DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY

DESY 74/50
November 1974

Is Vector Dominance Still Alive?

by

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Is Vector Dominance still Alive?[+]

by

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[+]Lecture presented at the International School of Subnuclear Physics, Erice, Sicily, July 1974.

IS VECTOR DOMINANCE STILL ALIVE?

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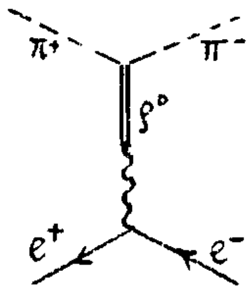
When the director of this famous summer school invited me to this beautiful site to give a talk, I suggested "Recent Developments in Generalized Vector Dominance". But Professor Zichichi translated into "Is Vector Dominance still Alive?". Thus I will attempt to convince you that the subject is alive by describing to you some new results recently obtained within the framework of what we called "Off-Diagonal Generalized Vector Dominance". At the end of my talk I might explicitly come back to the question posed by the title of this lecture.

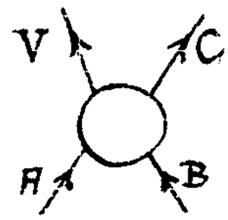
1. ρ^0, ω, ϕ DOMINANCE AND HADRONLIKE BEHAVIOUR OF THE PHOTON

Let me begin by briefly reminding you of the basic ingredients of ρ^0, ω, ϕ dominance [1] as a convenient starting point for the ensuing discussion of Generalized Vector Dominance.

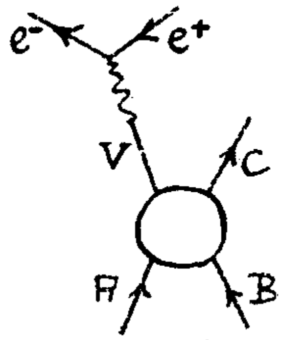
As has been well known for about seven years, e^+e^- annihilation below 1.1 GeV c.m. energy is dominated by production of the vector mesons ρ^0, ω and ϕ. Photons of the correct mass can thus make transitions into vector mesons. Conversely, to every hadronic



interaction containing a vector meson V, say A + B $\rightarrow$ V + C(I), there exists a corresponding reaction A + B $\rightarrow e^+e^-$ + C(II), in which the vector meson is replaced by an e^+e^- pair. The e^+e^- pair appears as a strong maximum in the vicinity of the mass of the vector meson V, which maximum may be described by a Breit Wigner formula or a pole at the mass m_V of the vector meson V in the zero width approximation. What we are interested in now is, what happens, if the timelike virtual photon of mass squared $q^2 = -m_V^2$ in reaction (II)

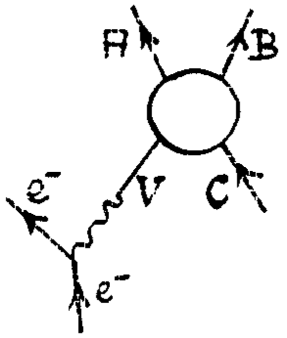


A + B $\rightarrow$ V + C (I)



A + B $\rightarrow e^+e^-$ + C (II)

(or rather in the time reversed reaction e^+e^- + C $\rightarrow$ A + B) is replaced by a real or a spacelike one with four momentum squared $q^2 \gtrless 0$ (reaction III)



$\gamma(q^2 \geqq 0)$ + C $\rightarrow$ A + B (III)

Let us first look at the transverse helicity amplitude for $\gamma(q^2 \geq 0)$ + C $\rightarrow$ A + B. Assuming that the photon interacts exclusively via the vector mesons ρ^0, ω, ϕ with the hadronic target (saturation of the electromagnetic current by the ρ^0, ω, ϕ fields) and moreover that the q^2 dependence is solely given by the vector meson poles (smoothness), we arrive at the well known basic relation of ρ^0, ω, ϕ dominance

$$f^{\lambda=\pm 1}(\gamma A\to)_{q^2\geq 0} = \sum_{V=\rho^0,\omega,\phi} \sqrt{\frac{\alpha\pi}{\gamma_V^2}}\, \frac{1}{\left(1+\frac{q^2}{m_V^2}\right)}\, f^{\lambda=\pm 1}(VA\to B)_{q^2=-m_V^2}\,, \qquad (1)$$

which connects the transverse helicity amplitudes for photon induced processes with the ones for their hadronic counterparts. For the longitudinal amplitude current conservation has to be taken into account in addition when requiring smoothness, leading to

$$f^{\lambda=0}(\gamma A\to B)_{q^2\geq 0} = \sum_{V=\rho^0,\omega,\phi} \sqrt{\frac{\alpha\pi}{\gamma_V^2}}\sqrt{\frac{q^2}{m_V^2}}\, \frac{1}{\left(1+\frac{q^2}{m_V^2}\right)}\, f^{\lambda=0}(VA\to B)_{q^2=-m_V^2}\,, \qquad (2)$$

where the factor $\sqrt{q^2/m_V^2}$ assures vanishing of the photon amplitude for $q^2 \rightarrow 0$. The dominant part in (1) and (2) is the ρ^0 contribution, as according to the quark model $\gamma_\rho^{-2} : \gamma_\omega^{-2} : \gamma_\phi^{-2} = 9:1:2$, which relation is roughly consistent with experiment.

Equations (1) and (2) imply that the same features should be observed experimentally as a function of the kinematic variables in photon induced reactions as are found to be present in hadron hadron interactions, more precisely, in vector meson induced hadron reactions. Photons should show hadronlike behaviour at high energies, i.e. for c.m. energies squared $W^2 \gg q^2$.

First of all, for real photons ($q^2 = 0$) hadronlike behaviour has been well established. In fact, ten years of photon hadron physics in the multi GeV energy range may be summarized by stating that photons do behave hadronlike. As it is the primary aim of this lecture to discuss deep inelastic scattering within the framework of vector dominance, a detailed discussion of the experimental evidence for hadronlike behaviour [1] cannot be given here. Let me just remind you that it has become standard terminology to subdivide photon induced reactions into "elastic"

$$\gamma N \to \rho^0(\omega, \phi) N \qquad\qquad \rho^0(\omega, \phi) N \to \rho^0(\omega, \phi) N$$

and "inelastic" ones

$$\gamma N \to \pi N, \pi \Delta \qquad\qquad \pi N \to \rho^0 N, \rho^0 \Delta$$

in order to stress the strong similarity between these reactions and their hadronic counterparts. Real photons also show shadowing [2] in their reactions with complex nuclei as a further characteristic feature for hadronlike behaviour. Qualitatively and semiquantitatively $q^2 = 0$ photon induced reactions may thus be understood on the basis of ρ^0, ω, ϕ dominance as formulated in (1) and (2).

For virtual spacelike photons ($q^2 > 0$), single exclusive channels like ρ^0 and ω, ϕ production are in at least semiquantitative agreement with the predictions from (1) and (2). For the most recent detailed discussion of the empirical evidence for hadronlike behaviour for real and virtual photons let me refer to Sakurai's 1973 Erice lecture [3].

As is well known by now to everyone in the audience, I suppose, simple ρ^0, ω, ϕ dominance is completely inadequate as soon as we look at the q^2 dependence of the total photoabsorption cross section from nucleons, or equivalently, the nucleon structure functions W_1 and νW_2. Keeping in mind the fruitfulness of the concepts of vector dominance and hadronlike behaviour on the qualitative and semiquantitative level for $q^2 \approx 0$, it appears as a fundamental question whether these notions, perhaps in appropriate generalization, are also relevant and useful in the large q^2 scaling region as explored in deep inelastic electron scattering.

Some insight into the role of vector mesons in the scaling region of deep inelastic scattering may most simply be obtained [4] by looking at the ρ^0 induced part of the total photoabsorption cross section on protons for moderately large $q^2 \gtrsim 1$ GeV^2, where nevertheless the precocious scaling behaviour of the structure function νW_2 has set in. The ρ^0 induced part of the transverse photoabsorption cross section σ_T is given by

$$\sigma_T^{\rho^0\,\mathrm{induced}}(W,q^2) = \frac{1}{(1+q^2/m_\rho^2)^2}\,\frac{\alpha\pi}{\gamma_\rho^2}\,\sigma_{\rho^0 p}(W)$$
$$= \frac{16\pi}{(1+q^2/m_\rho^2)^2}\sqrt{\frac{\alpha\pi}{\gamma_\rho^2}}\left(\frac{d\sigma}{dt}^{t=0}(\gamma_{\mathrm{real}}\,p\to\rho^0 p)\right)^{\frac{1}{2}} \tag{3}$$
$$= \frac{16\pi}{\sigma_{\rho^0 p}}\,\frac{d\sigma}{dt}^{t=0}(\gamma_{\mathrm{virt.}}\,p\to\rho^0 p).$$

At $q^2 = 0$, in photoproduction, the ρ^0 induced part of the cross section amounts to about 66 %, as obtained [5] from the measured [6] coupling $\gamma_\rho^2/4\pi = 0.64 \pm 0.06$ and the measured[7] ρ^0 photoproduction cross section. The fall off with the ρ^0 propagator squared of $\sigma_T^{\rho^0\,\mathrm{induced}}$ is supported by the experimental results [8] on ρ^0 electroproduction. The role of ρ^0, ω, ϕ in deep inelastic ep scattering is best seen by looking at the transverse part of the proton structure function νW_{2T}

$$\nu W_{2T}(\omega, q^2) = \frac{\omega(\omega-1)\cdot q^2}{4\pi^2\alpha(\omega^2+4M^2/q^2)}\,\sigma_T(W,q^2) \tag{4}$$

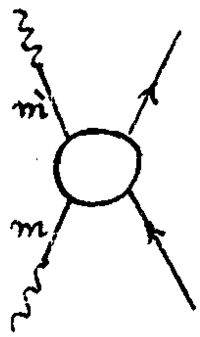
at fixed ω(or rather $\omega' \equiv W^2/q^2 + 1 = \omega + M^2/q^2$)as a function of q^2 in the large ω region, where vector dominance considerations are most likely to be relevant. The data on fig. 1 nicely show the precocious onset of scaling, which goes away completely, however, as soon as the ρ^0, ω, ϕ induced parts of νW_2 are subtracted. On fig. 1, we have also indicated, what happens [4], if besides ρ^0, ω, ϕ a realistic $\rho'(1600)$ contribution is subtracted. Due to the higher mass of the ρ' meson, the fall-off with q^2 of the ρ' contribution to σ_T is considerably slower. Although at $q^2 = 0$ the ρ' contribution is only about 1/8 of the ρ^0 contribution, ρ^0 and ρ' become comparable as soon as q^2 is equal to about $q^2 \approx 2$ to 3 GeV^2. The lesson learnt from fig. 1 apparently is that the low lying vector mesons form an integral part of the scaling phenomenon. Even though the ρ^0, ω, ϕ contributions to νW_2 taken by themselves alone would clearly give rise to a nonscaling structure function, which would rapidly tend to zero at fixed ω for large q^2, these contributions are nevertheless essential for the early onset of scaling. This observation may suggest building up the virtual Compton forward amplitude in terms of vector state forward scattering, including all hadronic 1^- states produced in e^+e^- annihilation. Thus we are rather naturally led to Generalized Vector Dominance (GVD). Moreover, if scaling is explained alternatively in terms of unobservable pointlike constituents, such a description (from fig. 1) should apparently be viewed as being in some sense dual to an approach based on observable hadronic vector states.

2. GENERALIZED VECTOR DOMINANCE: THE DIAGONAL MODEL AND ITS PROBLEMS

Motivated by the qualitative and semiquantitative success of ρ^0, ω, ϕ dominance for $q^2 \cong 0$, let us keep the point of view that the q^2 dependence observed in deep inelastic electron scattering is due to the propagation of vector states. Thus in Generalized Vector Dominance [5,9,10] we start from a representation for the imaginary part of the transverse virtual forward Compton amplitude, or rather for σ_T, of the form

$$\sigma_T(W,q^2) = \int \frac{m^2 \tilde{\rho}(W,m^2,m'^2) m'^2}{(q^2+m^2)(q^2+m'^2)} dm^2 dm'^2 . \qquad (5)$$

The spectral weight function $\rho(W,m^2,m'^2)$ contains the product of the coupling of the photon to the vector state of mass m and the imaginary part of the forward amplitude for vector state nucleon scattering $V(m)N \rightarrow V(m')N$. Besides ρ^0, ω, ϕ more massive contributions



are taken into account in the integral (5), which contributions, due to their higher mass, as discussed in chapter 1, become increasingly important with increasing spacelike q^2. Well known qualitative lifetime arguments [11] based on the uncertainty principle, suggest that (5) (together with the mentioned interpretation of the spectral weight function ρ) should hold best for values of the photon energy ν and of q^2 fulfilling

$$\frac{2\nu}{(q^2+m_V^2)} \gtrsim 2R , \qquad (6)$$

R being the radius of the nucleon $R \sim 1/m_\pi$. Relation (6) implies large values of $\omega = 2M\nu/q^2$ or $\omega' = \omega + M^2/q^2$, which characterize the kinematic region where Pomeron exchange is presumably dominant in the forward Compton amplitude.

It is an immediate consequence of the GVD picture that the final states of e^+e^- annihilation should also appear diffractively produced in ep scattering at any fixed q^2, if only the center of mass energy W is sufficiently large such that ω' is large, say $\omega' \gg 10$ or even $\omega' \gg 50$. A comparison of the final state in e^+e^- annihilation with diffractive vector state production, e.g. by measuring the spectrum of massive e^+e^- pairs produced by real or virtual spacelike photons on nucleons in the forward direction in the 100 GeV energy range, thus allows a rather detailed test of the GVD approach as regards qualitative and quantitative features.

The quantitative model [5,9] for electron nucleon scattering developed by Sakurai and myself more than two years ago (and also the model of ref. 12 described by Greco at this school) is based on the diagonal approximation of (5). Motivated mainly by the experimental observation that hadronic diffraction dissociation amplitudes are smaller than elastic ones, (5) is simplified by neglecting off-diagonal transitions in the masses of the vector states, i.e. by writing

$$\tilde{\rho}(W, m^2, m'^2) = \rho(W, m^2)\,\delta(m^2 - m'^2). \tag{7}$$

The representation for σ_T then reads

$$\sigma_T(W, q^2) = \int \frac{m^4 \rho(W, m^2)}{(q^2 + m^2)^2}\, dm^2. \tag{8}$$

The ρ^0, ω, ϕ contribution to the spectral weight function in (8) is known from e^+e^- annihilation (couplings $\gamma_V^2/4\pi$) and vector meson photoproduction and is simply given by

$$\begin{aligned} \rho(W, m^2)^{\rho^0, \omega, \phi} &= \sum_{V=\rho^0, \omega, \phi} \frac{\alpha\pi}{\gamma_V^2}\, \delta(m^2 - m_V^2)\, \sigma_{Vp}(W) \\ &= \sum_{V=\rho^0, \omega, \phi} r_V\, \delta(m^2 - m_V^2)\, \sigma_{\gamma p}(W), \end{aligned} \tag{9}$$

r_V being the percentage of the total photoproduction cross section induced by the vector meson V as determined [5] from vector meson photoproduction, $r_\rho \cong 0.66$, $r_\omega \cong 0.07$, $r_\phi \cong 0.05$. The higher mass contribution to σ_T in the model by Sakurai and myself is described by a continuum, which starts at the mass $m_c \cong 1.4$ GeV at which e^+e^- annihilation becomes appreciable [13] beyond ρ, ω, ϕ

$$\rho(W, m^2)^{cont.} = r_c \frac{m_0^4}{m^4}\, \Theta(m^2 - m_0^2)\, \sigma_{\gamma p}(W), \tag{10}$$

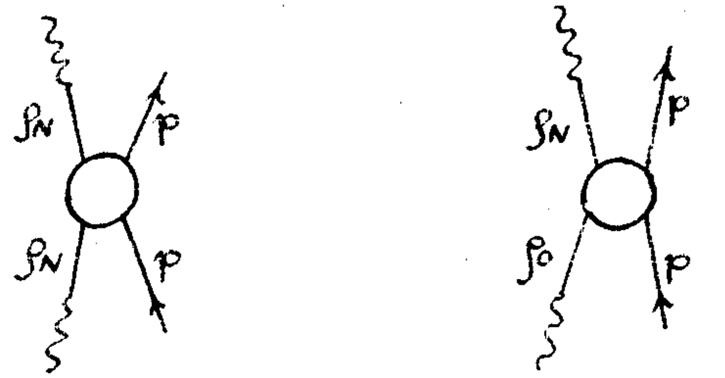
r_c being determined from photoproduction to be $r_c \cong 0.22$. Upon substitution of (9) and (10) into (8), quantitative agreement [5] with the data for σ_T and the transverse part of νW_2 is obtained for large ω' . The model has been extended [9] to also describe the small ω' region by introducing a physically motivated t_{min} correction factor. For details, also as regards the treatment of the longitudinal photoabsorption cross section and the neutron to proton ratio I have to refer to the original literature [5,9] and previous reviews [10]. Let me just show you a comparison with experiment of the transverse part of νW_2 for ep scattering on fig. 2 and of $R \equiv \sigma_S/\sigma_T$ on fig. 3.

Even though the model presented so far is quantitatively successful in describing electron nucleon deep inelastic scattering, there are some problems connected with our Ansatz (10) for the continuum contribution $\rho \sim 1/m^4$, which problems became increasingly serious, when measurements of e^+e^- annihilation became available [14] at increasingly higher energies. In fact, the continuum generalization of (9) simply reads [15]

$$\rho(W, m^2) = \frac{1}{4\pi^2\alpha}\,\sigma_{e^+e^-\to\mathrm{hadrons}}(m^2)\,\sigma_{Vp}(W, m^2) \tag{11}$$

and $\rho\sim 1/m^4$ from (10), which Ansatz is necessary for scaling of $\nu W_{2p}\sim q^2\sigma_T$, then yields $\sigma_{e^+e^-\to h}(s)\sim 1/s^2$, provided σ_{Vp} is assumed to be constant, i.e. independent of the vector meson mass m. An e^+e^- annihilation cross section decreasing as $1/s$ is clearly ruled out nowadays, however, when even the $1/s$ scaling law is in doubt beyond 3.5 GeV c.m. energy (see fig. 4). Worrying about the approximate constancy of $\sigma_{e^+e^-\to h}$ from 3.5 GeV to 5 GeV later, with $\sigma_{e^+e^-\to h}\sim 1/s$ the correct spectral weight function $\rho\sim 1/m^4$ is most simply obtained, if $\sigma_{Vp}\sim 1/m_V^2$ is assumed. Such an assumption for the hadronic cross section as a function of the vector meson mass has mainly been advocated by Greco[12]. I find it intuitively somewhat disturbing, however, that a strong interaction cross section should so violently depend on the mass of the incoming particle. From e.g. simple quark model arguments one would rather expect the cross section to be vector meson mass independent. Moreover, there are more serious objections against simply assuming $\sigma_{Vp}\sim 1/m_V^2$ which objections I am going to describe next.

In fact, the assumption $\sigma_{Vp}\sim 1/m_V^2$ corresponding to strongly decreasing diagonal contributions to the forward Compton amplitude, makes the validity of the diagonal approximation (8) doubtful. This is most simply seen by e.g. comparing the $\rho_N p\to\rho_N p$



(N = 0, 1, ..., introducing a discrete Veneziano spectrum of vector mesons) contribution to the virtual forward Compton amplitude with the $\rho_0 p\to\rho_N p$ term. Due to the enhancement of the ρ_0 coupling relative to the ρ_N photon coupling (by a factor m_N, if $\sigma_{e^+e^-\to h}\sim 1/s$), the imaginary part of the $\rho_0 p\to\rho_N p$ amplitude would have to fall stronger than $1/m_N^3$ for t = 0 in order to be negligible compared with the diagonal $\rho_N p\to\rho_N p$ term, which by assumption behaves as $1/m_N^2$. A $1/m_N^3$ behaviour of the $\rho_0 p\to\rho_N p$ amplitude would imply

$$\frac{d\sigma}{dm_N^2}(\rho_0 p\to\rho_N p)\sim 1/m_N^6 \tag{12}$$

for the hadronic diffraction dissociation reaction $\rho_0 p\to\rho_N p$. The behaviour (12) cannot be compared directly with the empirical diffraction dissociation law found to be valid in

$\pi p \to X p,$

$$\frac{d\sigma}{dm^2}(\pi p \to X p) \sim 1/m^2, \tag{13}$$

as in $\rho_0 p \to \rho_N p$ the spin of the vector meson is conserved, while in $\pi p \to X p$ the spin of the system X is not restricted. Nevertheless, it seems difficult to imagine that spin projection will reduce the power law behaviour in (13) to a fall off stronger than $1/m_N^6$ as required according to (12). If e.g. the number of spin states populated in $\pi p \to X p$ were to increase linearly with m^2, spin projection would reduce the $1/m^2$ behaviour to $1/m^4$, still appreciably larger than (12). Thus from the magnitude observed for diffraction dissociation amplitudes like $\pi p \to X p$, it seems unlikely that off-diagonal contributions to the forward Compton amplitude can be neglected, if at the same time the diagonal hadronic amplitude $\rho_N p \to \rho_N p$ is assumed to strongly decrease ($\sim 1/m_N^2$) with increasing mass of the vector state. Moreover, if a decreasing hadronic cross section is taken literally for the lowest lying vector meson already, i.e.

$$\sigma_{\rho_N p} = \sigma_{\rho^0 p} \frac{m_\rho^2}{m_N^2}, \quad (N = 0, 1, \cdots), \tag{14}$$

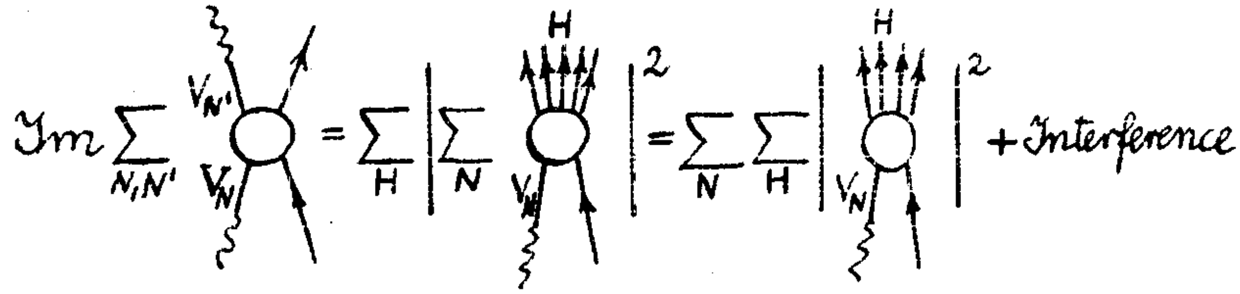
then we predict (in the diagonal framework) for $\rho''(1600)$ production

$$\frac{d\sigma}{dt}(\gamma p \to \rho'' p) \Big/ \frac{d\sigma}{dt}(\gamma p \to \rho^0 p) = \frac{\gamma_\rho^2}{\gamma_{\rho''}^2}\left(\frac{m_\rho}{m_{\rho''}}\right)^4 \cong 0.01, \tag{15}$$

where the e^+e^- annihilation result [13] $\gamma_{\rho''}^2/4\pi = (4.1 \pm 1.3)\gamma_\rho^2/4\pi$ has been used. Experimentally, however, one finds [8]

$$\frac{d\sigma}{dt}(\gamma p \to \rho'' p) \Big/ \frac{d\sigma}{dt}(\gamma p \to \rho^0 p) \cong 0.14. \tag{16}$$

Thus it seems natural and almost compelling to drop the diagonal approximation and the $\sigma_{V_N p} \sim 1/m_N^2$ law, which it engenders and to rather start from the more general non-diagonal representation (5) for the imaginary part of the transverse Compton amplitude or σ_T, and retain a constant mass independent cross section $\sigma_{V_N p}$. Off-diagonal transitions correspond to interference terms between different incoming vector mesons. Such terms



are not necessarily positive. They may thus allow the incorporation of the 1/s law for e^+e^- annihilation, while keeping $\sigma_{V_N p}$ vector meson mass independent, cancelling the logarithmic divergence due to the diagonal terms by destructive interference. A simple quantitatively successful model along this line of thought has recently been developed [16] by Fraas, Read and myself. The model explicitly demonstrates that scaling in the spacelike region in ep scattering may be derived from a scaling annihilation cross section $\sigma_{e^+e^-\to h} \sim 1/s$ and vector meson mass independent vector meson absorption cross sections σ_{Vp}, if destructive interference due to off-diagonal transitions of reasonable magnitude is taken into account. Let me turn next to a description of this model. Subsequently we will discuss how the results for the spacelike region of ep scattering are expected to be modified, if most recent results on e^+e^- annihilation, indicating constancy of the cross section for $12 \leq s \leq 25$ GeV^2, are taken into account.

3. GENERALIZED VECTOR DOMINANCE: A MODEL WITH INCLUSION OF OFF-DIAGONAL TRANSITIONS

It is our aim to develop a quantitative model for deep inelastic electron nucleon scattering within the framework of the non-diagonal representation (5), first of all concentrating on the large ω' diffraction region. The vector state photon couplings are to be taken from e^+e^- annihilation. Using reasonable assumptions on the underlying vector state nucleon interaction in addition, the q^2 dependence of deep inelastic scattering is to be predicted.

The model [16] by Fraas, Read and myself, mainly for technical reasons, has been formulated in terms of a discrete Veneziano type spectrum of vector mesons with masses

$$m_N^2 = m_0^2 (1 + 2N), \qquad N = 0, 1, \cdots . \tag{17}$$

The couplings of the photon to the vector mesons V_N are chosen [12] to decrease as $1/m_N^2$

$$\frac{1}{\gamma_N^2} = \frac{1}{\gamma_0^2} \frac{m_0^2}{m_N^2}, \tag{18}$$

the normalisation being given by the coupling to the lowest lying vector meson, $\rho^0(\omega, \phi)$, which coupling thus sets the scale for the couplings of the higher ones, much in the spirit of Sakurai's "new duality" [17]. As $1/\gamma_N^2$ measures the total strength of transition of the photon to the hadronic vector state V_N

$$\frac{\alpha\pi}{\gamma_N^2} = \frac{1}{4\pi^2\alpha} \sum_{F_n} \int \sigma_{e^+e^-\to V_N^{(s)} \to F_n} \, ds \tag{19}$$

because of (18) and the equal spacing rule (17), the total e^+e^- annihilation cross section into hadrons is to decrease as 1/s when averaged over the vector meson peaks. In the narrow width approximation we in fact obtain for $\sigma(e^+e^- \to$ hadrons)

$$\sigma_{e^+e^-\to h}(s) = \frac{\pi}{\lambda\left(\frac{\gamma_\rho^2}{4\pi}\right)}\,\sigma_{\mu\,pair}(s) \cong 2.5\,\sigma_{\mu\,pair}, \tag{20}$$

where the level spacing λ is chosen to be $\lambda = 2$. As seen on fig. 4, (20) describes the data reasonably well as long as $\sqrt{s} \lesssim 3.5$ GeV. The couplings (18) may thus be used as a starting point for the prediction of the q^2 dependence of the total photoabsorption cross section for spacelike values of q^2. The modifications induced by the approximate constancy of $\sigma_{e^+e^-\to h}$ beyond 3.5 GeV will subsequently be discussed in chapter 4.

Next let us specify the hadron physics required for a formulation of a model for the virtual forward Compton amplitude. As mentioned, we will assume the vector meson nucleon forward amplitude $V_Np \to V_Np$, or rather the total vector meson nucleon cross section to be independent of the mass of the vector meson V_N in the high energy diffraction region. This assumption is in agreement with what one would expect from most naive quark model arguments and is also quite in line with results [18] on the absorption of multipion systems in complex nuclei. Next we will have to specify the diffraction dissociation amplitudes from the lowest lying state V_0 to higher ones V_N,

$$V_0p \to V_Np\,, \qquad N = 1, 2, \ldots, \tag{21}$$

and more generally the amplitudes

$$V_Np \to V_{N'}p\,, \quad (N \neq N'), \tag{22}$$

which enter the forward Compton amplitude as off-diagonal transitions. The only hint from experiment is the observed [19] power law

$$\frac{d\sigma}{dm^2}\left(\pi p \to Xp\right) \sim 1/m_X^2 \tag{23}$$

for pion diffraction dissociation, which law would have to be appropriately modified to take spin conservation into account. Exploratory calculations [20] have actually been carried out by generalizing the $1/m^2$ behaviour (23) to a power law $(1/m^2)^p$, leaving the power p as a parameter and summing over all diagonal and off-diagonal contributions $V_Np \to V_{N'}p$ to the forward Compton amplitude. The essential features as regards inclusion of off-diagonal terms may be most simply seen, however, by taking into account transitions to next neighbors only, $V_Np \leftrightarrow V_{N+1}p$ besides the diagonal ones. These next neighbor off-diagonal terms are to be considered as "effective" terms, describing in a global way the effect of summing over all off-diagonal contributions of the kind $V_Np \leftrightarrow V_{N'}p$ ($N' = N+1, N+2, \ldots$). As can be shown under rather general conditions, the sum over infinitely many terms $V_Np \leftrightarrow V_{N'}p$ ($N' = N+1, N+2 \ldots$) is in fact equivalent to taking into account next neighbor transitions only. So let me describe to you the simple model with inclusion of next neighbor transitions only, which has been constructed [16] by

Fraas, Read and myself.

Denoting then the ratio of the first off-diagonal to diagonal (t=0) transition amplitude as

$$C_N \equiv T_{\rho_N p \leftrightarrow \rho_{N+1} p} \, / \, T_{\rho_N p \rightarrow \rho_N p} \tag{24}$$

we obtain the isovector photon part of the transverse virtual photoabsorption cross section by writing down the $\rho_N \rightarrow \rho_N$, $\rho_N \rightarrow \rho_{N+1}$ and $\rho_{N+1} \rightarrow \rho_N$ contributions to the imaginary part of the forward Compton amplitude and summing over N:

$$\begin{aligned} \sigma_T^{(I=1)}(W, q^2) = \sigma_{\rho^0 p} \sum_{N=0}^{\infty} \alpha\pi \left(\frac{m_N^2}{\gamma_N^2} \frac{1}{(q^2+m_N^2)} \right) \times \\ \times \left(\frac{1}{(q^2+m_N^2)} \frac{m_N^2}{\gamma_N} - 2\, C_N \frac{1}{(q^2+m_{N+1}^2)} \frac{m_{N+1}^2}{\gamma_N} \right). \end{aligned} \tag{25}$$

Clearly, for $C_N \equiv 0$ we recover diagonal GVD requiring (with (18)) $\sigma_{\rho_N p} \sim 1/m_N^2$ for convergence and scaling. As mentioned, the model is to be constructed such that this logarithmic divergence is cancelled by introducing negative off-diagonal terms. Therefore a minus sign has been introduced in front of the off-diagonal term in (25), for definiteness assuming C_N to be real and positive (and smaller than 1), and the sign of the coupling to alternate (i.e. $\gamma_N \sim (-1)^N$, N = 0, 1, ...).

The ratio C_N of first off-diagonal to diagonal transition is not very well known experimentally, except for the fact that C_N for N=0 has to be smaller than 1. Also, although in our Ansatz (25) we have explicitly taken into account next neighbour transitions only, as mentioned, C_N should rather be thought of as an effective transition standing for the combined effect of all $\rho_N p \leftrightarrow \rho_n p$ $(n \geqq N+1)$ contributions. Anyway, let us suppose a power law for C_N, written with the real parameter δ as

$$C_N = \text{const } (m_N/m_{N+1})^{1+2\delta}, \tag{26}$$

which for large N gives (neglecting order $1/m_N^4$)

$$C_N = \text{const}(m_N/m_{N+1}) \; (1 - \delta\lambda m_0^2/m_N^2) \; . \tag{27}$$

Then the sum in (25) turns out to be convergent, provided the constant in (26) and (27) is chosen to be 1/2. Thus inserting (18) and (27) into (25), the result of the summation is easily calculated to be

$$\sigma_T^{(I=1)}(W,q^2)=\frac{\alpha\pi}{\gamma_\rho^2}\sigma_{\rho^0 p}\frac{1}{\lambda}\left(\frac{q^2+\lambda(1+\delta)m_\rho^2}{(q^2+m_\rho^2)}-\frac{q^2}{\lambda m_\rho^2}\psi^{(1)}\left(\frac{q^2+m_\rho^2}{\lambda m_\rho^2}\right)\right), \tag{28}$$

where $\psi^{(1)}(z)$ is the derivative of the digamma function $\psi(z)$

$$\psi^{(1)}(z)\equiv\frac{d}{dz}\psi(z)=\sum_{k=0}^{\infty}\frac{1}{(z+k)^2}\sim\frac{1}{z}+\frac{1}{2z^2}+\mathcal{O}\left(\frac{1}{z^3}\right). \tag{29}$$

Our result (28) contains two parameters, the level spacing λ, which from $\sigma(e^+e^-\rightarrow$ hadrons) has been fixed to be $\lambda = 2$, and the parameter δ, which according to (26) and (27) determines the magnitude of the effective hadronic diffraction dissociation with spin conservation. δ is obtained from the normalization of σ_T to photoproduction at $q^2 = 0$. Generalizing (28) by taking into account the isoscalar contribution and evaluating at $q^2 = 0$ we have

$$\sigma_T(W,q^2=0)\equiv\sigma_{\gamma p}=\alpha\pi\left(\gamma_\rho^{-2}\sigma_{\rho p}+\gamma_\omega^{-2}\sigma_{\omega p}+\gamma_\phi^{-2}\sigma_{\phi p}\right)(1+\delta). \tag{30}$$

From the mentioned empirical result that ρ^0, ω, ϕ saturate photoproduction at $q^2 = 0$ only up to approximately 78 %, we obtain $(1+\delta)^{-1}\cong 0.78$ or $\delta\cong 0.28$. Introducing $\sigma_{\gamma p}$ into (28), our final result for σ_T may be written as

$$\sigma_T(W,q^2)=\frac{1}{\lambda}\left(\frac{\lambda(1+\delta)+q^2/m_\rho^2}{1+q^2/m_\rho^2}-\frac{q^2}{\lambda m_\rho^2}\psi^{(1)}\left(\frac{1+q^2/m_\rho^2}{\lambda}\right)\right)\frac{\sigma_{\gamma p}}{(1+\delta)}. \tag{31}$$

As λ has been fixed from e^+e^- annihilation and δ from the normalization to photoproduction, the q^2 dependence in (31) is predicted without free parameters.

Asymptotically for $q^2\rightarrow\infty$, with (29), σ_T becomes

$$\sigma_T(W,q^2)\sim\frac{\bar{m}^2}{q^2}\sigma_{\gamma p}, \tag{32}$$

where

$$\bar{m}^2=\frac{1+2\delta}{2+2\delta}m_\rho^2\cong 0.61\,m_\rho^2=0.36\ GeV^2. \tag{33}$$

The $1/q^2$ dependence in (32) corresponds to scaling of the transverse contribution to the structure function νW_2 given in (4). The asymptotic behaviour (32) suggests a simple interpolation formula as an approximation to (31), which formula reads

$$\sigma_T(W, q^2) = \frac{\bar{m}^2}{(q^2 + \bar{m}^2)} \sigma_{\gamma p} . \tag{34}$$

Even though (31) may easily be evaluated numerically from the tables for $f^{(1)}(z)$, formula (34) is obviously much simpler and in fact agrees with (31) within 2 % (around $q^2 = 3$ GeV^2, where deviations from (31) are largest). It is amusing to note that the simple pole formula (34), which is equivalent to (31), had previously been shown [4] to describe extremely well the data for the transverse part of νW_2 in the $\omega' \gtrsim 8$ region. From eyeball fits to the data $\bar{m}^2$ had been obtained to be $\bar{m}^2 = (0.611)^2 = 0.37$ GeV^2, compared with $\bar{m}^2 = 0.36$ GeV^2 as calculated in the present model by adjusting the magnitude of diffraction dissociation (δ) by requiring the correct normalization of σ_T at $q^2 = 0$ to the photoproduction cross section. Also, as remarked by Sakurai [3], the pole formula (34) implies that the modified scaling variable [21] $\omega_W \equiv (2M\nu + b^2)/(q^2 + a^2)$ is a good scaling variable, provided $\bar{m}^2 \equiv a^2$. In the fits to the data, at low and high values of ω', a^2 has been found[21] to be $0.37 \lesssim a^2 \lesssim 0.42$ GeV^2 in good agreement with our calculated value of $\bar{m}^2 = 0.36$ GeV^2. Agreement with the data for σ_T and the transverse part of νW_2 for large ω' is explicitly displayed on figures 5 and 6 (curve a).

Let us add a remark at this point on the connection between our final result (34) and the diagonal model defined by using the diagonal approximation (8). The simple pole formula (34) first arose in the diagonal model. It is obtained from (8), if we substitute

$$\rho(W^2, m^2) = \frac{\bar{m}^2}{m^4} \Theta(m^2 - \bar{m}^2) \sigma_{\gamma p} . \tag{35}$$

This Ansatz according to (11) with $\sigma_{e^+e^- \to h} \sim 1/s$ corresponds to a decreasing vector state proton cross section $\sigma_{Vp} \sim 1/m_V^2$. Destructive interference from off-diagonal terms in the forward Compton amplitude thus may appear equivalent in practice to a decreasing vector meson nucleon cross section within the diagonal Ansatz (8). Such a statement of equivalence is misleading, however, as this equivalence is lost, as soon as exclusive channels, like ρ^0 electroproduction, are considered. There is an additional difference between the diagonal and the off-diagonal model as regards the mass parameter $\bar{m}$. In the diagonal model, as formulated with a continuous spectral weight function, the mass $\bar{m}$ appears as an effective threshold for e^+e^- annihilation. It is adjusted to the data such that the correct q^2 dependence is obtained. In the off-diagonal model, I have described, the mass $\bar{m}$, which determines the asymptotic behaviour of σ_T and νW_{2T} (ω' large) is actually calculated just by requiring the virtual photoabsorption cross section σ_T to reduce to the correct empirical value of $\sigma_{\gamma p}$ at $q^2 = 0$. As mentioned, the q^2 dependence (for large ω') within the off-diagonal model described, is thus predicted without a free parameter.

Within the non-diagonal framework we have concentrated so far on the large ω' diffraction region. The extension to the small ω' region may be accomplished in a way identical to the procedure used [9] in the case of the diagonal model. The isospin 1 exchange in the t-channel necessary for the n over p ratio is attributed to higher mass vector mesons, and a physically motivated t_{min} correction factor takes care of the threshold behaviour for $\omega' \to 1$.

4. DO RECENT e^+e^- ANNIHILATION DATA IMPLY VIOLATIONS OF SCALING IN DEEP INELASTIC ELECTRON SCATTERING?

Up to now we have assumed that e^+e^- annihilation shows scaling behaviour $\sigma(e^+e^- \to \text{hadrons}) \sim 1/s$. Even though this seems roughly true for e^+e^- c.m. energies less than about 3.5 GeV ($s \lesssim 12$ GeV^2), recent CEA and SPEAR data indicate approximate constancy of $\sigma(e^+e^- \to \text{hadrons})$ for $12 \lesssim s \lesssim 25$ GeV^2. Iwai and myself have recently attempted [22] to quantitatively estimate the effect of this constant behaviour of e^+e^- annihilation on deep inelastic scattering in the large ω' diffraction region within the off-diagonal model just described.

For the purpose of predicting the effect on ep scattering, the constant behaviour of e^+e^- annihilation is simply parameterized by assuming constancy of the vector meson photon couplings

$$\frac{1}{\gamma_N^2} = \text{const} = \frac{1}{\gamma_N^2}\frac{m_0^2}{m_{N_1}^2}, \quad (N_1 \leqq N \leqq N_2) \tag{36}$$

within a restricted range $N_1 \leqq N \leqq N_2$. The values of N_1 and N_2 are given by the lower and upper bound in s for which e^+e^- annihilation is assumed to be constant i.e. $s_{1,2} = m_0^2(1+2N_{1,2}^2)$. As indicated by the e^+e^- data, $s_1 \cong 12$ GeV^2 will be adopted. $s_2 \to \infty$ is not excluded apriori, but unitarity bounds [23] tell us that the present behaviour of $\sigma_{e^+e^-\to h} \approx$ const. and $R \equiv \sigma_{e^+e^-\to h}/\sigma_{\mu^+\mu^-} \approx$ const. $\cdot$ s cannot go on indefinitely, but should rather change below $s \lesssim 1700$ GeV^2. The value of s_2 will thus be left as an open parameter to be specified later for our numerical estimates. For $s \gtrsim s_2$ we assume $\sigma_{e^+e^-\to h} \sim 1/s$ and accordingly put

$$\frac{1}{\gamma_N^2} = \frac{1}{\gamma_0^2}\frac{m_{N_2}^2}{m_{N_1}^2}\frac{m_0^2}{m_N^2}, \qquad N \geqq N_2 . \tag{37}$$

Substituting then (18), (36) and (37) into the expression (25) for σ_T, doing the summation and simplifying by expanding the ψ and ψ' functions, we obtain [22]

$$\sigma_T(W, q^2) = \left(\frac{\bar{m}^2}{(q^2+\bar{m}^2)} + \frac{\bar{m}^2}{s_1}\ln\frac{q^2+s_2}{q^2+s_1}\right)\frac{\sigma_{\gamma p}}{\left(1+\frac{\bar{m}^2}{s_1}\ln\frac{s_2}{s_1}\right)}, \tag{38}$$

where $\bar{m}^2$ as in (34) is given by $\bar{m}^2 = 0.61\, m_\rho^2$.

As a side remark, let me say that one may convince oneself that (38) may also be obtained within the diagonal model, if again one assumes that σ_{Vp} effectively decreases as $1/m_V^2$.

Let us now discuss the physical implications of our result (38). Quite trivially, for the limiting case $s_1 = s_2$ we have $(e^+e^- \to h) \sim 1/s$ for arbitrary s, and consequently σ_T in (38) reduces to the scaling expression (34). If we assume $s_2 \gg s_1$, corresponding to a constant e^+e^- annihilation cross section for $s_1 \leq s \leq s_2$, from (38) and (4), scaling will be violated approximately linearly in q^2 for $q^2 \lesssim s_2$, a scaling limit being reached for $q^2 \gg s_2$ only, when the log term becomes negligible. For $s_1 \cong 12$ GeV^2, as indicated by the data, $\bar{m}^2/s_1 = 0.03$, and thus the slope of the scale breaking term is quite small as long as s_2 is only moderately large. Thus from the empirical fact that the onset of approximate constancy of $\sigma(e^+e^- \to$ hadrons) is at about 3.5 GeV only, we expect scaling violations in deep inelastic ep scattering to be moderately large for not too large spacelike q^2 (keeping s_2 finite). As a numerical example, in fig. 6 (curve (b)), I first of all show you the result obtained for νW_{2T} from constancy of $\sigma(e^+e^- \to$ hadrons) in the CEA SPEAR range of 12 GeV$^2 \leq s \leq 25$ GeV^2. Scaling violations become more dramatic as soon as s_2 is raised to e.g. $s_2 = 50$ GeV^2 (corresponding to $R \equiv \sigma(e^+e^- \to h)/\sigma_{\mu^+\mu^-} \cong 10$ at $\sqrt{s_2} \cong 7$ GeV). In fact, the corresponding curve (c) on fig. 6 may be considered to be at variance with the plotted SLAC-MIT data as available in the low q^2 region. Thus, if our results are taken literally on the quantitative level, and not as an indication of qualitative trends only, one may even be bold enough to infer that $\sigma(e^+e^- \to h)$ should after all start to go down as $1/s$ not too far beyond the presently explored region. As long as s_2 is finite, νW_{2T} will eventually scale, the scaling limit being enhanced approximately by a factor s_2/s_1 compared with the result obtained from $\sigma(e^+e^- \to h) \sim 1/s$:

$$\nu W_{2T} \sim \frac{1}{4\pi^2\alpha}\, \bar{m}^2\, \sigma_{\gamma p}\,(W \to \infty)\, \frac{s_2}{s_1}\, \frac{1}{\left(1 + \frac{\bar{m}^2}{s_1} \ln \frac{s_2}{s_1}\right)} \tag{39}$$

For $s_2 \cong 25$ GeV^2 and $s_1 \cong 12$ GeV^2 (SPEAR range) the enhancement factor is about 2, the scaling limit being reached at $q^2 \cong 100$ GeV^2 only, however.

If instead of $\sigma(e^+e^- \to$ hadrons) $\sim$ const. we assume a fall-off somewhat weaker than $1/s$, e.g. $1/\sqrt{s}$, which may also be compatible with available data, the corresponding scaling violations in deep inelastic scattering are also present, but are somewhat smaller, depending, of course, on the values of s_1 and s_2. As regards the longitudinal photoabsorption cross section σ_S, not considered so far, we have estimated that even with $\sigma(e^+e^- \to$ hadrons) being constant for $s_1 \leq s \leq s_2$, the prediction [5] for the ratio $\sigma_S/\sigma_T \sim \ln q^2/m_\rho^2$ remains essentially unchanged. We thus expect an additional small logarithmic violation of scaling, when instead of the transverse part the whole structure function νW_2 is taken into consideration.

Within the framework of GVD, we are thus led to conjecture [24] that positive violations of scaling, approximately linear in q^2, are to be expected in the large ω' diffraction region of ep scattering as a consequence of the approximate constancy of e^+e^- annihilation in the CEA SPEAR energy range. As regards the magnitude of ω', values of $\omega' \gg 10$ are certainly required. Well known qualitative lifetime arguments would suggest [24] even larger values, $\omega' > 50$ to fully see the effect. Should scaling violations of roughly the magnitude we are predicting not be confirmed in future experiments at large ω', such a situation would seem to be difficult to understand within the framework of GVD. Even though the general concept that the q^2 dependence in deep inelastic scattering is due to the propagation of vector states, i.e.

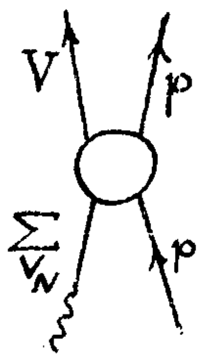
$$\sigma_T(W,q^2) = \int \frac{m^2 \rho(W,m^2,m'^2)\, m'^2}{(q^2+m^2)(q^2+m'^2)} \, dm^2 dm'^2 \tag{40}$$

would clearly not be affected, a rather artificial cancellation between hadronic vector state nucleon amplitudes would have to be invoked to cancel the large coupling of the photon to higher mass states reflected in the constancy of the CEA SPEAR e^+e^- annihilation cross section. Thus even though the detailed off-diagonal model I have presented to you may seem somewhat specific, I am rather convinced that positive scaling violations will be found at large values of ω'.

Experimentally, tests of scaling for large ω' require lepton beam energies in the 100 GeV range presently available at FNAL. It is of great interest in connection with our conjecture that an indication of a positive violation of scaling of roughly 20 % for $\omega' > 3$ and $5\ \text{GeV}^2 \lesssim q^2 \lesssim 10\ \text{GeV}^2$ has actually been reported [25] quite recently as a first result of the FNAL muon beam experiment. In this experiment a muon beam is scattered from an iron target. The result of the experiment is shown on fig. 7. The figure shows the ratio of the 150 GeV measurement to the result to be expected on the basis of the SLAC measurements, if these are fitted by a scaling expression. Unity of the ratio would mean that scaling is valid. Due to the kinematics of inelastic lepton scattering, the lowest q^2 bin in fig. 7 belongs to a rather large average value of $\omega \doteq 20$, while in the highest q^2 bin the average ω is equal to $\omega \doteq 2.5$ only. The point of relevance to us is the lowest q^2 point, which shows a violation of scaling of about 20 % (upper part of the figure), which violation of scaling vanishes, if the high ω data points are excluded (lower part of the figure). These data thus indicate scaling violations of the same sign and roughly of the magnitude expected from our estimates.

5. VECTOR MESON ELECTROPRODUCTION: OFF-DIAGONAL TRANSITIONS AS A MODEL FOR "PHOTON SHRINKAGE"

The influence of off-diagonal transitions should be visible in diffractive production of hadronic vector states (or e^+e^- pairs) by virtual photons. Fraas, Read and myself have recently quantitatively analysed [26] the simplest case, production of the lowest lying vector mesons ρ^0, ω, ϕ. Higher mass contributions in the initial photon state may affect



the q^2 dependence of the cross section $\gamma_{virt.}\, p \to V p$ at t = 0 (i.e. extrapolated to t = 0) and may also lead to a change of the slope of the t distribution with increasing q^2, if diffraction dissociation processes of the kind $\rho_0 p \to \rho_N p$ have a t-dependence differing from the one for the elastic reaction $\rho_0 p \to \rho_0 p$. Both effects should be visible in $\rho^0(\omega,\phi)$ electroproduction. For details I have to refer to ref. 26. Let me just briefly summarize the main results.

Let us again assume a Veneziano type spectrum of vector mesons and vector meson photon couplings $1/\gamma_N^2 = (1/\gamma_0^2)(m_0^2/m_N^2)$ as in (18). The constancy of $\sigma_{e^+e^- \to h}$ for higher energies does not bother us here, as transitions $\rho_N p \to \rho_0 p$ for very large N will be strongly suppressed. To keep the Ansatz as general as possible not only an effective next neighbor transition is taken into account, as in Compton scattering, but the summation over a series of vector mesons (N = 0,1,2,...) in the initial state is actually carried through, assuming a power law Ansatz for the hadronic amplitudes of the form

$$T^{\rho_0 p \to \rho_N p} = T^{\rho_0 p \to \rho_0 p} \left(\frac{m_0}{m_N}\right)^{2p+1}, \quad \begin{pmatrix} N = 1, 2, \cdots \\ p \geq 0 \end{pmatrix}. \tag{41}$$

For p = 0 one obtains the empirical diffraction dissociation law $d\sigma/dm^2 \sim 1/m^2$ from (23). Actually p has been left as an open parameter in the calculation, p = 1/2 or p = 1 being reasonable choices. Only numerical results, but not the functional q^2 behaviour, depend on the choice of p. With the mentioned photon couplings and the diffraction dissociation law (41), the sum of poles in the Ansatz for vector meson production may be carried out analytically for arbitrary p. Referring to ref. 26 for details, let me just give the final result, which may be approximated by the simple formula (valid in the region of $\omega' \gtrsim 10$)

$$\frac{d\sigma}{dt}^{t=0}(W, q^2) = \frac{\tilde{m}^4}{(q^2 + \tilde{m}^2)^2} \, \frac{|\vec{q}_{real}|}{|\vec{q}_{virt.}|} \, \frac{d\sigma}{dt}^{t=0}(W, q^2 = 0). \tag{42}$$

The t = 0 production cross section for e.g. $\gamma p \to \rho^0 p$ thus behaves as a simple pole squared in q^2, just as in ρ^0 dominance, except for the value of the mass parameter $\tilde{m}$. The effect of the off-diagonal transitions consists in replacing the ρ^0 mass m_ρ by the effective mass $\tilde{m}$. The numerical value of $\tilde{m}$ depends upon the sign chosen for the photon vector meson couplings and the power p in the diffraction dissociation Ansatz (41). For the alternating sign assumption made in chapter 3, one obtains $\tilde{m} < m_\rho$ corresponding to a suppression of the cross section relative to simple ρ^0 dominance. As the exact diffraction dissociation behaviour (i.e. the power p) is not known, $\tilde{m}$ cannot be exactly predicted. Realistic values of $\tilde{m}$ should roughly lie between $\tilde{m}^2 \cong 0{,}4\, m_\rho^2\, (p=0)$ and $\tilde{m}^2 \cong 0{,}7\, m_\rho^2,\ (p=1)$, however. The experimental data [27] actually show a somewhat faster fall-off in q^2 than expected from simple ρ^0 dominance and thus support our result (42) with $\tilde{m} < m_\rho$, as obtained with the alternating sign assumption. We have accordingly suggested [26] that future accurate data be fitted by varying $\tilde{m}$ (rather than the power of the q^2 dependence).

In order to extend the calculations of the effect of off-diagonal transitions to values of $t \neq 0$, the t-distribution for diffraction dissociation with spin conservation, $\rho_0 p \to \rho_N p$, has to be known. Empirically, processes like $pp \to pN^*$ and $\pi p \to A_1 p$ show [19,28] steeper slopes than the corresponding elastic reactions. Indeed, a recent analysis of diffraction dissociation in $pp \to pX$ at 12 and 24 GeV shows slopes [28] b as large as ~ 16 GeV^{-2} for $M_x^2 \lesssim 2$ GeV^2 with a rapid drop at larger masses M_x to or slightly below the elastic pp slope $b \cong 9$ GeV^2 in this energy range. Motivated by this empirical evidence, we conjectured [26] that a slope change relative to the corresponding elastic reaction is a genuine effect of diffraction dissociation quite independent of the projectile particle and thus also present in $\rho_0 p \to \rho_N p$. The effect of steeper slopes of $\rho_0 p \to \rho_N p$ on ρ^0 electroproduction is then qualitatively evident. For t = 0 we have a suppression of the cross section $(\tilde{m} < m_\rho)$ relative to diagonal vector dominance, as discussed. For $|t| > 0$, however, due to the steeper slopes of off-diagonal transitions, the suppression effect rapidly vanishes with increasing -t, thus yielding a flattening of slope with increasing values of q^2. Realistic numerical calculations show [26] that slopes b for ρ^0 production by virtual photons may well drop from values of 6 to 8 GeV^{-2} for photoproduction, $q^2 = 0$, to values of 4 to 6 GeV^2 for $q^2 \sim 5 m_\rho^2$, the main slope change with q^2 being expected for small values of $-t \lesssim 0.2$ GeV^2. Referring to ref. 26 again for details, let me show you the result of a calculation with inclusion of off-diagonal transitions in comparison with recent DESY-data on fig. 8.

Off-diagonal transitions of reasonable magnitude thus allow for suppression effects in $d\sigma/dt\,(\gamma^v p \to V p)$ at t = 0 of an estimated magnitude of approximately 30 % to 50 % at $q^2 \gtrsim 1.5$ GeV^2, and moreover may yield a flattening of slope b with increasing q^2 from $b \cong 6$ to 8 GeV^{-2} at $q^2 = 0$ to $b \cong 4$ to 6 GeV^{-2} for $q^2 \cong 2.5$ GeV^2. In concluding this chapter, let me add a more general remark concerning slope changes with increasing q^2. A flattening of slope with increasing q^2 in vector meson electroproduction has first been conjectured [29] by Cheng and Wu in analogy to results from QED calculations. Lightcone arguments have been added [30] and photon shrinkage with q^2 seemed to appear as a rather universal property of spacelike photons. Such a universal property, once verified in vector meson production, would then allow one to draw [31] far-reaching conclusions for other photon induced processes, as, e.g. π^0 electroproduction. We think that our interpretation of a possible slope change by linking it with properties of hadronic diffraction dissociation is less universal, but perhaps more realistic. Clearly, whether similar "radius type" effects also appear in different reactions, if once verified accurately in vector meson electroproduction, is in our interpretation very much dependent upon the hadron dynamics of the specific reaction under consideration.

6. SUMMARIZING CONCLUSIONS

Let me finally briefly summarize the main points, which have been made. This may implicitly also answer Zichichi's question, as given by the title of this lecture.

1. The concept of hadronlike behaviour as formulated by ρ^0, ω, ϕ dominance is qualitatively and semiquantitatively successful in photoproduction and low q^2 exclusive electroproduction in the multi GeV energy range. This has essentially been our starting point. Due to lack of time, we referred to previous reviews for a discussion of the empirical evidence for hadronlike behaviour.

2. From fig. 1 we learnt that the low lying vector mesons form an integral part of the scaling phenomenon, at least in the large ω' region. Without the ρ^0, ω, ϕ induced parts of the cross section scaling can no longer be precocious. This observation naturally suggests building up the forward Compton amplitude in terms of vector state forward scattering, including higher mass states, i.e. the GVD approach. As an immediate qualitative consequence, diffractively produced vector states of arbitrarily high mass should be observed in electroproduction at any q^2 provided the available energy is sufficient such that ω' is large ($\omega' \gtrsim 10$ or even $\gtrsim 50$). Thus looking for higher mass vector states, beyond $\rho^0, \omega, \phi, \rho'(1600)$ in diffractive production will be an important experimental test of the model. An unambiguous way to convince oneself of the correctness of the basic features of the model would clearly be the isolation of further vector mesons, which might be buried in the Frascati e^+e^- annihilation continuum.

3. Our discussion in chapter 2 showed that off-diagonal contributions (in mass) to the forward Compton amplitude should actually be taken into account. By including such terms, a quantitative model for νW_2 has been constructed, valid in the large ω' region. Scaling for the transverse part of νW_2 follows from scaling of the total e^+e^- annihilation cross section $\sigma(e^+e^- \to h) \sim 1/s$ and reasonable assumptions on the hadron physics. Precocity of scaling is natural in such a model. The mass which sets the scale has actually been computed to be slightly smaller than the ρ^0 mass, $\bar{m}^2 \cong 0.6 m_\rho^2$.

4. As a reflection of the observed constancy of $\sigma(e^+e^- \to h)$ for $12 \lesssim s \lesssim 25$ GeV^2 scaling violations at large ω' in deep inelastic scattering should be found. Even though the detailed quantitative model calculations within the off-diagonal framework I have presented to you may seem somewhat specific, I am rather convinced that scaling violations of roughly the magnitude predicted in fig. 6 will be isolated experimentally. In fact, first indications have been observed as shown on fig. 7.

5. Finally, we have seen in chapter 5 that off-diagonal transitions are strong enough to yield observable effects in electroproduction of even the lowest lying vector mesons ρ^0, ω, ϕ. Off-diagonal transitions may in fact be responsible for "photon shrinkage type" effects.

6. I have hardly discussed the small ω' region of deep inelastic scattering, apart from briefly mentioning the t_{min} effect. At present I believe it may be reasonable [32] to start from the GVD representation (5), even for small ω', disregarding anomalous singularities. For this region in ω' the $m^2, m'^2 > W^2$ behaviour of the spectral weight function $\rho(W, m^2, m'^2)$ is mainly relevant. I conjecture that the behaviour of ρ in this region should be related to inclusive e^+e^- annihilation, $e^+e^- \rightarrow \bar{p}X$, and hope to come back to this point in the near future.

REFERENCES

1) For a more detailed discussion of the basic elements of ρ^0, ω, ϕ dominance, its empirical validity and a list of relevant literature we refer to e.g. J.J. Sakurai, Erice lectures 1971, UCLA/71/TEP 139; D. Schildknecht, Springer Tracts in Modern Physics, Vol. 63 p. 57 (1973).

2) D. Schildknecht, Nucl. Phys. B66, 398 (1973) and the list of references given there to earlier work on shadowing by Brodsky, Gribov, Gottfried, Nauenberg, Stodolsky, Yennie and others.

3) J.J. Sakurai, Erice Lecture (1973), UCLA/73/TEP/89.

4) B. Gorczyca and D. Schildknecht, Phys. Letters 47B, 71 (1973).

5) J.J. Sakurai and D. Schildknecht, Phys. Letters 40B, 121 (1972).

6) e.g. Lefrancois, in Proc. 5th Internat. Symposium on Electron and Photon Interactions at High Energies, Cornell 1971.

7) e.g. G. Wolf, in Proc. 5th Internat. Symposium on Electron and Photon Interactions at High Energies, Cornell 1971.

8) e.g. K.C. Moffeit, Proc. of the 6th Internat. Symposium on Electron and Photon Interactions, Bonn 1973.

9) J.J. Sakurai and D. Schildknecht, Phys. Letters 41B, 489 (1972) and 42B, 216 (1972)

10) For reviews on GVD we refer to J.J. Sakurai, Proc. of the 1972 McGill University Summer School, p. 435 and UCLA/72/TEP/63 (1972).
D. Schildknecht, Proc. of the Eighth Rencontre de Moriond, ed. by J. Tran Thanh Van, Vol. 1, p. 181 (1973).
See also J.D. Bjorken, Proc. of the Summer Institute on Particle Physics, SLAC Report No. 167 (1973).

11) e.g. K. Gottfried, Cornell University report 1969; T.H. Nieh, Phys. Rev. D1, 3161 (1970); B.L. Joffe, Phys. Letters 30B, 123 (1969); V.N. Gribov, Soviet Physics, JETP 30, 709 (1970).

12) A. Bramon, E. Etim and M. Greco, Phys. Letters 41B, 609 (1972); M. Greco, Nucl. Phys. B63, 398 (1973).

13) $\pi\mu$-group: F. Ceradini et al., Phys. Letters 42B (1972) 501, 47B (1973) 80;
$\gamma\gamma$-group: C. Bacci et al., Phys. Letters 44B (1973) 533;
boson group: B. Bartoli et al., Phys. Rev. D6 (1972) 2374
also the review: V. Silvestrini, Proc. of the 16th Internat. Conf. on High Energy Physics, Chicago-Batavia 1972 Vol. 1, p. 1, ed. by J.D. Jackson and A. Roberts.
BCF group: A. Zichichi, CERN report 27 Feb. 1974, to be published in Nuovo Cim. Rev.

14) A. Litke et al., Phys. Rev. Letters 30, 1189, 1349E (1973),
G. Tranopolsky et al., Phys. Rev. Letters 32, 432 (1974)
B. Richter, Invited Talk, 17th International Conference on High Energy Physics, London 1974.

15) V.N. Gribov, Soviet Physics, JETP 30, 709 (1970)

16) H. Fraas, B.J. Read and D. Schildknecht, DESY 74/23 (1974), Nuclear Physics to be published.

17) J.J. Sakurai, Phys. Letters 46B, 207 (1973).

18) e.g. C. Bemporad et al., Nucl. Phys. B33, 397 (1971), A.M. Cnops et al., Phys. Rev. Letters 25, 1132 (1970).

19) e.g. L. Foà, Proc. 2nd Internat. Conference on Elementary Particles, Aix-en-Provence (1973), Supp. J. de Phys. 34, 317 (1973).

20) H. Fraas, B.J. Read and D. Schildknecht, in preparation.

21) V. Rittenberg and H. Rubinstein, Phys. Letters 35B, 50 (1971)
F.W. Brasse et al., Nucl. Phys. B39, 521 (1972).

22) S. Iwai and D. Schildknecht, DESY 74/42, submitted to Physics Letters B.

23) N. Cabibbo, G. Karl and L. Wolfenstein, Phys. Letters 51B, 387 (1974).

24) The conjecture of positive scaling violations has recently also been put forward by Nieh in a way closely related to our reasoning. Compare H.T. Nieh, ITP-SB-79-22 Stony Brook (1974).

25) L.N. Hand et al., Cornell preprint CLNS-278 (1974).

26) H. Fraas, B.J. Read and D. Schildknecht, Daresbury Report in preparation, submitted to Nuclear Physics.

27) e.g. the DESY streamer chamber results, V. Eckardt et al., DESY 74/5 (1974).

28) J. Benecke et al., Max Planck Institute report MPI-PAE/Exp. El, 38 (1974),
D. Leith, SLAC-PUB-1330, Supplement (11-73).

29) H. Cheng and T.T. Wu, Phys. Rev. 183, 1324 (1969).

30) e.g. J.D. Bjorken, Proc. of the 1971 Int. Symposium on Electron and Photon Interactions at High Energies, Cornell, Ithaca, N.Y. (Ed. N.B. Mistri) p. 281.

31) H. Harari, Phys. Rev. Letters 27, 1028 (1971).

32) H.D. Dahmen and F. Steiner, Phys. Letters 43B, 217 (1973)

FIGURE CAPTIONS

Fig. 1. The transverse part of the proton structure function as a function of q^2 for fixed ω' (from ref. 4). For the purpose of the discussion given here curves (a), (b) and (c) only are important. Curve (a) fits the data. Curves (b) and (c) show, what happens, if the ρ^0 induced part and the ($\rho^0 + \rho'(1600)$) induced parts, respectively, are subtracted.

Fig. 2. GVD predictions for the transverse part of νW_2 (from ref. 9).

Fig. 3. The ratio $R \equiv \sigma_S / \sigma_T$ according to GVD (from ref. 5).

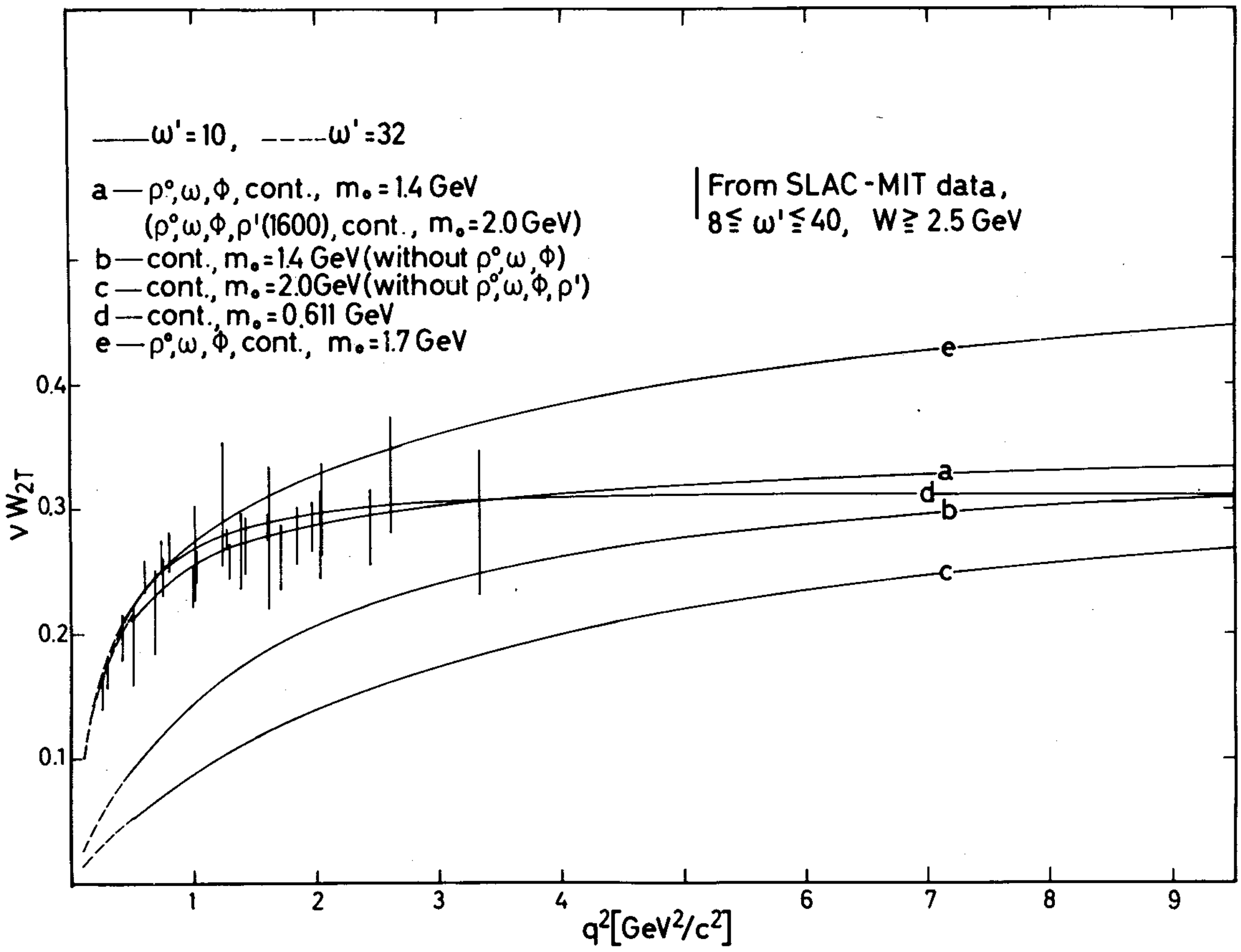
Fig. 4. The total e^+e^- annihilation cross section compared with GVD (——) according to (20). Data from references 13 and 14. Also indicated is the modified behaviour (-.-.-) resulting from the couplings (36) and (37), which couplings are used to quantitatively estimate the effect of approximate constancy of $\sigma(e^+e^- \rightarrow h)$ on ep scattering (from ref. 22).

Fig. 5. Off-diagonal GVD prediction according to (34) for the transverse virtual photo-absorption cross section on protons, $\sigma_T(W,q^2)$, as a function of the virtual photon four momentum squared q^2 (from ref. 16).

Fig. 6. Off-diagonal GVD prediction for the transverse part of the proton structure function $\nu W_2'$ at fixed ω' as a function of q^2. Curve (a) is obtained from scaling behaviour of e^+e^- annihilation. Curves (b) and (c) show the violations of scaling expected in the large ω' region as a reflection of the approximate constancy of e^+e^- annihilation for $s_1 \leq s \leq s_2$ (Fig. from ref. 22).

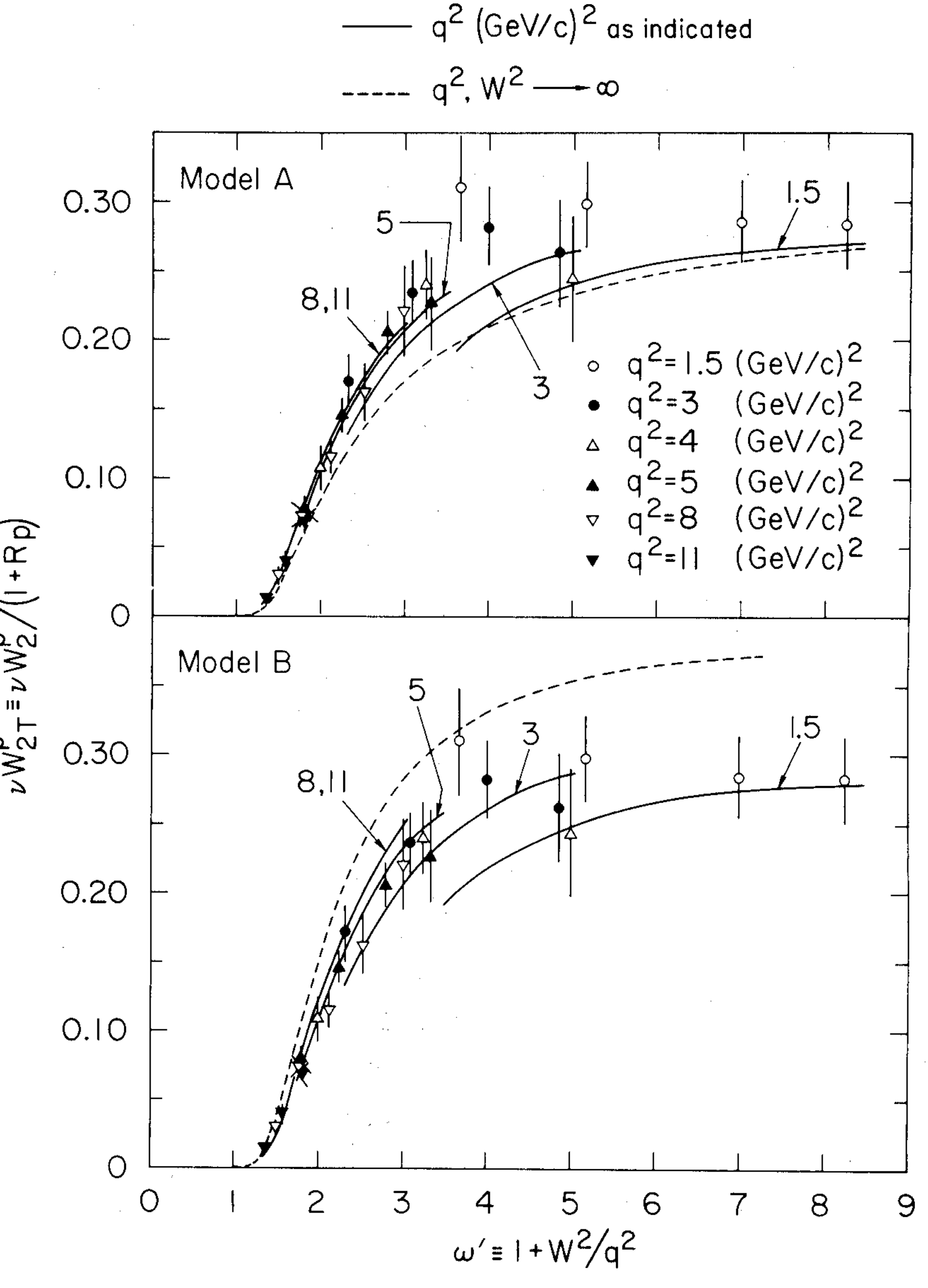
Fig. 7. FNAL muon beam results (from ref. 25). Ratio of 150 GeV yields to the yields expected on the basis of the SLAC-MIT data (assuming scaling). Ratio is unity, if scale invariance holds.

Fig. 8. ρ^0 electroproduction data [27] compared with vector dominance predictions obtained with inclusion of off-diagonal terms (from ref. 26).



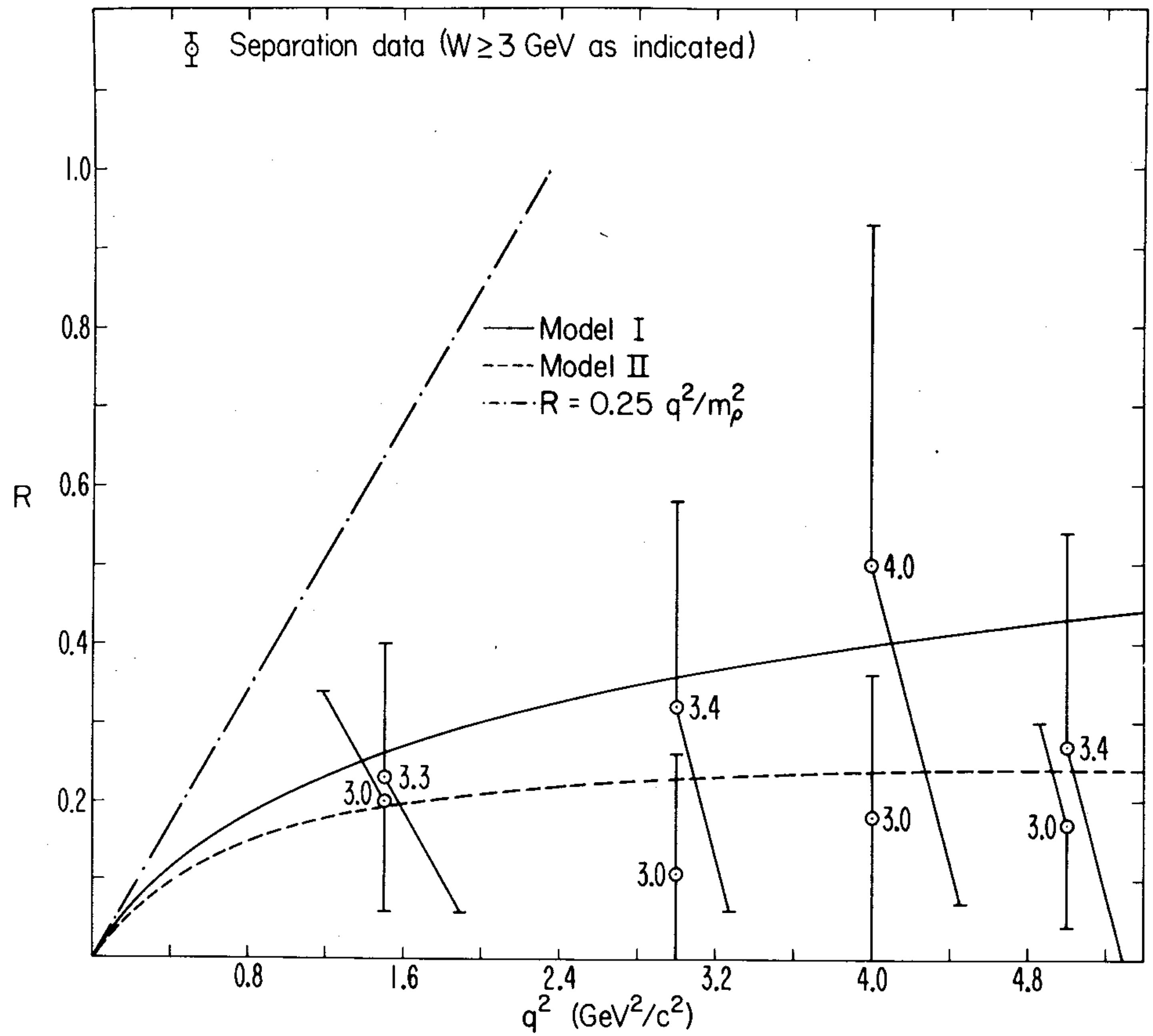
—— ω' = 10, ---- ω' = 32
a — ρ°, ω, Φ, cont., m₀ = 1.4 GeV
(ρ°, ω, Φ, ρ'(1600), cont., m₀ = 2.0 GeV)
b — cont., m₀ = 1.4 GeV (without ρ°, ω, Φ)
c — cont., m₀ = 2.0 GeV (without ρ°, ω, Φ, ρ')
d — cont., m₀ = 0.611 GeV
e — ρ°, ω, Φ, cont., m₀ = 1.7 GeV
From SLAC-MIT data,
8 ≦ ω' ≦ 40, W ≧ 2.5 GeV
ν W2T
0.4
0.3
0.2
0.1
a
b
c
d
e
1
2
3
4
6
7
8
9
q²[GeV²/c²]

Fig. 1



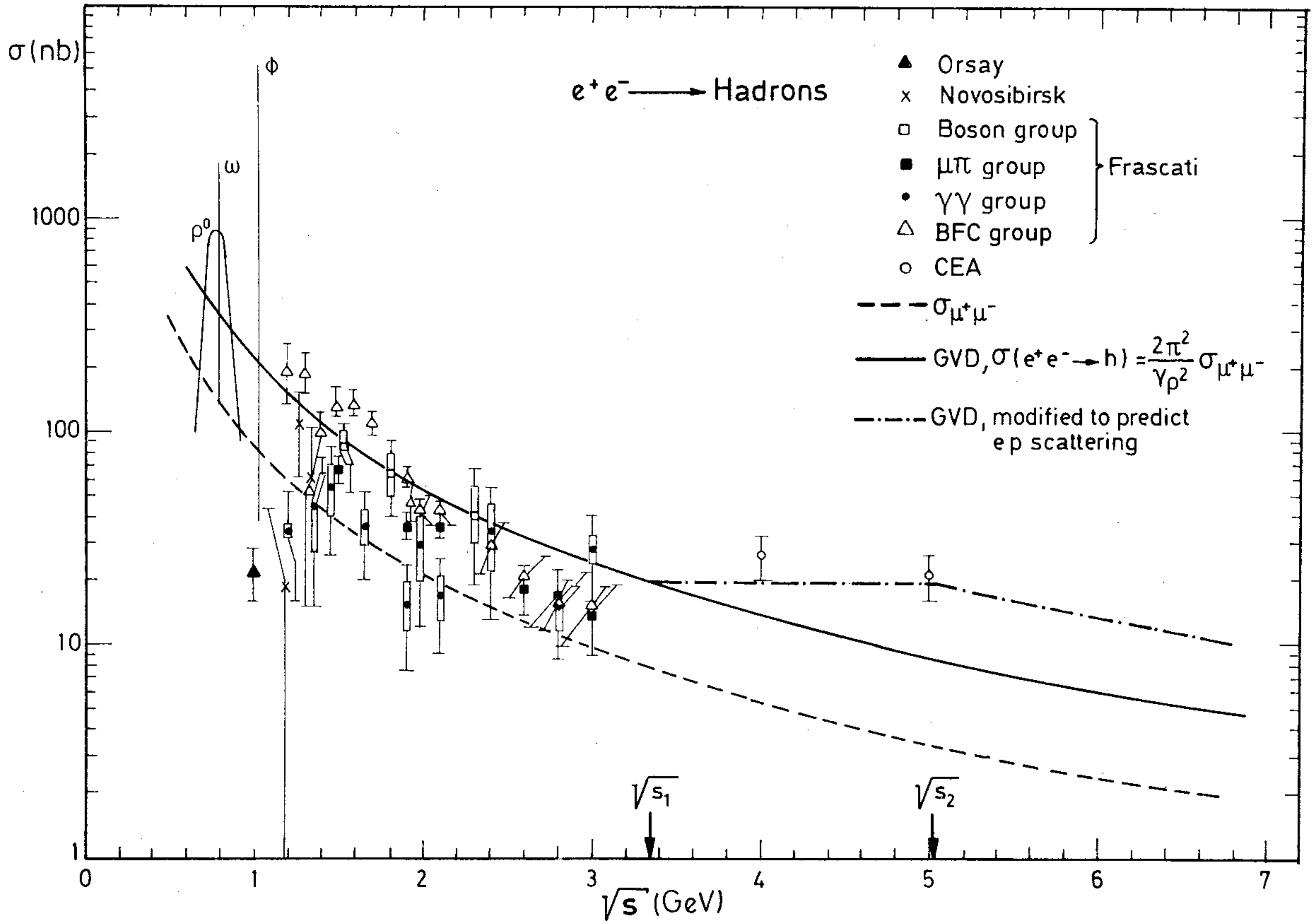
q² (GeV/c)² as indicated
q², W² → ∞
Model A
Model B
0.30
0.20
0.10
0
5
8,11
3
1.5
q²=1.5 (GeV/c)²
q²=3 (GeV/c)²
q²=4 (GeV/c)²
q²=5 (GeV/c)²
q²=8 (GeV/c)²
q²=11 (GeV/c)²
νW₂Tᵖ ≡ νW₂ᵖ/(1+Rp)
0 1 2 3 4 5 6 7 8 9
ω′ ≡ 1 + W²/q²

Fig. 2



Separation data (W ≥ 3 GeV as indicated)
Model I
Model II
R = 0.25 q²/m²ρ
R
1.0
0.8
0.6
0.4
0.2
0.8
1.6
2.4
3.2
4.0
4.8
q² (GeV²/c²)
3.0
3.3
3.0
3.4
4.0
3.0
3.0
3.4

Fig. 3



σ(nb)
1000
100
10
1
0
1
2
3
4
5
6
7
$\sqrt{s}$ (GeV)
$e^+e^- \longrightarrow$ Hadrons
Orsay
Novosibirsk
Boson group
$\mu\pi$ group
$\gamma\gamma$ group
BFC group
Frascati
CEA
$\sigma_{\mu^+\mu^-}$
GVD, $\sigma(e^+e^- \rightarrow h) = \frac{2\pi^2}{\gamma_\rho^2}\sigma_{\mu^+\mu^-}$
GVD, modified to predict e p scattering
ρ^0
ω
ϕ
$\sqrt{s_1}$
$\sqrt{s_2}$

Fig. 4

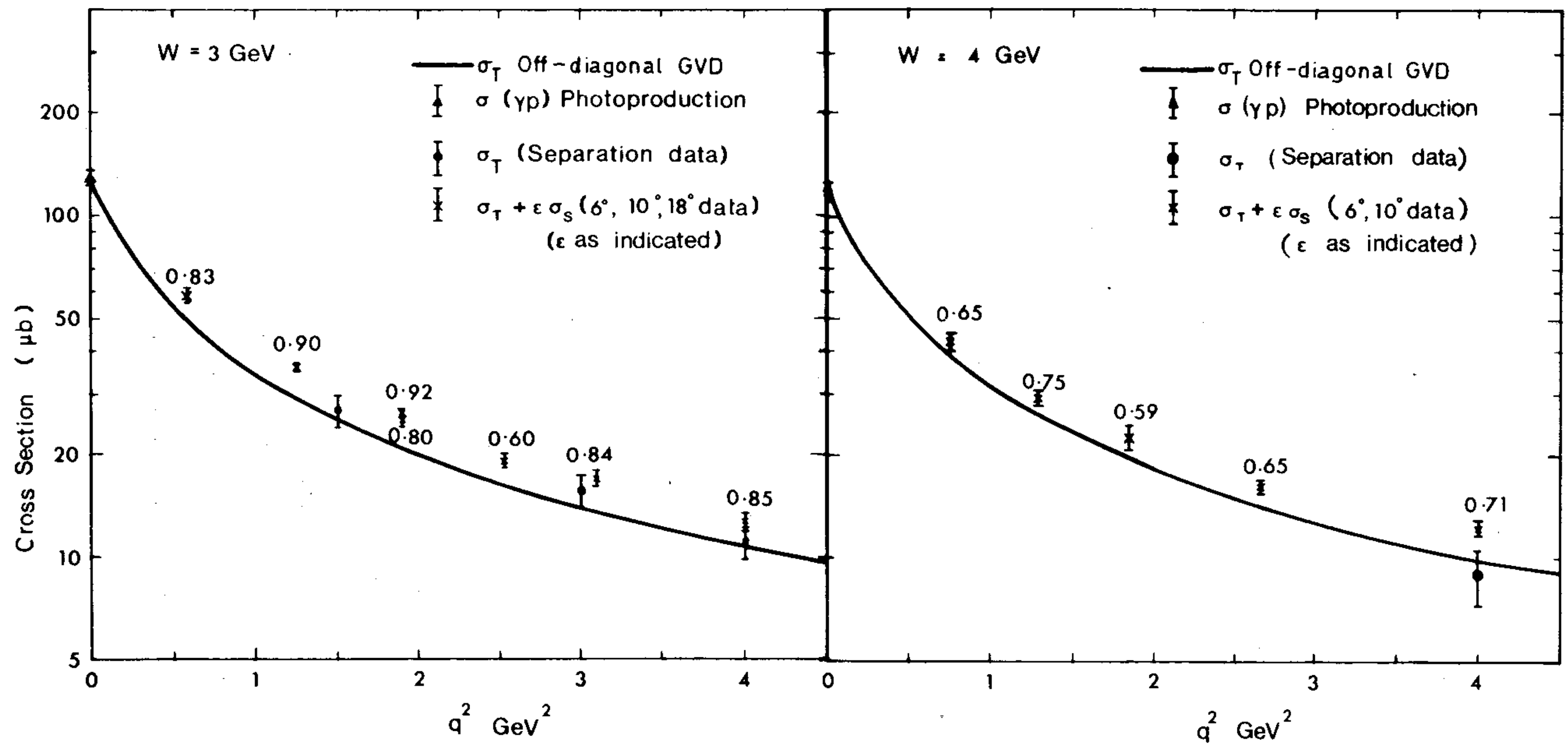

W = 3 GeV
σT Off-diagonal GVD
σ (γp) Photoproduction
σT (Separation data)
σT + ε σS (6°, 10°, 18° data)
(ε as indicated)
0·83
0·90
0·92
0·80
0·60
0·84
0·85
W = 4 GeV
σT Off-diagonal GVD
σ (γp) Photoproduction
σT (Separation data)
σT + ε σS (6°, 10° data)
(ε as indicated)
0·65
0·75
0·59
0·65
0·71
Cross Section (μb)
200
100
50
20
10
5
0
1
2
3
4
q2 GeV2

Fig. 5

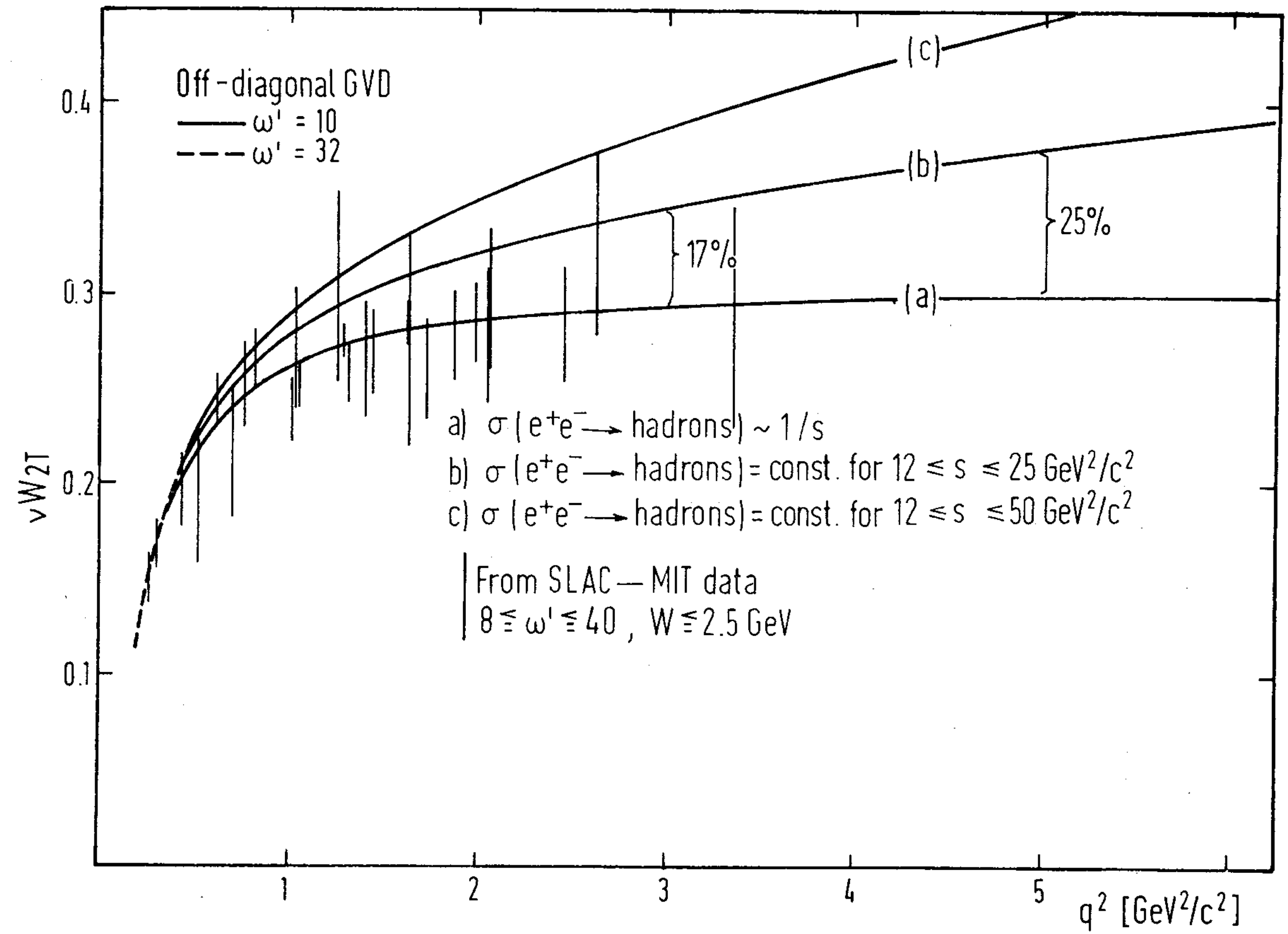

Off-diagonal GVD
ω' = 10
ω' = 32
(c)
(b)
(a)
25%
17%
a) σ (e⁺e⁻ → hadrons) ~ 1/s
b) σ (e⁺e⁻ → hadrons) = const. for 12 ≤ s ≤ 25 GeV²/c²
c) σ (e⁺e⁻ → hadrons) = const. for 12 ≤ s ≤ 50 GeV²/c²
From SLAC — MIT data
8 ≤ ω' ≤ 40 , W ≤ 2.5 GeV
νW2T
0.4
0.3
0.2
0.1
1
2
3
4
5
q² [GeV²/c²]

Fig. 6

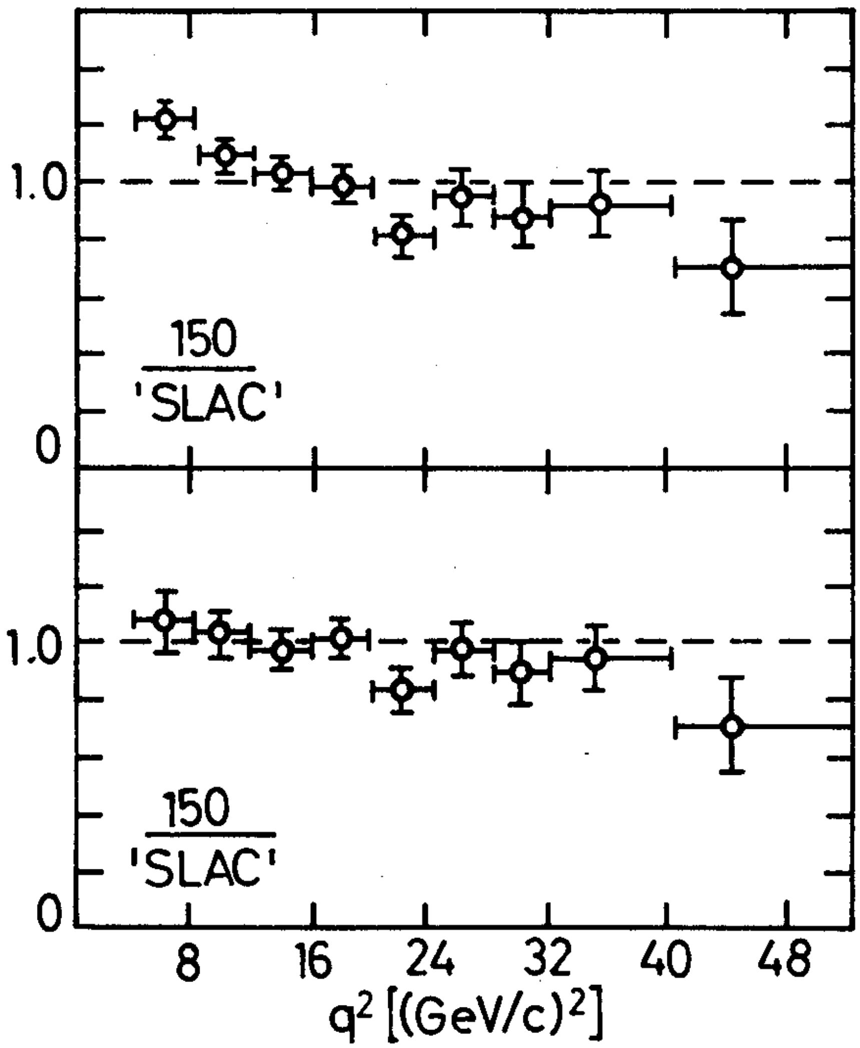
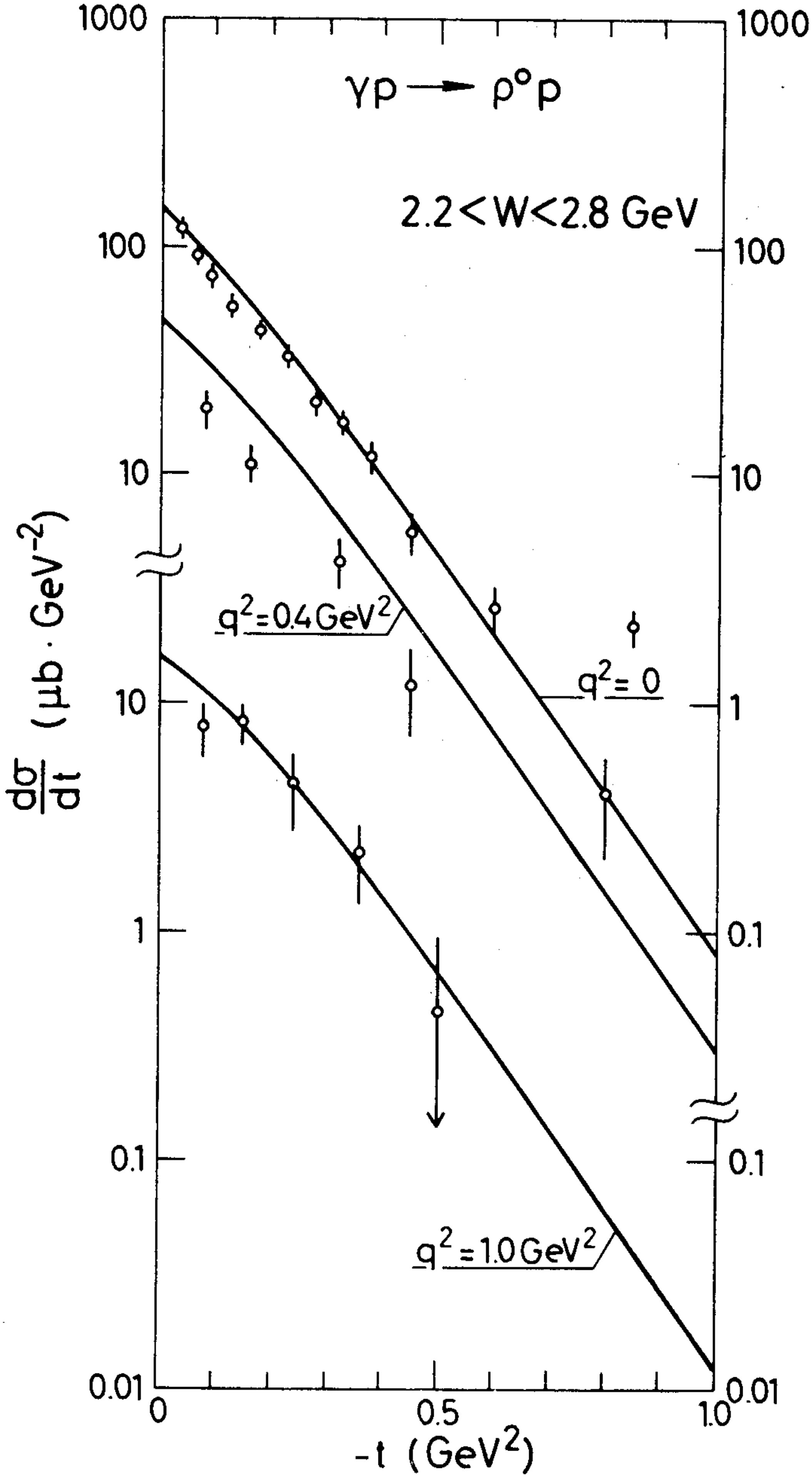


Fig. 7



γp → ρ°p
2.2<W<2.8 GeV
q²=0.4GeV²
q²= 0
q²=1.0GeV²
dσ/dt (μb · GeV⁻²)
-t (GeV²)
1000
100
10
10
1
0.1
0.01
1000
100
10
1
0.1
0.1
0.01
0
0.5
1.0

Fig. 8