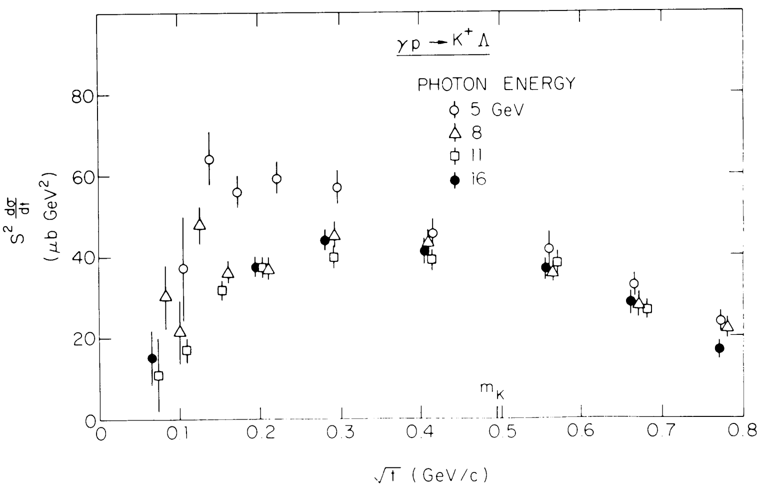

Fig. 4

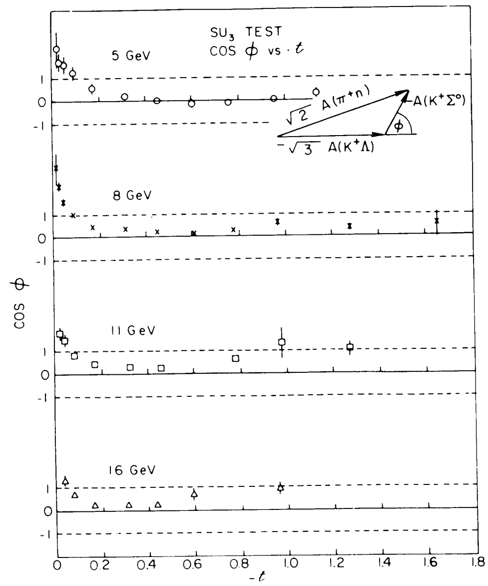

Fig. 5

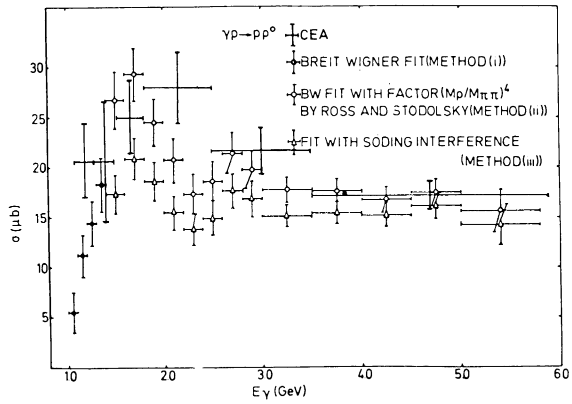

Fig. 6

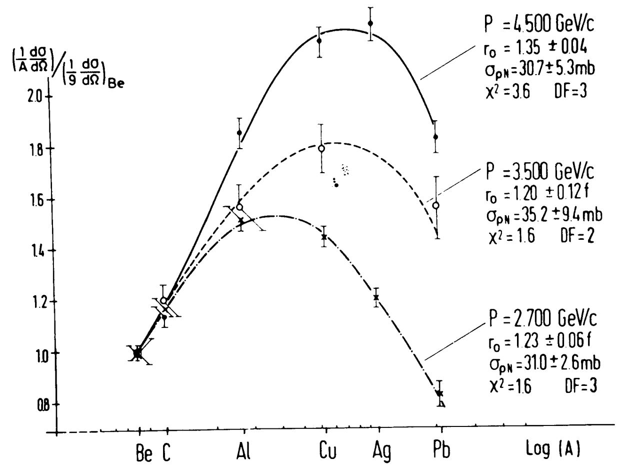

Fig. 7

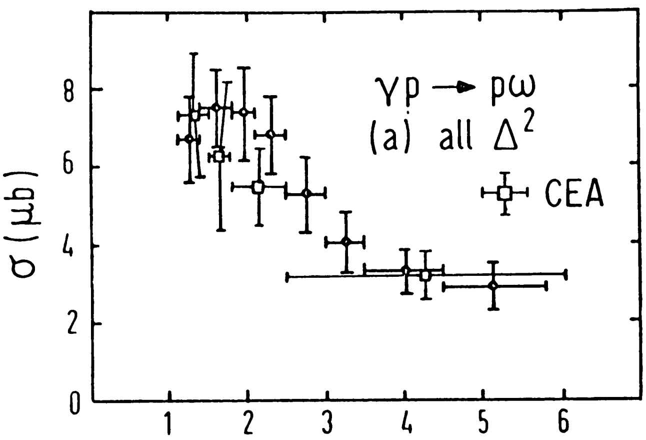

Fig. 8

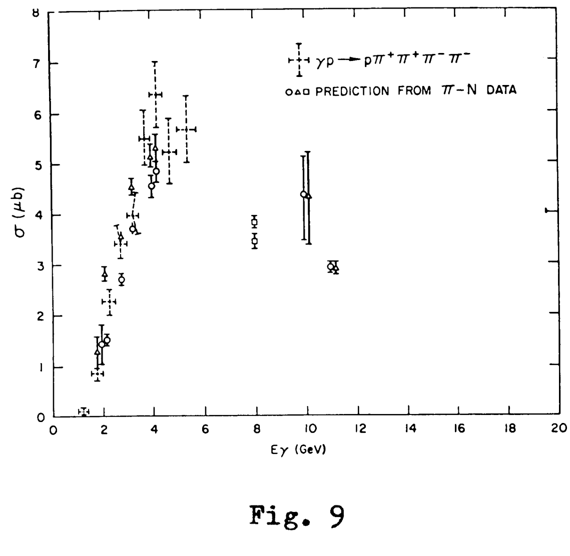

Fig. 9