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ELECTROMAGNETIC INTERACTIONS

by

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+Rapporteur's talk to The Heidelberg International Conference on Elementary Particles, Heidelberg, September 20-27, 1967.

In this Review Talk of 30 minutes' duration on the theoretical aspects of "Electromagnetic Interactions" I am asked to present a general picture of the situation at the time of the conference, and I am supposed to emphasize whatever trends or new ideas have emerged in the course of the discussion sessions and the conclusions to be drawn from them!

Professor Panofsky and I agreed to split up all the material on electromagnetic interactions into different topics rather than treat theory and experiments separately. So I shall talk on:

1. General Properties of the E.M. Current Operator.
2. The Pion Form Factor.
3. The Leptonic Decays of Vector Mesons.
4. Photoproduction of Vector Mesons.
5. Multipion Photoproduction.
6. Photoproduction of Pions at Low and Medium Energies.
7. E.M. Coupling Constants and Radiative Decays.

1. General Properties of the e.m. Current Operator.

The electromagnetic (e.m.) interaction of the elementary particles is described by the e.m. current operator $J_\mu(x)$. The smallness of the coupling constant α allows the treatment of the electromagnetic part of the interaction in perturbation theory; the matrix elements of J_μ may be therefore measured in many cases. But currents which can be measured are important nowadays.

Which are the general properties of this current we believe to know and which would we like to know?

A) Symmetry Properties.

The e.m. current is conserved [1] : $\partial_\mu J_\mu(x) = 0$. We may separate the e.m. current into a hadronic j_μ^{had} and a leptonic j_μ^{lep} part: $J_\mu = j_\mu^{had} + j_\mu^{lep}$, which are individually conserved if we neglect weak interactions [2] .

Usually it is assumed that j_μ^{had} is odd under charge conjugation of the strongly interacting particles; but recently it was proposed in connection with CP-violation that there may be also an even part $k_\mu(x)$ [3] : $j_\mu^{had} = j_\mu + k_\mu$, $C_s j_\mu C_s = -j_\mu$, $C_s k_\mu C_s = k_\mu \neq 0$? - The Gell-Mann-Nishijima formula suggests that j_μ is a sum of two conserved currents: $j_\mu = j_\mu^{(3)} + \frac{1}{2} j_\mu^{(y)}$, the currents of the 3-component of I-spin and of the hypercharge Y respectively [4] . This implies for first order e.m. interaction the selection rule $\Delta I = 0,1$, a rule for which one would still like to have more experimental checks in high energy e.m. interactions [5] . (The hypothetical k_μ is, according to T.D. Lee [6] , isoscalar).

In the SU(3)-symmetry scheme one assumes that j_μ transforms, like the charge, as U-spin scalar of the octet adjoint representation [7] . Because of SU(3)-breaking, which is strong compared to the e.m. interaction, the relations which follow from U-spin conservation are difficult to check [8] . Therefore, the results following from current commutator algebra - CCA is an attempt to formulate broken SU(3) symmetry [9] - are particularly important for the determination of the symmetry properties of j_μ. But the inverse is even more true: The best known elements of the current commutator algebra, whose structure equations are now considered as fundamental equations of particle physics, are the e.m. currents $j_\mu^{(3)}$ and $j_\mu^{(y)}$. As the sources of the e.m. field these currents are most accessible to experimental investigation.

B) Analyticity Properties.

The e.m. current is a relativistic, local vector field which is relatively local to the fields of the different particles. For some of the matrix elements of j_μ one may therefore derive dispersion relations from first principles; for others one assumes analyticity in the usual manner. Examples are the pion form factor [10] :

$$< p_\pi \mid j_\mu(0) \mid p'_\pi > = (2\pi)^{-3}(p + p')_\mu \; F_\pi((p - p')^2)$$

$$F_\pi(k^2) = \frac{1}{\pi} \int \frac{A(t)dt}{t - k^2 - i\varepsilon} \qquad (1)$$

and the production amplitude T for the process $\gamma + N \to \pi + N$ [11] :

$$T = \sum_{i,k} A_k^{(i)} (s,t) \, M_k g_i$$

$$\mathrm{Re}\, A(s,t) = A_{pole}(s,t) + \frac{1}{\pi} P \int_{(M+m)^2}^{\infty} ds' \; \mathrm{Im}\, A(s',t) \left\{ \frac{1}{s' - s} \pm \frac{1}{s' - \bar{s}} \right\} \qquad (2)$$

M denotes invariant spin amplitudes, g_i isospin amplitudes.

Estimates of the high energy behaviour of the invariant amplitudes A(s,t) from Regge analysis etc. lead to superconvergence relations, for example for the pion photoproduction amplitudes [12] :

$$\frac{1}{\pi}\int_{(M+m)^2}^{\infty} ds \; \mathrm{Im}\, A^{(-,-,+,-)}_{1,2,3,4}(s,t) = \frac{eg}{2},\; -\frac{eg}{t-m},\; \frac{g(\mu_n-\mu_p)}{2},\; \frac{g(\mu_n-\mu_p)}{2} \tag{3}$$

(μ_p, μ_n: proton, neutron anomalous magnetic moment; $\frac{g^2}{4\pi} \approx 14,5$) which might be tried to be saturated by low lying resonances. For the calculations of magnetic moments and form factors the interest in the so-called sidewise dispersion relations has increased [13] .

C) Vector Meson Dominance of the e.m. Interaction.

Scattering theory in the framework of general field theory [14] allows to equalize a superposition of phenomenological vector meson fields to the e.m. hadron current [15]

$$j_\mu(x) = -\left[\frac{m_\rho^2}{2\gamma_\rho}\rho^o_\mu(x) + \frac{m_\omega^2}{2\gamma_\omega}\omega_\mu(x) + \frac{m_\phi^2}{2\gamma_\phi}\phi_\mu(x)\right] \tag{4}$$

m_v denotes the masses of the vector mesons $v = \rho^o, \omega, \phi$.

The photon-vector meson coupling constants γ_v are defined by the normalization of the vector fields: $< 0|j_\mu(0)|V > = -\frac{m_v^2}{2\gamma_v} e_\mu(V)$. From a general point of view, Equ. (4) is only a definition. Its importance follows from the fact that the assumption of slow variation in k for matrix elements of $(k^2 - m_v^2)\, j^v_\mu(k)$ allows to relate matrix elements for photoproduction

$$T(\gamma + A\to B+C) = e(2\pi)^{5/2} < p_B,p_C|j_\mu(0)|\; p_A> a^s_\mu(k) \;;\; (\, p_B+ p_C- p_A\,)^2 = 0 \tag{5}$$

to matrix elements for reactions induced by transversally polarized vector mesons:

$$T(V+A\to B+C) = \frac{2\gamma_v}{m_v^2}(2\pi)^{5/2} <p_B,p_C|(\Box-m_v^2)j^v_\mu(0)|p_A> e^s_\mu(k);\; (p_B+ p_C- p_A)^2 = m_v^2 \tag{6}$$

Disregarding all types of subleties in this extrapolation procedure [16], one gets the approximate formula

$$\sigma\ (\gamma + A \to B + C) = \sum_{V} \frac{\alpha\pi}{\gamma_V^2}\, \sigma_{tr}\ (V + A \to B + C) + \text{interference terms.} \tag{7}$$

The determination of the coupling constants γ_V is of the greatest importance in this framework. On the one hand it allows estimates of the photoproduction cross-sections by Formula (7). On the other hand their ratio determines the position of the e.m. current in the symmetry frame fixed by the position of the vector mesons. Pure SU(3) with ideal ω-ϕ mixing gives

$$\gamma_\rho : \gamma_\omega : \gamma_\phi = 1 : 3 : -\frac{3}{\sqrt{2}} \tag{8}$$

From current algebra follows a type of Weinberg sum rule [9]

$$\frac{1}{3}\frac{m_\rho^2}{\gamma_\rho^2} = \frac{m_\omega^2}{\gamma_\omega^2} + \frac{m_\phi^2}{\gamma_\phi^2} \tag{8'}$$

together with the current mixing model one may get [9] :

$$\frac{m_\omega}{m_\rho}\frac{\gamma_\rho^2}{\gamma_\omega^2} = 0{,}074, \qquad \frac{m_\phi}{m_\rho}\frac{\gamma_\rho^2}{\gamma_\phi^2} = 0.195 \tag{8''}$$

D) Lagrangian Models.

In the framework of canonical field theory the e.m. current is expressed by the particle fields. The classical example is quantum electrodynamics. Other examples are the quark model [19] and Schwinger's effective Langrangian approach [20] . Finally I would like to mention the recent Lagrangian formulation of the vector meson dominance model of the e.m. interaction by Kroll, Lee and Zumino [21] with its applications to current algebra. This formulation allows a consistent application of the ideas of vector meson dominance to virtual hadron contributions to quantum electrodynamics.

What are the conclusions to be drawn from this general picture of theoretical ideas on the problem of e.m. interactions? Never before, the theory of e.m. interaction was related so intimately to the whole field of particle physics. Many aspects of the e.m. interaction, like CP-violation, current algebra, sum rules, symmetry, the quark model etc. will therefore be discussed in other sections. I shall restrict myself to the less profound topics treated in the papers contributed to our discussion session. These are mainly related to the vector meson dominance picture and to the dispersion theoretic treatment. As I have mentioned above, the information I shall try to give is of a mixed theoretical and experimental nature.

2. Pion Form Factor.

The hypothesis of the vector meson dominance of the e.m. current was developed from the dispersion theoretic analysis of the nucleon form factors, which led to the prediction of the ρ^o-meson by Nambu, Fulco and Frazer [22] . It is therefore particularly satisfying to see today the first - and still preliminary - results of the reaction $e^+ + e^- \to \pi^+ + \pi^-$ from the storage rings in Novosibirsk [23] and Orsay [24] . One sees from the graph in Fig. 1a. that the total cross section of this reaction is directly proportional to the square of the absolute value of the pion form factor F_π (k) in the time-like momentum region of the virtual photon [25] :

$$\sigma(E) = \frac{\pi}{12}\alpha^2 \frac{\beta^3}{E^2} |F_\pi(2E)|^2 \simeq \frac{3}{4}\pi \bar{\lambda}^2 \frac{\Gamma(\rho^o \to e^+ + e^-)\Gamma(\rho^o \to \pi^+ + \pi^-)}{(2E-m_\rho)^2 + \Gamma^2/4} \tag{9}$$

with E = energy of the $e^\pm$ in the rest system, $\beta = (1 - \frac{m_e^2}{E^2})^{1/2}$.
The experimental results (Fig.2) show clearly the ρ^o peak at the correct mass value, but with a somewhat smaller width Γ of 93 ± 15 MeV. One can see how much smaller the form factor of the point-like pion - $F_\pi = 1$ - is in this region. A description of the cross section by a simple Breit-Wigner formula - the second part of Equ. (9) - shows the maximum value as being proportional to the branching ratio $B = \Gamma(\rho^o \to e^+ + e^-) / \Gamma(\rho^o \to \pi^+ + \pi^-)$:

$$\sigma(\frac{m_\rho}{2}) = 12\pi B / m_\rho^2 \; ; \; \Gamma \simeq \Gamma(\rho^o \to \pi^+ + \pi^-). \tag{10}$$

The results from the two laboratories are

$$\sigma_{max} = (1.2 \pm 0.2)\ \mu b,\ B = (4.9 \pm 0.8)\ 10^{-5} \qquad \text{(Novo-Sibirsk)}$$

σ_{max} = (1.34 ± 0.22)μb, B = (5.4 ± 0.9) 10^{-5} (Orsay)
with a systematic error of 29 percent.

This B determines the most important (γ - ρ^0) coupling constant, as we shall discuss later in more detail.

We may compare the approximation formula $|F_\pi|^2 = Km_\rho^4/((k^2 - m_\rho^2)^2 + m_\rho^2 \Gamma^2)$, which Novo-Sibirsk used to fit their data: K = 0.59 ± 0.15, with the simple pole formula of the vector meson dominance model in the zero width limit $F_\pi = -m_\rho^2 / (k^2 - m_\rho^2)$. The experimental F_π is different by a factor $\sqrt{K}$ = 0.77 ± 0.08. If one takes the experimental result at its face value, one may say sloppily that the pion form factor is dominated by the ρ^0 to about 77 percent. May I remined you that Gell-Mann and others [26] got their first estimate of B = 5.4 · 10^{-5} (Γ = 100 MeV) from the assumption K = 1. There is a contribution to this conference by Antoniau and Bowcock [27] ,who give - by the problematic methods of dispersion theory and on the basis of some experimental pion-pion phase shifts - an estimate of the contribution to the pion form factor from the non-resonant background. Their figure is $\sqrt{K} \simeq$ 69 percent. C.W. Akerlof et al. [28] contributed a new value of the pion charge radius r_π = (0.8 ± 0.1)f from their data on electroproduction of pions. This value is compatible with that following from ρ-dominance $r_\pi = \sqrt{6} / m_\rho$ = 0.63f, and it is also compatible with the value of the nucleon radius r_N = 0.8f. M.M. Block et al. [29] reported a value r_π < 0.5 from the comparison of π^+ and π^- scattering on He.

The last two problems mentioned may also indicate how much more interesting this type of physics will become when we have more, and more precise, data from the storage rings, in the region of the resonance and everywhere else.

3. Leptonic Decays of Vector Mesons.

Let us now look at the inverse reaction $V \to \ell^+ + \ell^-$; ℓ = μ or e. Three papers on this process have been submitted to this conference and some others were published recently. (See Table I) Since the quality of each sample of ρ^0's, for instance its polarization, its admixture of ω, etc., depends on the way it is produced, it is very difficult to determine the very small branching ratio $B = \Gamma(\rho^0 \to \ell^+ + \ell^-) / \Gamma(\rho^0 \to \pi^+ + \pi^-)$. For a detailed discussion of the problems involved here I would like to refer to the report given by S.C.C. Ting at the recent Stanford Conference on

"Electron and Photon Interactions at High Energies" (1967) [37] .

There is now consistency between the recent measurements within a 20 percent error. The average value is

$$B = (5.8 \pm 0.8) \cdot 10^{-5}$$

This is in nice agreement with the storage ring data mentioned above.

From the graph of Fig. 1b we may get the partial width [38] :

$$\Gamma\ (V \to \ell^+ + \ell^-) = \frac{\alpha^2}{12} \ \frac{4\pi}{\gamma_V^2} \ m_V + O((\frac{m_e}{m_V})^4) \qquad (11)$$

So B, m_ρ = 770 MeV, $\Gamma\ (\rho^o \to \pi^+ + \pi^-)$ = (130 ± 10) MeV determine this most important constant $\gamma_\rho^2/4\pi = 0.47 \pm 0.12$. This is really very close to the value $\gamma_\rho^2/4\pi = 1/2$ predicted by Gell-Mann several years ago [26] .

Unfortunately there are no reliable measurements of the leptonic decays of ω [39] and ϕ. The $e^+ - e^-$-decay of the ϕ is observed, and measurements are under way [40] . With the possible experiments on the storage rings included, we should get all these coupling constants γ_V for ω, ρ^o, ϕ , within one or two years.

In my introduction I have already emphasized the great importance of the ratio of these coupling constants for the symmetry properties of j_μ.

4. Photoproduction of Vector Mesons.

Now I would like to discuss the photoproduction of vector mesons. The experimental data which I shall consider come mainly from the CEA-Bubble Chamber Group (Brown-Harvard-MIT-Weizmann Inst.) [41-44] and from the DESY Bubble Chamber Collaboration (Aachen-Berlin-Bonn-Hamburg-Heidelberg-München) [45-52] . The results of the two groups agree within the errors.

Fig. 3 shows the total cross section for ρ^o photoproduction [41,48,51] as function of the γ energy in the lab.system. After some possible bumps in the resonance region, this cross section becomes approximately energy independent. Its value is then σ = (17 ±)μb. The difficulty of the separation of the ρ^o from the non-resonant two pion background contributes essentially to the error. The figure shows points from different methods of evaluation. The energy independence of σ at higher energies is explained by the diffraction-dissociation model [53-55,62] . This model essentially sets the photoproduction cross section proportional to the elastic vector meson-proton diffraction cross section. So it represents a special case of Equ. (7). We shall make some more quantitative considerations later.

In the total ω photoproduction cross section [42,47,51] , Fig. 4, people see more energy dependence at higher energy than in the ρ^ocross-section. This is attributed to a peripheral one-pion exchange contribution. According to SU(3) this contribution is larger for the ω than for the ρ^o [8] . I think one can also see a bump and a diffraction cross section! Therefore a separation of the peripheral and diffraction parts, which was tried by DESY group, is a difficult problem. Fig.4 and Table II show the good agreement between DESY and CEA data.

The total ϕ photoproduction cross section is small, the statistics still rather poor. [44,47,51] , Fig.5.

Now we look at the differential cross sections which show for the ρ^o (Fig.6) and for the ω (Fig.7) the typical diffraction peaks. DESY reports [51] that the slope B varies with the invariant mass $M_{\pi\pi}$ of the two pion system in the region of the ρ^o-resonance from $B = 9.3$ GeV^{-2} at $M_{\pi\pi} = 0.6$ GeV to $B = 5.0$ GeV^{-2} at $M_{\pi\pi} = 0.9$ GeV. The ϕ distribution (Fig.8.) seems to be flatter. A DESY spark chamber group [56] reported that the diffraction peak of the ρ^o cross section persists up to very small momentum transfers [57] . - No dip!

We shall now discuss the contributed results of the DESY-Columbia Collaboration on the A-dependence of the forward differential cross section for photoproduction of ρ^o on complex nuclei. [57,58] Fig.9. These are measurements with a two arm megnetic spectrometer. The diffraction dissociation model of Drell and Trefil [59] , and Ross and Stodolsky [54] describes this A-dependence as an interplay of partial coherence and absorption in the nucleus. Most important to us: The theoretical curves depend on the total ρ^o nucleon cross section, which may be so determined by a fitting procedure. The result at $p_{\rho,lab} = 4.5$ GeV/c is $\sigma_T(\rho^o N) = (30.7 \pm 5.3)$mb.

With Table III we try a short theoretical discussion. The aim is to check the formula [8,53,54,55] :

$$\sigma_{diff} (\gamma + P \to V + P) = \frac{\alpha}{4} (\frac{\gamma_V^2}{4\pi})^{-1} \sigma_{diff} (V + P \to V + P) \qquad (12)$$

which is a special case of Equ. (7). For this we must get the elastic diffraction V-P cross section from somewhere. We assume the usual form of the diffractive cross section

$$\frac{d\sigma}{d\Delta^2} = A\ e^{-\Delta^2 B} \qquad (13)$$

and a pure imaginary forward scattering amplitude; then we get with the help of the optical theorem,

$$\sigma_{diff} (V + P) = \frac{1}{16\pi B} \sigma_T^2 (V + P) \qquad (14)$$

In the case of the ρ^o we may take the experimental value for the total cross section just mentioned (Table III, line 4). For all vector mesons we may use cross section relations

$$\sigma_T (\rho^o P) = \sigma_T (\omega P) = \frac{1}{2} (\sigma_T (\pi^- P) + \sigma_T (\pi^+ P))$$

$$\sigma_T (\phi\ P) = 2\sigma_T (K^+ P) + \sigma_T (\pi^- P) - 2\sigma_T (\pi^+ P) \qquad (15)$$

$$\frac{1}{2} (\sigma_T (K^- P) + \sigma_T (K^+ P) + \sigma_T (K^- n) + \sigma_T (K^+ n) - \sigma_T (\pi^- P) - \sigma_T (\pi^+ P))$$

which follow from the quark model [60] or some Regge analysis [61] (Table III, line 5). The slope of the diffraction peak we take from the photoproduction data (Table III, line 3). So we calculate $\sigma_T(VP)$, (Table III, line 6 from line 4, and line 7 from line 5) and, by comparison with the photoproduction data (Table III, line 1), we may calculate the V-γ_V -coupling constant (Table III, line 8). For the ρ^o, the picture is quite consistent. The total cross section of the derived from the pion cross section agress very well with the value from photoproduction on complex nuclei, and the γ-ρ^o-coupling constant also agrees, within the errors, with the value determined from the leptonic decay of the ρ^o, (Table III, line 9). For the ω, one expects from SU(3) a $\gamma_\omega^2/4\pi$ nine times larger, and this means a nine times smaller photoproduction cross section. In a model of broken SU(3) by J.J. Sakurai [18] , this ratio is 1:13,5. The experimental data support the picture in this case also. For the ϕ one would expect from SU(3) or broken SU(3) a ratio $\gamma_\rho^2 : \gamma_\phi^2$ = 1:4.5 or 1:7. With the very poor experimental data this agrees not too good and not too bad.

The fun of this game is that we will soon have some further experimental data which will allow further checks, (In Table III marked by ?!). So we heard that experiments on the photoproduction of ϕ on complex nuclei and on the leptonic decay of the ϕ are under way.

One can expect further understanding of the model from the discussion of the observed polarization of the vector mesons produced by photons in the framework of the strong absorption model [62] , the Regge model [63] or the quark model [64] . Unfortunately limitation of time forbids to continue this topic any further.

In order to give a hint on what else one may find in the contributed papers of the CEA and DESY bubble chamber groups, I give in Table IV a list of observed reactions with some representative total cross sections. This compilation I owe to Dr. E. Lohrmann who supplemented the bubble chamber data [65] by some relevant data from counter experiments.

Both bubble chamber groups state that their data agree within the errors.

5. Multipion Photoproduction.

An example of the application of the vector meson dominance model for the e.m. interaction and of the approximate formula Equ. (7) to many-particle reactions is discussed in a contributed paper by H. Satz [81] . He studies the cross sections of the reactions $\gamma + P \to P + 2\pi^+ + 2\pi^-$ and $\gamma + P \to P + 3\pi^+ + 3\pi^-$. The cross section of the reaction $V + P \to P + 4\pi$, or $V + P \to P + 6\pi$ is related by the quark model and by isospin analysis to the cross section of the reactions $\pi + P \to N + 4\pi$, or $\pi + P \to N + 6\pi$ respectively. From $\sigma(V + P \to P + n\pi)$, Equ.(7) of the vector meson dominance model predicts the corresponding photoproduction cross sections. Fig. 10 shows the result for $\gamma + P \to P + 2\pi^- + 2\pi^+$. The points and triangles are the predictions from the pion data; the crosses represent the bubble chamber data for photoproduction [51].

6. Photoproduction of Pions at Low and Medium Energies.

Now I come to a somewhat different topic. About 20 percent of the papers contributed to Session VIII treat the photoproduction of pions at low energies.

There are new interesting experimental data on π^0-photoproduction near threshold [82] and in the resonance region [83,84,85] ; these show significant deviations from older data. There are new data on π^0 production by polarized γ beams [86] and measurements of the polarization of the recoil proton in π^0 photoproduction [87,88] .

On the other hand, there are several theoretical papers which try to explain such data. For a layman like me, it is difficult to judge on the significance of these theoretical attempts. There seems to be agreement on the fact that a description by fixed-t dispersion relations which take into account the Born terms and the contribution of the Δ (1238) resonance given by the well-known CGLN formula [11] can explain most of the important features within an accuracy of about 20 percent. [89]

The following points remain unsatisfactory:

(a) The determination of the amplitude E_{1+} which determines critically the π^0 production in the backward direction [90] ;
also the determination of the other small amplitudes [95] .

(b) π^0 production near threshold [92] .

(c) The theoretical understanding of the CGLN formula in the framework of "Ananlyticity and unitarity" for relativistic partial wave amplitudes.

The following remedies are advised in contributed papers:

(1) New methods for the solution of the coupled partial wave equations, the so-called conformal mapping technique [91] . The photoproduction amplitudes are calculated from pion nucleon scattering phase shifts without additional free parameters.

(2) Vector meson exchange for π^0 production near threshold [92,93] .

(3) Using CDD poles in the solution of partial wave equations as fitting parameters [93] .

(4) Use of iterated Born terms for the lefthand cut of partial wave dispersion relations [94] .

(5) Discussion of higher energy contributions in the fixed-t dispersion relations [95] .

(6) Isobar models with many known resonances in the s,t and u channels [96].

The main goal of the last two contributions is to extend the analysis to higher energies.

Figures 11 - 13 given an impression of the success of these attempts. The exitation curve at 90^{o} for π^{o} photoproduction is most sensitive to the amplitude $M_{1+}(3/2)$; there the descriptions of the different theories are good (Fig. 11). Fig.12 shows an angular distribution somewhat off the resonance energy. One sees the old data and the new data and the older theory ([91] without free parameter) and the new theory ([93] with free parameter). In Fig. 13 we see the new experimental data of π^{o} photoproduction near threshold, compared with Donnachie's theory within [91] and with vector meson exchange [92] . Further the result of Rollnik's calculation [93] is shown, which contains less vector meson exchange.

My personal opinion is that only the inclusion of new phenomena in the discussion will allow to decide between these different dynamical descriptions of the π-N system at low energies. I would like to mention two examples of such phenomena: (1) The N-N^{*}-form factors at high momentum transfer are sensitive to the π-N binding forces at small distances. We have seen some experimental data on this subject at this conference [97] . (2) Maybe one has to include a larger energy region in the discussion of small effects at low energies. New experimental results which may be used for this purpose were presented at this conference. As an example I show the π^{o} production at 180^{o} up to energies $E_{\gamma} \sim 5$ GeV, which shows exciting structure in the region of the higher resonances. [98] Fig. 14.

7. E.M. Coupling Constants and Radiative Decays.

Finally let me make some remarks on the problem of e.m. coupling constants. Maybe I first remain with the subject I have discussed in the last section.

Isobar models and isobar approximations play an important role in the explanation of low and medium energy π-photoproduction data. So the above mentioned papers [99] contain a great number of parameters which are closely related to isobar-nucleon-gamma coupling constants. But, of course, every author has his own form of coupling terms and his own normalizations. I would like to suggest that everybody who works with isobar and related models should express his coupling constants also in the physical quantity of a partial decay width. Dr. Gutbrod, the secretary of this session, tried to collect these partial decay widths from the different submitted papers. He found great inconsistencies in these numbers. The origin of this trouble is that the bumps seen in the integrated photoproduction cross section at the position of the higher resonances come mainly from an interference between the real part of the resonating multipole and a poorly known background. Therefore a lot of uncertainties enter in the determination of the imaginary part of the multipole amplitude. In standard resonance theory, the square of this imaginary part is the product of the partial decay width for πN and γN decay. Since in each bump more than one resonance may be excited, it is not surprising that the results given by various authors may differ by more than a factor 2, with the exception of the Δ (1238) where $\Gamma(N^* \to \gamma P) \simeq 0.65$ MeV [100] . Maybe one should look at the radiative decays directly, as was suggested at this conference [101] . The incertainty in the knowledge of these decay widths makes the attempts to saturate photoproduction sum rules [12] , Equ. (3), quite problematical.

One remark on the radiative decays of the mesons [102] . There is a confirmation of the $\omega \to \pi^0 + \gamma$ partial width:

$$\frac{\Gamma(\omega \to \pi^0\gamma)}{\Gamma(\omega \to \pi^+\pi^-\pi^0} = (13 \pm 4)\% \, [103] \; .$$

Unfortunately the bubble chamber groups did not find A_1 and A_2 photoproduction [51] . This, with the help of the one-pion exchange model, sets some rough upper limit on the $A \to \pi\gamma$ width, which is by a factor 6-8 smaller than what one would expect from the vector meson dominance model. [104]

There are new measurements of the Σ^+ magnetic moment [105, 106] , so that the situation for SU(3) on this subject does now look rather nice. (Table V)

I would like to remind you once more of the determination of the very important $\gamma - \rho^{o}$-coupling constant $\gamma_{\rho}^{2}/4\pi = 0.47 \pm 0.12$. Prof. V.W. Hughes gave a compilation of experimental values of the best known e.m. coupling constant, the fine structure constant α:

$\alpha = 137.0388 \pm .0012_{(exp)}$ (from fine structure, Lamb),
$\alpha = 137.0359 \pm .0008_{(exp)}$ (from Josephson effect),
$\alpha = 137.0383 \pm .0026_{(exp)}$ (from muonium hyperfine structure [107])
$\alpha = 137.0382 \pm .0064_{(exp)}$ (from g-2 of the electron)
$\alpha = 137.0359 \pm .0.0002$ (known theory) + (unknown theory); (from hyperfine structure). These figures reflect the great accuracy low-energy quantum electrodynamics has reached in experiment and theory [108]. As the errors are two standard deviations, people still wonder about some slight discrepancies in the last decimals!

I think everybody agrees that we have to go a very long way until we reach such a precision in hadron electrodynamics.

Acknowledgement.

I am very grateful to the leaders of the discussion groups J. Perez y Jorba, H. Rollnik and G. Weber. I thank very much Dr. F. Gutbrod for all the help he gave me in the preparation of this talk. Many colleagues working in this field contributed to this report by stimulating discussions and with valuable informations. I thank them for this collaboration.

Footnotes and References.

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Dubna, February 1967..I have to thank Prof. Yennie for many discussion
on this subject.

Figure Captions

Fig. 1 Feynman graphs for the reactions $e^+ + e^- \to \pi^+ + \pi^-$ (a) and $V \to e^+ + e^-$ in the vector meson dominance model.

Fig. 2 Experimental values of $F_\pi(E)$ approximated by the Breit-Wigner formula (V.L. Auslander et al. Novo Sibirsk).

Fig. 3 Total cross section for the reaction $\gamma + p \to p + \rho^o$ as a function of the photon energy E_γ. The different points were obtained by three fitting methods as indicated in the figure. [44, 51]

Fig. 4 Total cross section for $\gamma p \to p\omega$ as a function of the photon energy. [51]

Fig. 5 Total cross section for $\gamma p \to p\Phi$ as a function of the photon energy. [51]

Fig. 6 Differential cross section for $\gamma + p \to p + \rho$. [51]

Fig. 7 Differential cross section for $\gamma + p \to p + \omega$. [51]

Fig. 8 Differential cross section for $\gamma + p \to p + \Phi$. [51]

Fig. 9 Dependence of the forward production cross section of ρ^o on complex nuclei $A^{-1} \frac{d\sigma}{d\Omega}$ upon A, the atomic number of the target nucleus. Results are shown for average ρ^o momentum $p = 2.7$, 3.5, 4.5 GeV/c. The curves are best fits to the model of Drell and Trefil [59]. The data are normalized to 1 for Beryllium. [58]

Fig. 10 Total cross section for the reaction $\gamma p \to p\pi^+\pi^+\pi^-\pi^-$. [51], [81]

Fig. 11 Reaction $\gamma + p \to \pi^o + p$. Excitation curve at 90°. (ours = [93]. Berends [90], experimental data [82-85].

Fig. 12 Reaction $\gamma + p \to \pi^o + p$. Differential cross section at $E_\gamma = 300$ MeV. (ours = [93], Berends [90], experimental data [82-85].

Fig. 13 Reaction $\gamma + p \to \pi^o + p$. Differential cross section near threshold at $E_\gamma = 180$ MeV. (ours = [93], Berends [90], experimental data [82].

Fig. 14 Reaction $\gamma + p \to \pi^o + p$. Differential cross section at 180° as function of energy E_γ [98].

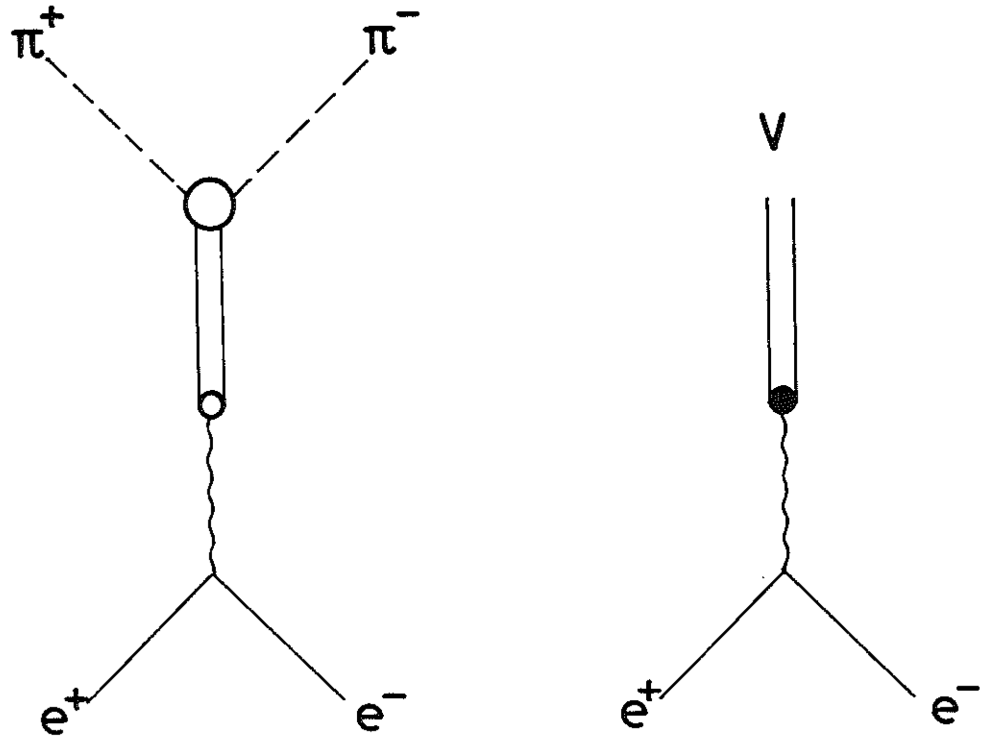
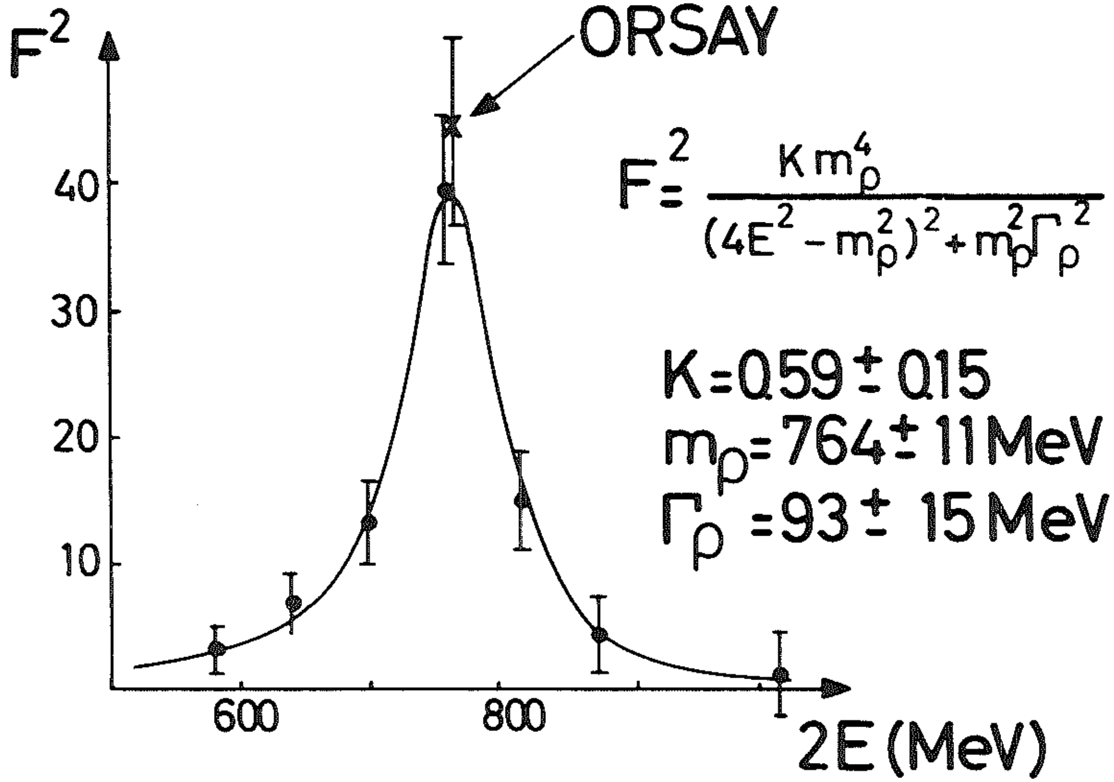


Fig.1a Fig.1b

Fig.1



Experimental values of F (E) approximated by the Breit-Wigner formula. (V.L. Auslander et.al. Novosibirsk)

Fig. 2

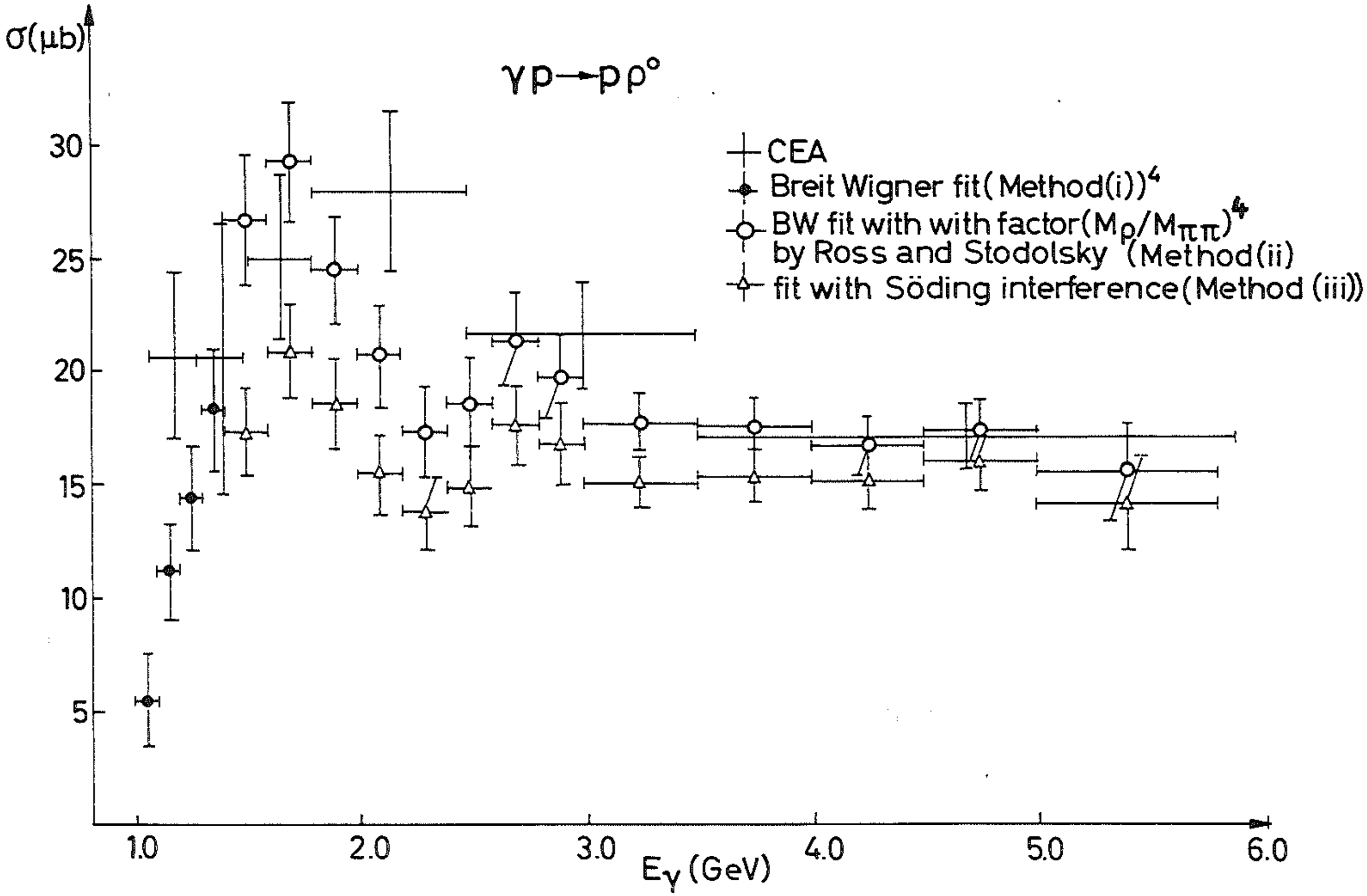

σ(μb)
γp → pρ°
CEA
Breit Wigner fit (Method(i))4
BW fit with with factor(Mρ/Mππ)4
by Ross and Stodolsky (Method(ii)
fit with Söding interference (Method (iii))
30
25
20
15
10
5
1.0
2.0
3.0
4.0
5.0
6.0
Eγ (GeV)

Fig.3

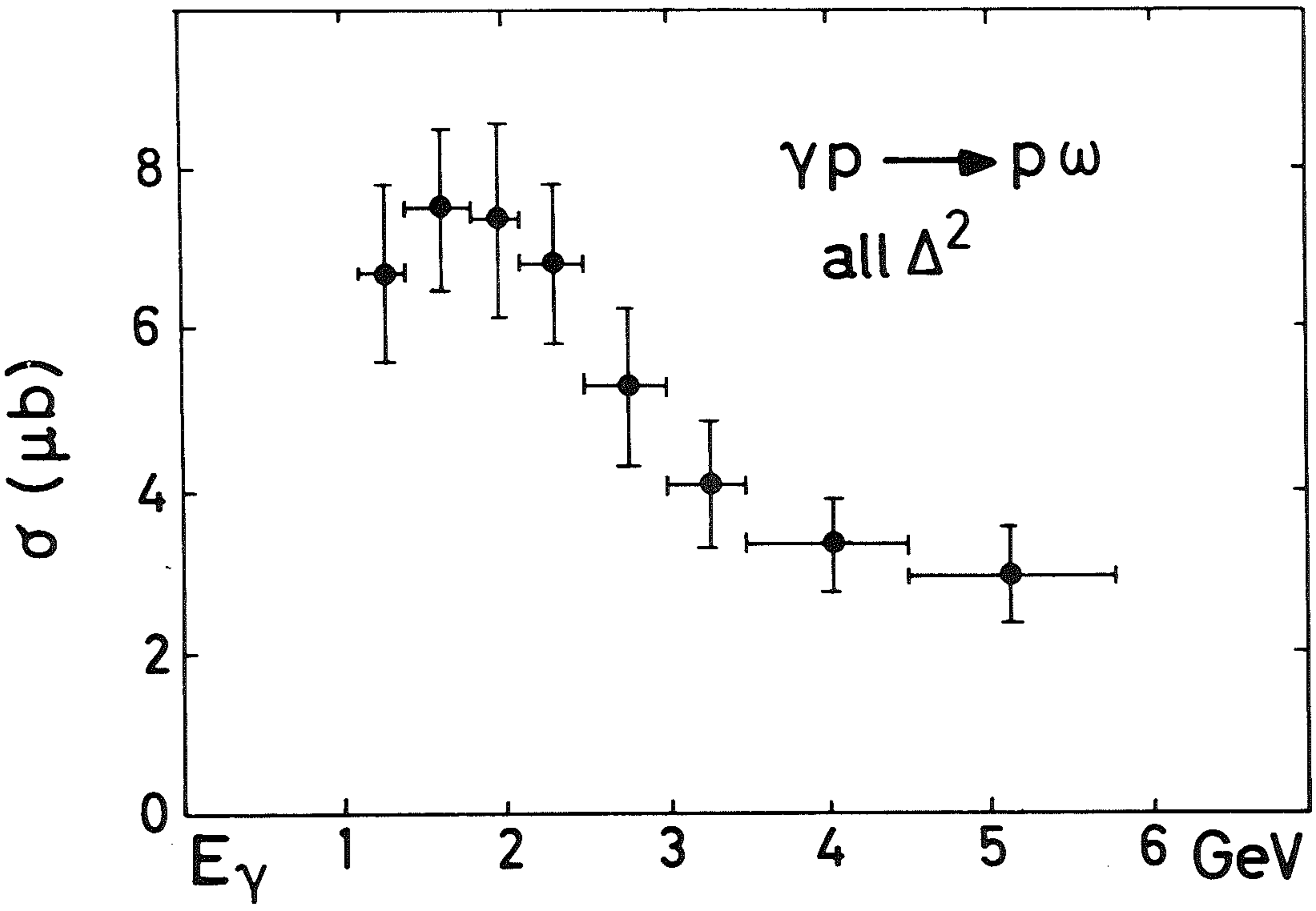


Fig.4

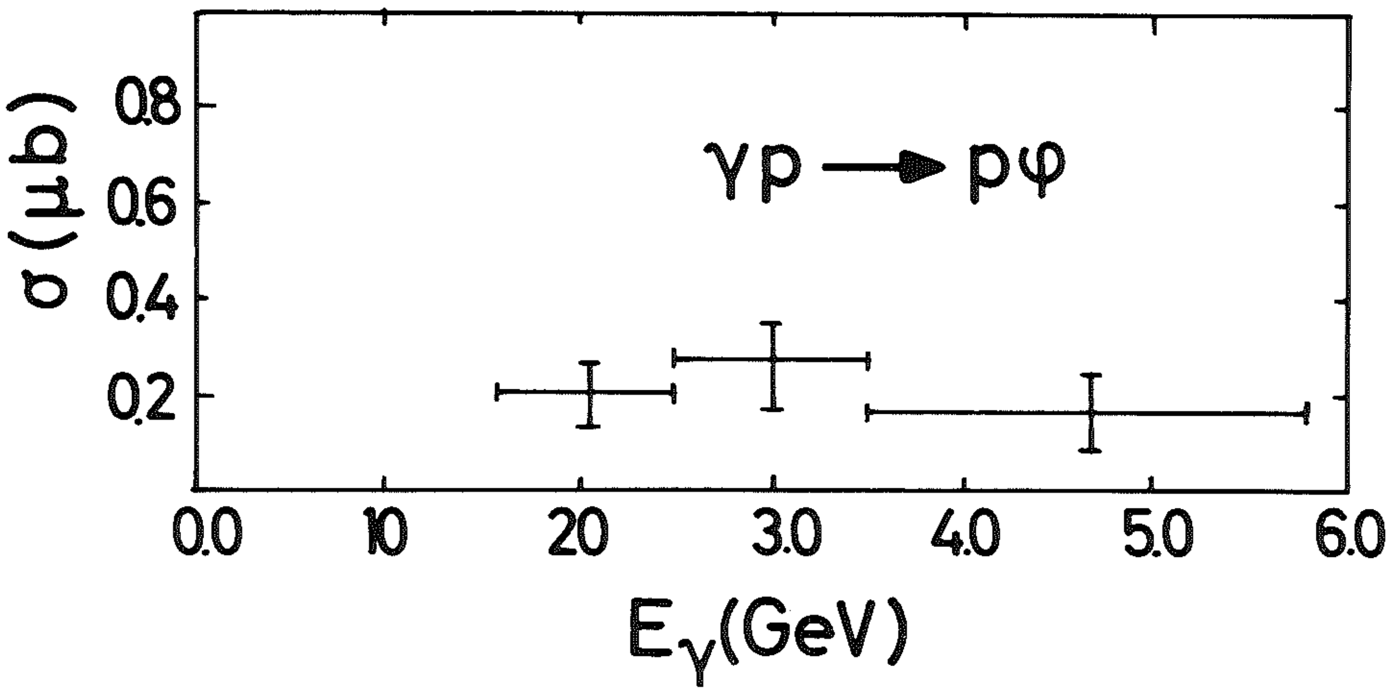


Fig.5

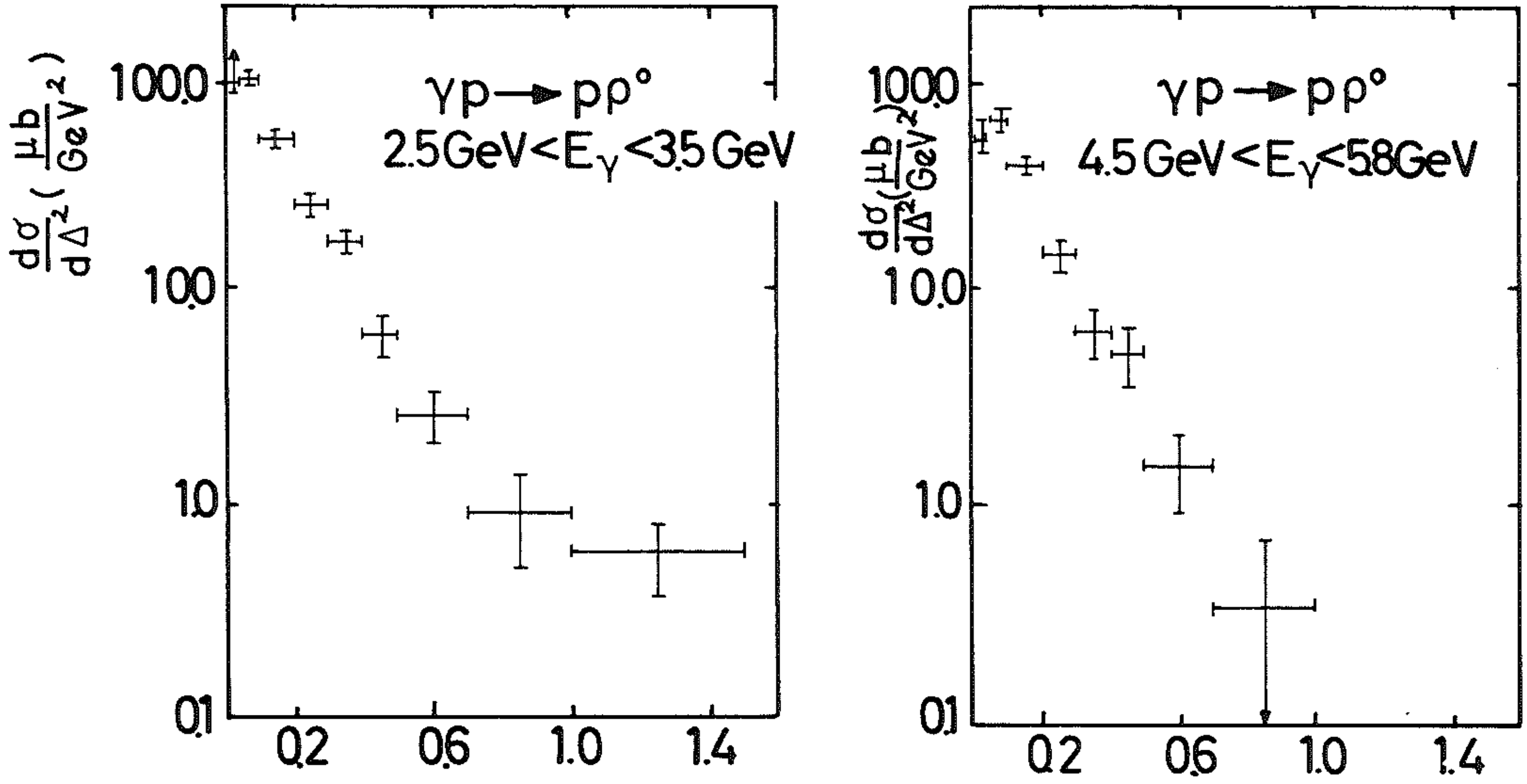

γp → pρ°
2.5GeV<Eγ<3.5GeV
γp → pρ°
4.5GeV<Eγ<5.8GeV
dσ/dΔ² (μb/GeV²)
100.0
10.0
1.0
0.1
0.2
0.6
1.0
1.4

Fig.6

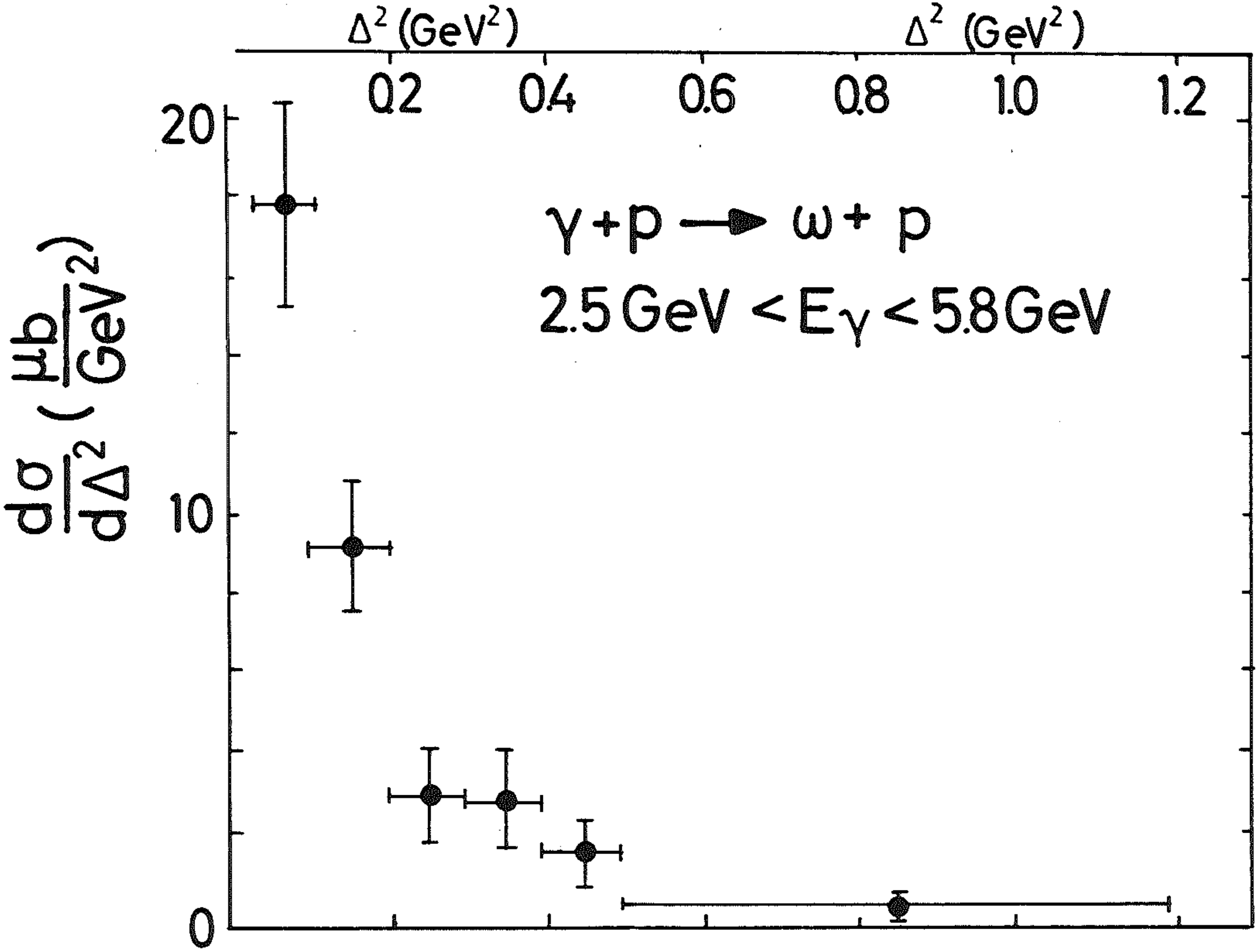

Δ² (GeV²)
Δ² (GeV²)
0.2
0.4
0.6
0.8
1.0
1.2
20
10
0
dσ/dΔ² (μb/GeV²)
γ + p ⟶ ω + p
2.5 GeV < Eγ < 5.8 GeV

Fig.7

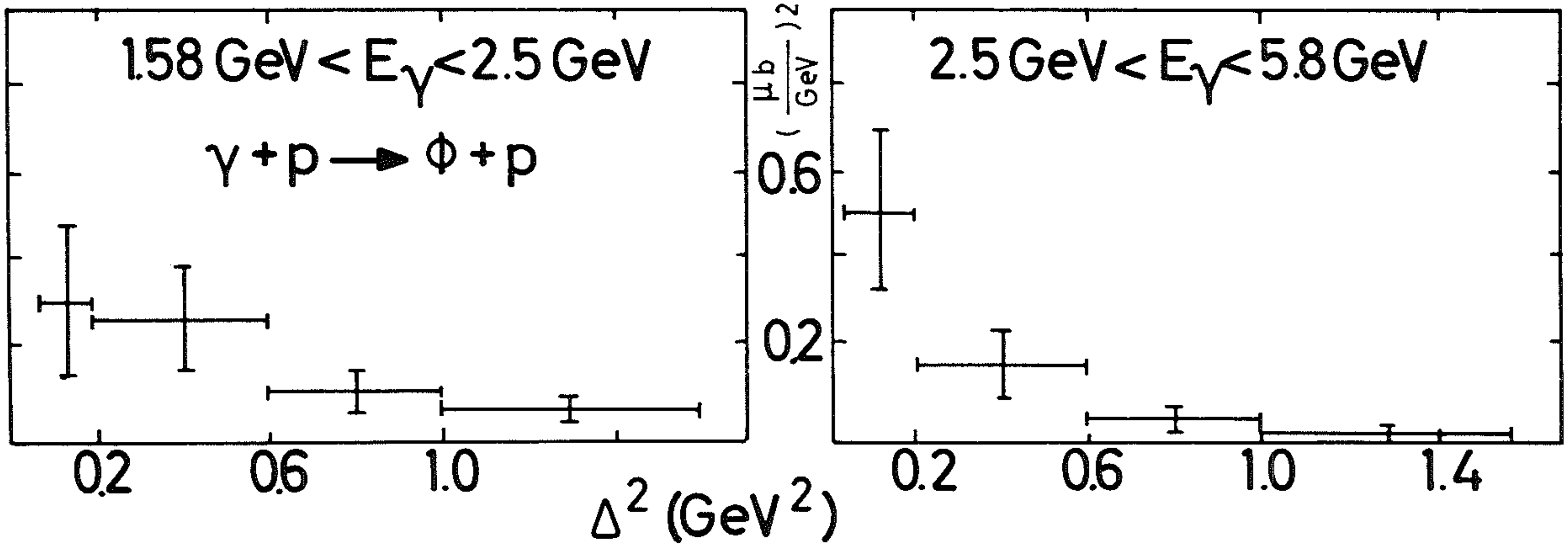

1.58 GeV < Eγ < 2.5 GeV
γ + p → Φ + p
2.5 GeV < Eγ < 5.8 GeV
(μb/GeV)2
0.6
0.2
0.2
0.6
1.0
0.2
0.6
1.0
1.4
Δ2 (GeV2)

Fig. 8

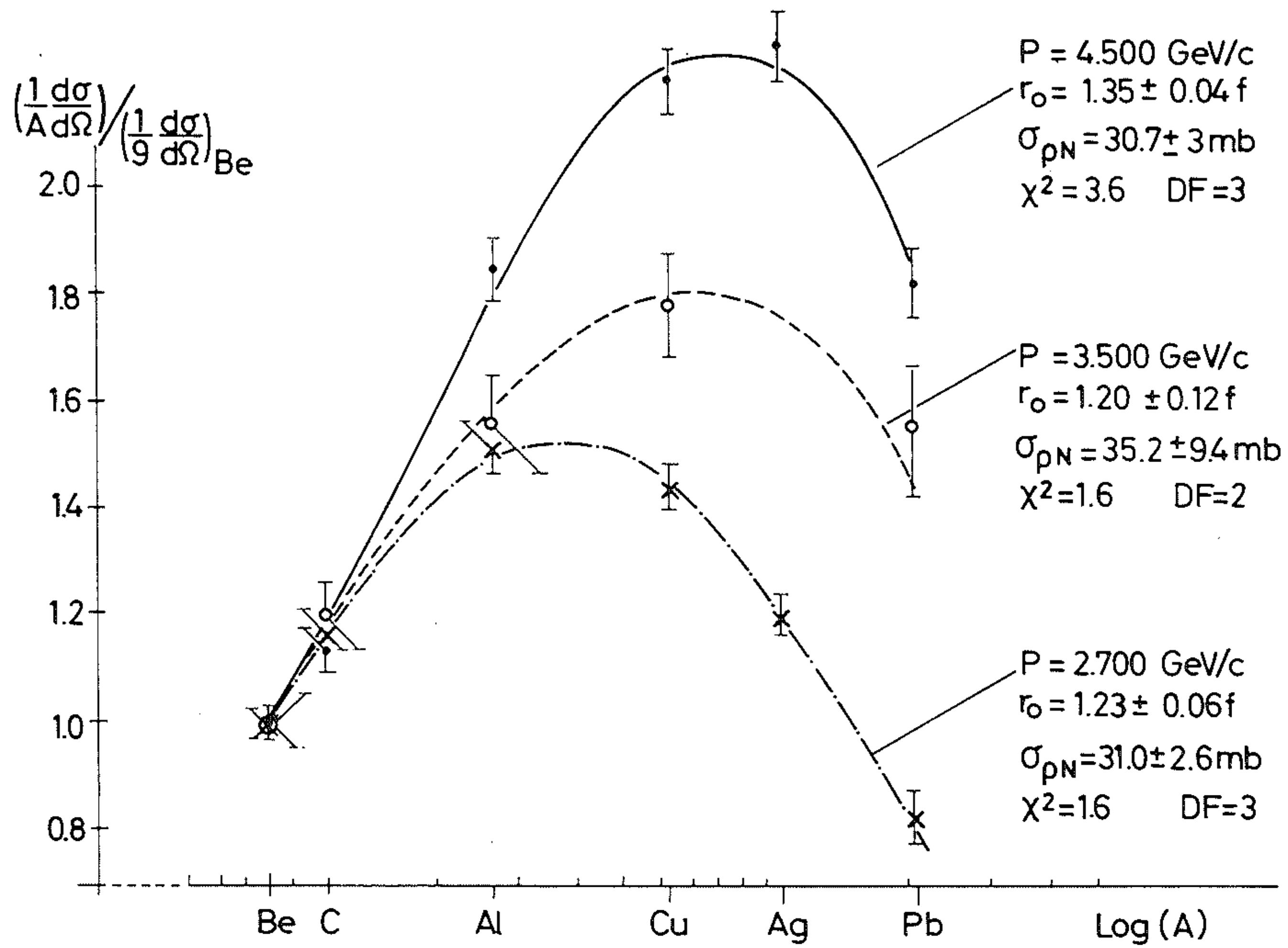

$\left(\frac{1}{A}\frac{d\sigma}{d\Omega}\right) / \left(\frac{1}{9}\frac{d\sigma}{d\Omega}\right)_{Be}$
2.0
1.8
1.6
1.4
1.2
1.0
0.8
Be
C
Al
Cu
Ag
Pb
Log (A)
P = 4.500 GeV/c
r_o = 1.35 ± 0.04 f
$\sigma_{\rho N}$ = 30.7 ± 3 mb
χ^2 = 3.6 DF = 3
P = 3.500 GeV/c
r_o = 1.20 ± 0.12 f
$\sigma_{\rho N}$ = 35.2 ± 9.4 mb
χ^2 = 1.6 DF = 2
P = 2.700 GeV/c
r_o = 1.23 ± 0.06 f
$\sigma_{\rho N}$ = 31.0 ± 2.6 mb
χ^2 = 1.6 DF = 3

Fig.9

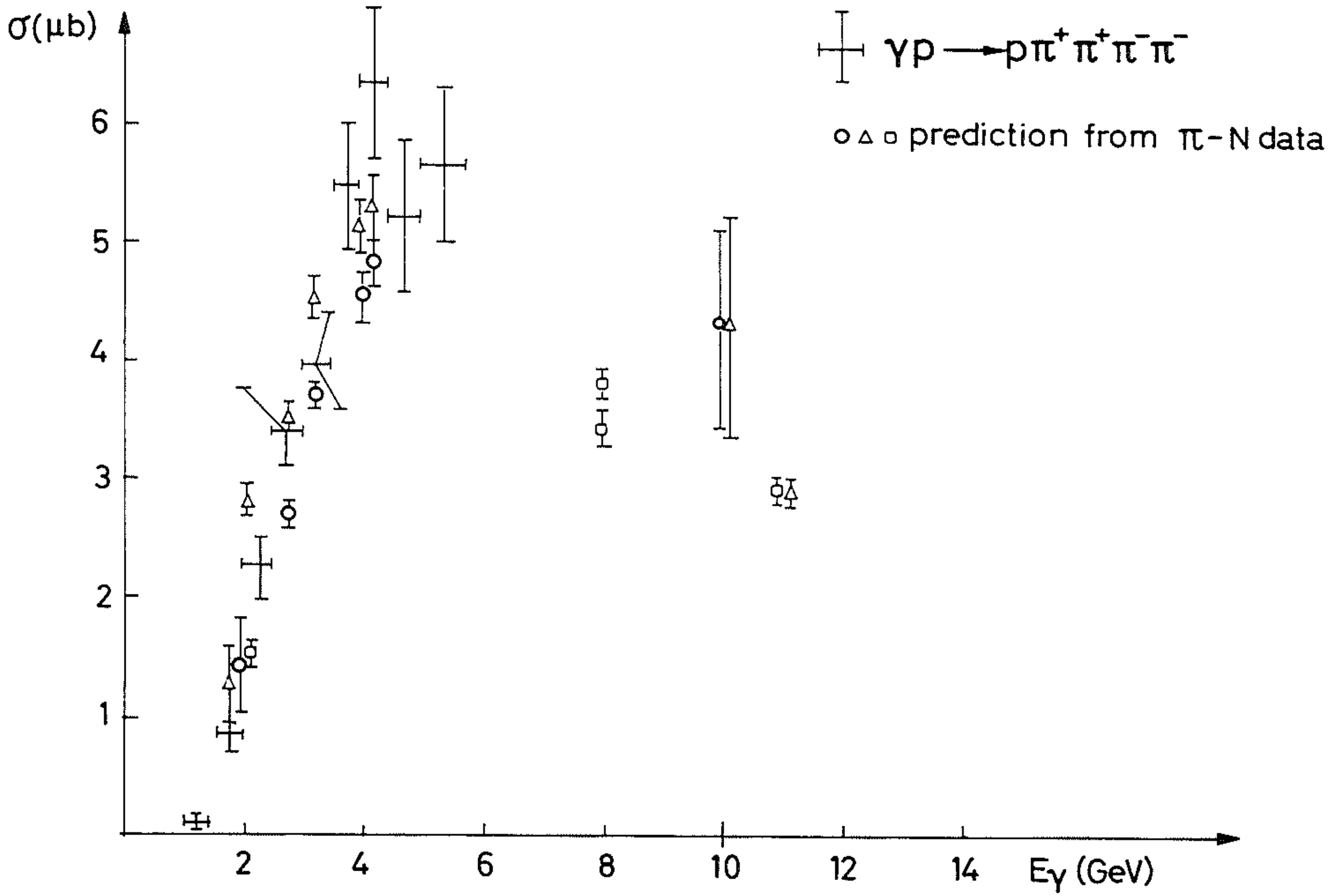

σ(μb)
6
5
4
3
2
1
2
4
6
8
10
12
14
Eγ (GeV)
γp ⟶ pπ⁺π⁺π⁻π⁻
o △ □ prediction from π-N data

Fig.10

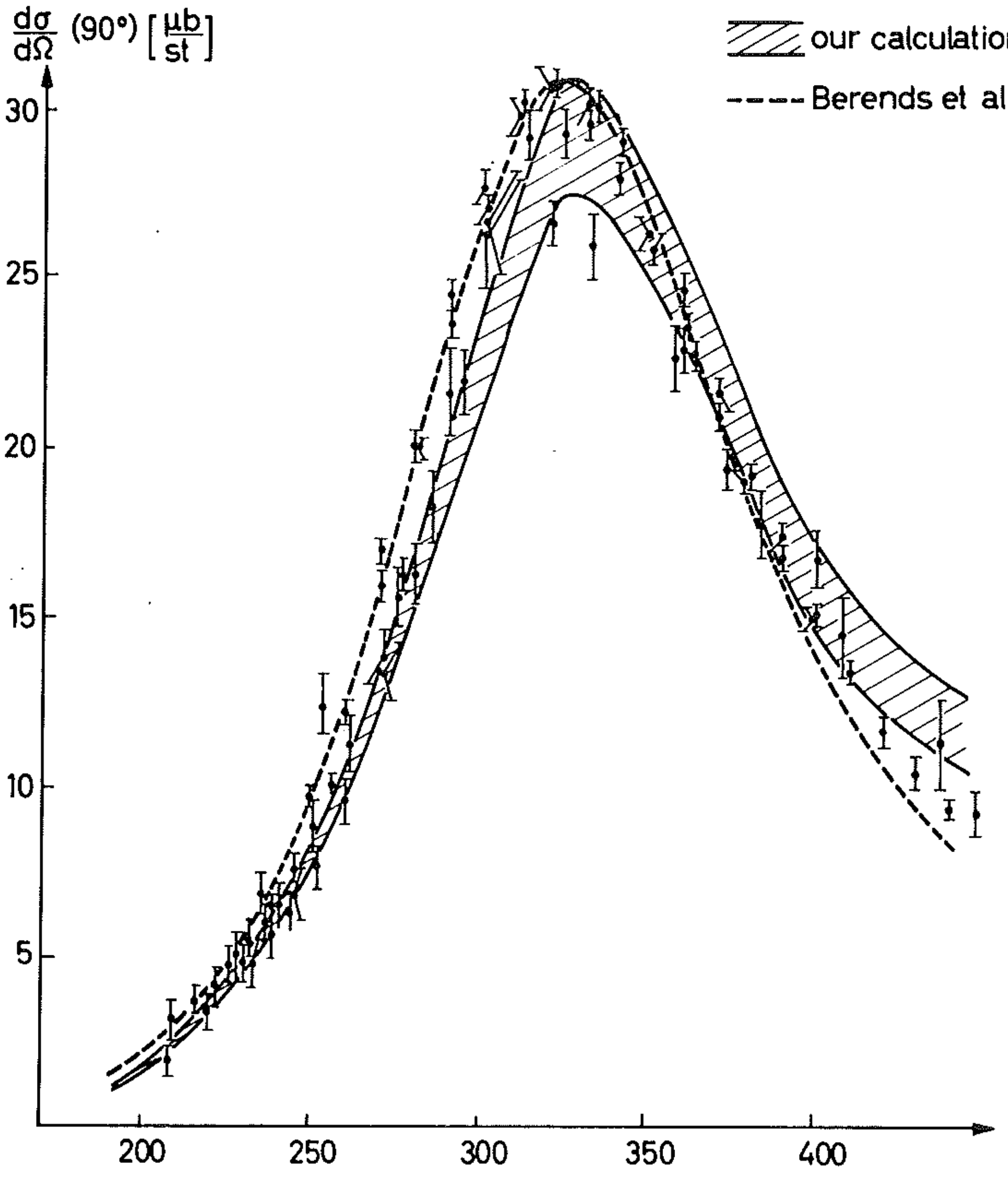
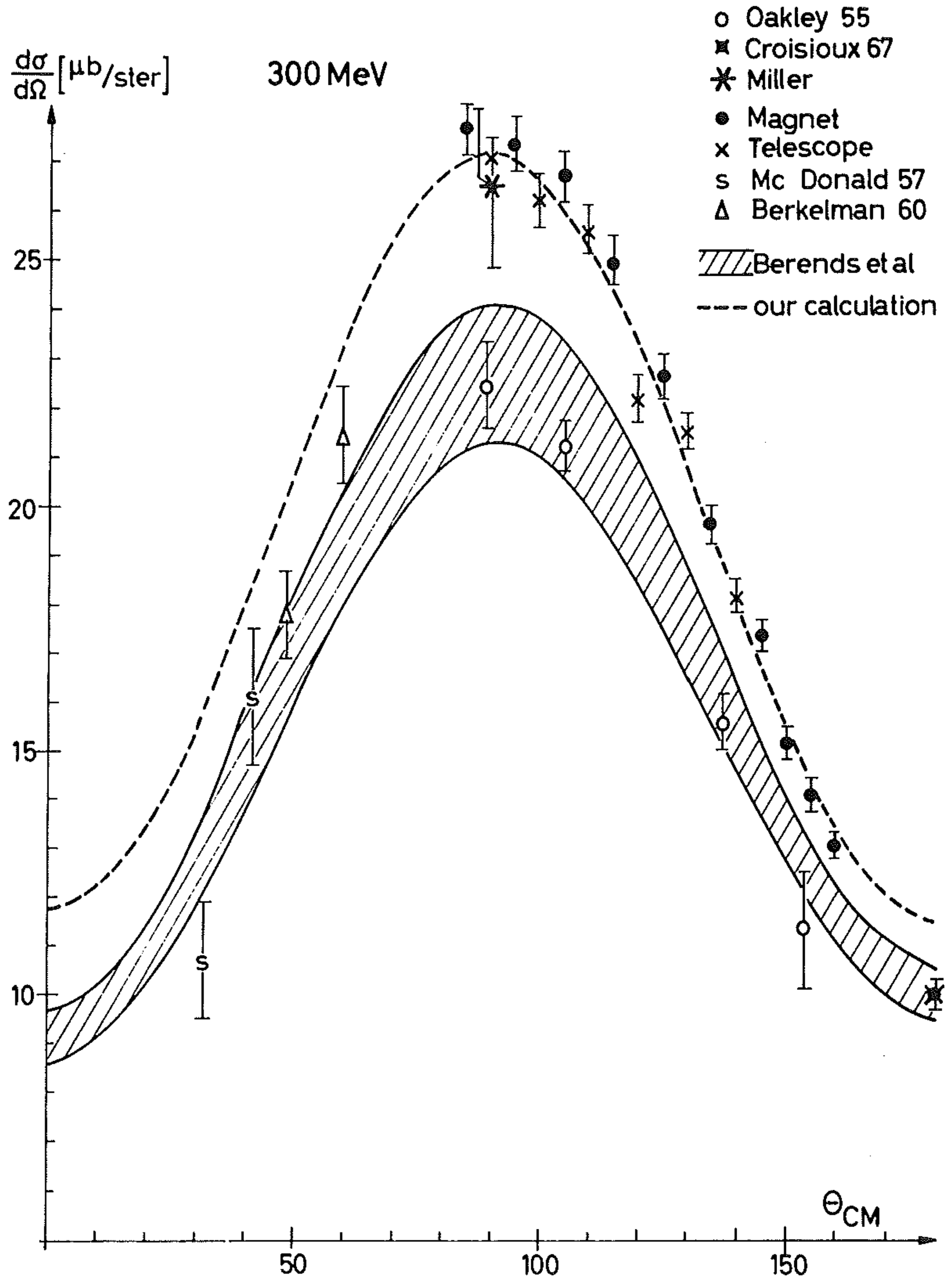

dσ/dΩ (90°) [μb/st]
our calculation
Berends et al.
30
25
20
15
10
5
200
250
300
350
400

Fig.11



dσ/dΩ [μb/ster]
300 MeV
o Oakley 55
Croisioux 67
Miller
Magnet
x Telescope
s Mc Donald 57
Δ Berkelman 60
Berends et al
--- our calculation
25
20
15
10
50
100
150
Θ_CM

Fig.12

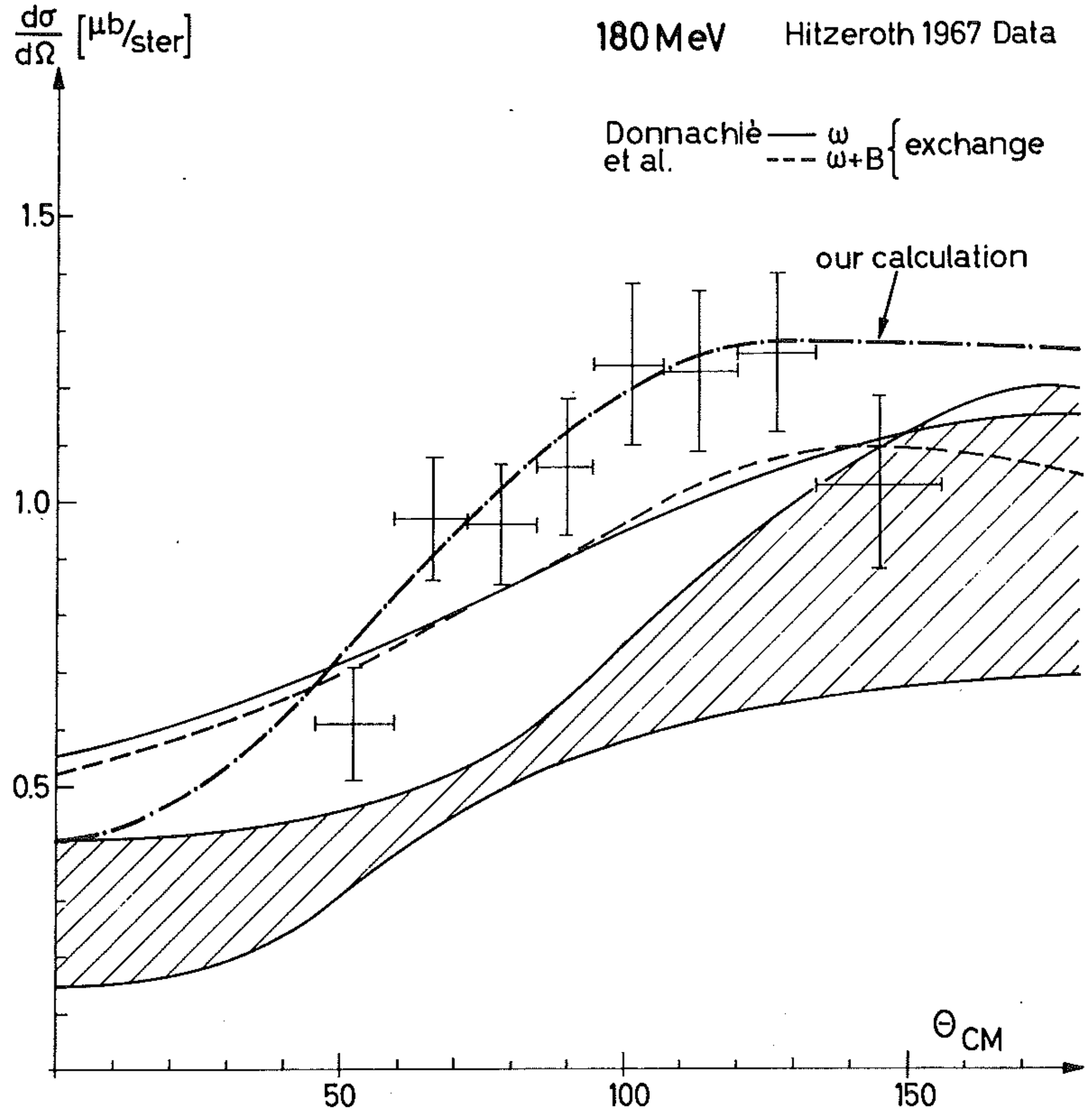

dσ/dΩ [μb/ster]
180 MeV
Hitzeroth 1967 Data
Donnachie et al.
ω
ω+B
exchange
our calculation
1.5
1.0
0.5
Θ CM
50
100
150

Fig. 13

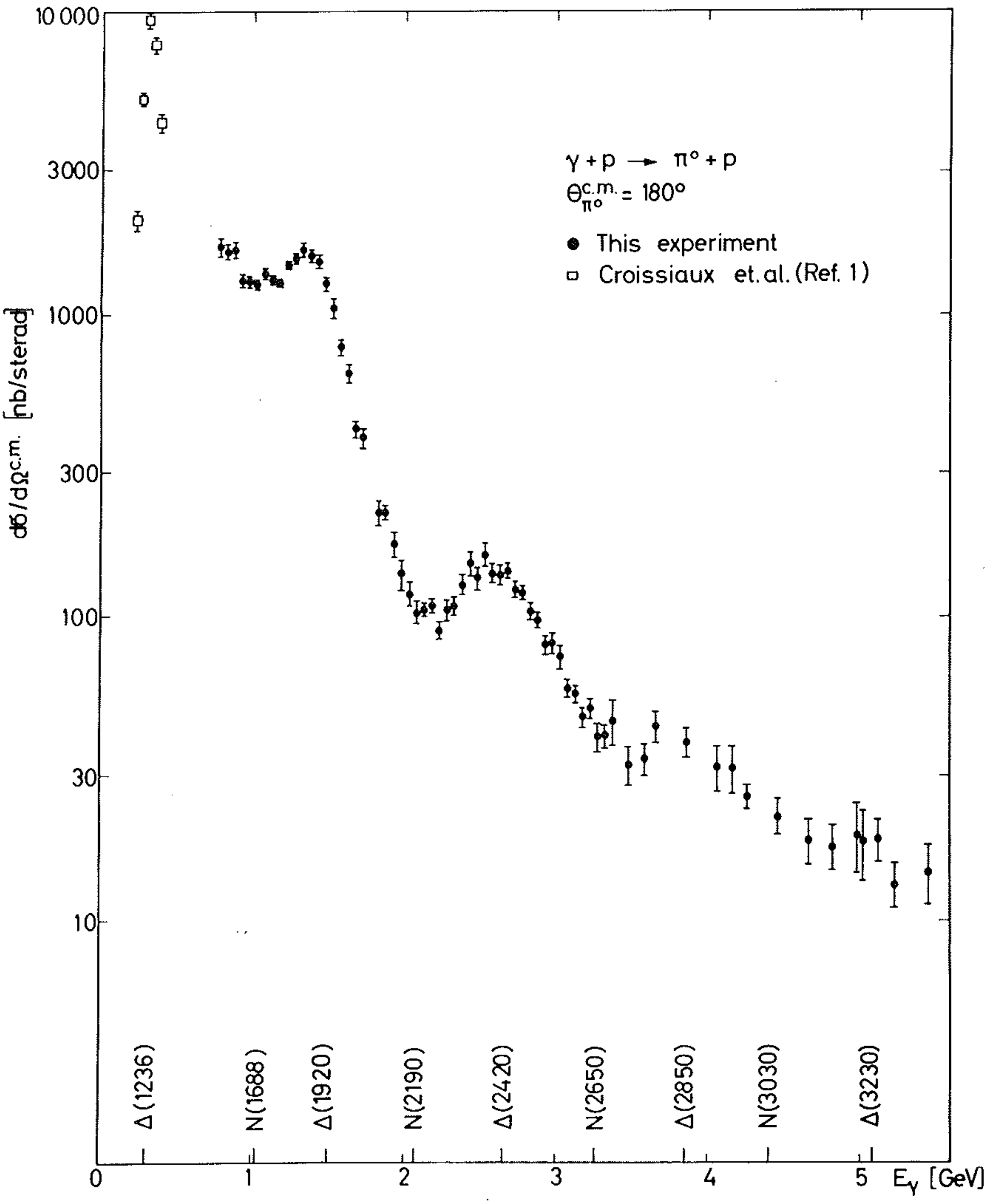

10 000
3000
1000
300
100
30
10
dσ/dΩ^c.m. [nb/sterad]
γ + p → π° + p
Θ^c.m._π° = 180°
● This experiment
□ Croissiaux et.al.(Ref. 1)
Δ(1236)
N(1688)
Δ(1920)
N(2190)
Δ(2420)
N(2650)
Δ(2850)
N(3030)
Δ(3230)
0
1
2
3
4
5
E_γ [GeV]

Fig.14

Decay	$B(\times 10^5)$	Production Reaction	Reference
$\rho^o \to \mu^+ + \mu^-$	5.9 ± 1.5	$\gamma + C \to \rho^o + C$	[30]
$\rho^o \to \mu^+ + \mu^-$	5.8 ± 1.2	$\pi^- + C, Fe \to \rho^o + ..$	[31]
$\rho^o \to \mu^+ + \mu^-$	$9.7 {}^{+2}_{-2.3}$	$\pi^- + LiH \to \rho^o + ..$	[32]
$\rho^o \to e^+ + e^-$	$5 {}^{+6}_{-3}$	$\pi^- + P \to \rho^o + n$	[33]
$\rho^o \to e^+ + e^-$	3.9 ± 1.2	$\pi^- + P \to \rho^o + n$	[34]
$\rho^o \to e^+ + e^-$	6.5 ± 1.4	$\gamma + C \to \rho^o + C$	[35]
$\phi \to e^+ + e^-$	< 200	$\pi^- + P \to \phi + n$	[36]

Table I. Leptonic Decays of Vector Mesons.

B_γ Interval (BeV)	Total Cross-Section (μb) $\gamma p \longrightarrow p\omega$
1.1 - 1.5	7.3 ± 1.6
1.5 - 1.8	6.3 ± 1.9
1.8 - 2.5	5.5 ± 1.0
2.5 - 6.0	3.2 ± 0.6

Table II. Total Cross-Section for the Reaction $\gamma p \to p\omega$ as Function of the Energy B_γ. [42]

$3.5 < E_\gamma < 5.5$ GeV $(2.5 < E_\gamma < 5.5)^*$GeV			ρ^o	ω	ϕ	
$\sigma_{diff}(\gamma + P \rightarrow V + P)$		1	17 ± 2	~ 1.3 (3 ± 0.5)	0.2 ± 0.1	μb
$\frac{d\sigma}{d\Delta^2}(\gamma + P \rightarrow V + P)$	A	2	140 ± 13	27.2 ± 3.8*	0.73 ± 0.21*	$\frac{\mu b}{GeV^2}$
	B	3	8 ± 0.5	7.5 ± 0.9*	3.35 ± 0.7*	GeV^{-2}
$\sigma_T(VP)$	exp.	4	30.7 ± 5.3		?!	mb
	Equ. (15)	5	28.1 ± 0.2	28.1 ± 0.2	11.5 ± 1.5	mb
$\sigma_{diff}(V + P \rightarrow V + P)$	exp.	6	6.1 ± 2		?!	mb
	Equ. (15)	7	5.1 ± 0.3	5.4 ± 0.4	2.2 ± 0.6	mb
$\frac{\gamma_V^2}{4\pi}$	$\gamma + P \rightarrow V + P$	8	0.65 ± 0.2	7.6 ± 3	~ 20	
	$V \rightarrow \ell^+ + \ell^-$	9	0.47 ± 0.12	?!	?!	

Table III. Data for a Check of the Diffraction Dissociation Model of the Reaction $\gamma + P \rightarrow V + P$.

REACTION $\gamma P \rightarrow$	PHOTON ENERGY 1GeV	2GeV	3GeV	4.5GeV	REFERENCES
$P\pi^{o}$	24	4.7	1.5	0.6	66, 67, 68, 70
$n\pi^{+}$	50	5	2.2	1.0	66, 68, 69, 71, 72
$P\rho^{o}$	-	20	17	17	41, 43, 48, 51
$P\omega$	-	7	4	3	42, 47, 51
$P\phi$	-	~ 0.2	~0.3	~0.2	51
$P\eta$	6	<1	<1	<0.2	47, 51, 74, 75, 76
$PX^{o}(959)$	-	~0.7	~0.2	~0.2	47, 51
Pf^{o}	-	-	~0.9	~0.3	48, 51
$\Delta^{++}(1238)\pi^{-}$	48	8	4	2	46, 51, 73, 77, 78
$\Delta^{o}\pi^{+}$	2				51, 73
$\Delta^{++}\rho^{o}$		~4	~2	~1	48, 51, 73
ΛK^{+}	2	~1	~0.5	~0.25	49, 69, 79, 80
$\Sigma^{o}K^{+}$	-	~ 0.6	~ 0.2	~0.1	49, 69
$\Sigma^{+}K^{o}$	-	<0.2	<0.2	<0.2	49
$Y^{*o}(1385)K^{+}$	-	~ 0.5		~ 0.2	49
$Y^{*+}(1385)K^{o}$	-	~ 0.4		~ 0.1	49

Table IV. Photoproduction cross sections in μb.

	$\mu[e/2m_p]$ experimental	$\mu[e/2m_p]$ theory	Reference
N(938) p	2.79		Rosenfeld Jan.67.
N(938) n	-1.91		
$\Sigma^+(1189)$	2.2 ± 1		[105]
	3.5 ± 1.2	2.79	[106]
	2.6 ± 0.6		world average
$\Lambda(1115)$	-0.73 ± 0.16	-0.95	Rosenfeld Jan.67.
$\langle N\|\mu\|\Delta(1236)\rangle$	3.67 ± 0.08	2.63	[100]

Table V. Magnetic Moments of Baryons.