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Total Cross Sections for Two Off Shell Photons

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Abstract. The EVDM and factorization technique are extended to the case of two tagged photons. The results obtained from both methods are remarkably close, and in very good agreement with the recent measurements made by the PLUTO collaboration at PETRA. Predictions are made for higher values of Q^2 and P^2, where future experiments are planned, and these are compared with the relevant QCD calculations.

Recently it has been shown that models which originate in the hadronic sector have also been successful when applied to inclusive phenomena measured in two photon physics [1, 2]. These models were applied to the study of single tag experiments where the tagged probe photon has $Q^2 > 0$, whereas the target untagged photon is almost real $P^2 \approx 0$. The approach of EVDM [1] and factorization[2] was shown to reproduce the experimental data well, provided $Q^2 < 25\,\mathrm{GeV}^2$ and W is well above threshold. The main input assumption common to [1] and [2] is that the 2γ single tag total cross section can be parametrized as:

$$\sigma(W, Q^2) = A + B/W \tag{1}$$

A and B are then obtained (modulo log Q^2) by either EVDM calculations or estimated by factorization considerations. A parametrization such as (1) is particular to the photon hadronic sector where A is associated with the diffractive and B with the Regge contribution to the inclusive 2γ process. We note that the photon point-like sector, which to lowest order couples to the quark box diagram, is expected to contribute terms that are more singular in W and have an explicit log Q^2 dependence. In the zero order (parton model) we thus expect that (1) be replaced by

$$\sigma(W, Q^2) = A + B/W + C/W^2 \tag{2}$$

If approximate scaling is a viable property of deep inelastic $e-\gamma$ scattering we expect that $A = a/Q^2$, $B = b/\sqrt{Q^2}$ and C is Q independent, all modulo log Q^2 dependences.

Accordingly, the detection of the photon point-like sector contribution to $\sigma(W, Q^2)$, and its growing importance in the high Q^2 limit, amounts to the detection of a C/W^2 term in $\sigma(W, Q^2)$. This behaviour is equivalent to the known high x maxima expected to be seen in $F_2^\gamma(x, Q^2)$.

Very recently, the PLUTO collaboration [3] at PETRA have succeeded in making the first structure function measurements where both target (P^2) and probe (Q^2) photons are off mass shell (see Fig. 1). In this paper we extend both models to the two tagged photon case and compare our results with the data. Predictions are also made for values of Q^2 and P^2 which are expected to be investigated at DESY and SLAC in the near future.

The Extended Vector Dominance Model (EVDM) was originally suggested by Greco and collaborators [4] and first applied to the annihilation process $e^+e^- \to$ hadrons. They showed that if one assumed that the cross section for $e^+e^- \to$ hadrons was dominated by vector mesons (in the VMD sense) then this cross section scaled provided that:

(i) One sums over an infinite number of vector mesons, which have a Veneziano like mass relation, i.e. $m_n^2 = m_0^2(1 + \lambda n)$,

(ii) one assumes the following relation exists

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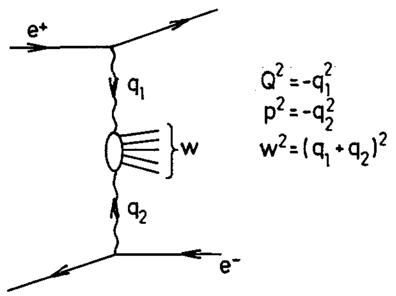

Fig. 1. Kinematics of $\gamma^* - \gamma^*$ processes

between masses and coupling constants of the vector mesons

$$\frac{m_n^2}{f_n^2} = \frac{m_0^2}{f_0^2}$$

where m_0 (m_n) and f_0 (f_n) denote the mass and coupling of the first (n^{th} recurrence) of the vector mesons ρ, ω, ϕ. We refer the reader to [1] and [4] for further details.

The EVDM factorizes in the variables W (the hadron energy), Q^2 (the probe four momentum squared), and P^2 (the target four momentum squared), so we can write

$$\sigma_{\gamma\gamma}(W, Q^2, P^2) = \sum_{i=D,R} \sigma^i_{\gamma\gamma}(W) F^i(Q^2) F^i(P^2) \qquad (3)$$

where the sum i is over the diffractive and Regge contributions. With $F^i(0) > 1$ we take

$$\sigma_{\gamma\gamma}(W, Q^2 = P^2 = 0) = 295 + 447/W \text{ nb}$$

·(with W in GeV)

first term being the diffractive (energy independent) and the second is the Regge term. Here the F functions are

$$F^D(K^2) = \sum_{n=0}^{\infty} \frac{1}{(1 + \lambda n + K^2/m_0^2)^2} \qquad (4a)$$

$$F^R(K^2) = \sum_{n=0}^{\infty} \frac{(1 + \lambda n)^{1/2}}{(1 + \lambda n + K^2/m_0^2)^2} \qquad (4b)$$

where K^2 stands either for Q^2 or P^2. The summations over the infinite series of vector mesons in the target and probe are coherent. As has become standard we take $\lambda = 2$ in (4a) and (4b). Both series are finite, and their asymptotic values are:

$$F^D(K^2) \xrightarrow[K^2 \to \infty]{} \frac{1}{2} \frac{m_0^2}{(m_0^2 + K^2)} \qquad (5a)$$

$$F^R(K^2) \xrightarrow[K^2 \to \infty]{} \frac{\pi}{4} \left(\frac{m_0^2}{m_0^2 + K^2} \right)^{1/2} \qquad (5b)$$

Note that a model like EVDM cannot accommodate a C/W^2 term in (1). Such a term is associated with a divergent form factor

$$F(K^2) = \sum_{n=0}^{\infty} \frac{(1 + \lambda n)}{(1 + \lambda n + K^2/m_0^2)^2}$$

We wish to point out that Ginzburg and Serbo [5] in their treatment of generalizing the standard vector dominance model have in addition to the usual summation over ρ, ω, and ϕ, appended an ad hoc term to approximate for the higher resonances and continuum, which both in shape and magnitude is very close to (5a). The unique feature which differentiates EVDM from other models of this type is the predicated gradual decrease of $F^R(K^2)$ as a function of K^2. Alexander et al. [2] have estimated the total cross sections of the virtual photons ($Q^2 > 0$) on quasi-real photon targets ($P^2 \simeq 0$) from $\gamma - p$, $\mu - p$ and $p - p$ total cross section data, using factorization. Here we extend the same technique to estimate the total cross section for two off shell photons.
The basic factorization relation is

$$\sigma_{\text{tot}}(\gamma_1^*, \gamma_2^*) = \frac{\sigma_{\text{tot}}(\gamma_1^* p)\, \sigma_{\text{tot}}(\gamma_2^* p)}{\sigma_{\text{tot}}(pp)} \qquad (6)$$

where $\sigma_{\text{tot}}(\gamma^* p)$ data is obtained from deep inelastic $e - p$ or $\mu - p$ experiments [6]. Following [2] factorization is applied as follows:

(i) The total cross sections are assumed to be given by (1). We use the factorization relation (6) separately for each energy dependent term.

(ii) Equation (6) relates channels with real and virtual masses. To account for the low energy kinematics, which is different for each channel, we apply (6) at the same initial *c.m.* momenta.

(iii) Since factorization applies to the transition matrix elements squared, we correct for the different flux factors, remembering that the flux factor is given by

$$\frac{1}{2qW} = \{W^4 - 2W^2(m_1^2 + m_2^2) + (m_1^2 - m_2^2)^2\}^{-1/2}$$

where $m_1^2 = -Q^2$ and $m_2^2 = -P^2$ for $\gamma^* - \gamma^*$ scattering, $m_1^2 = -Q^2, m_2^2 = M^2$ for $\gamma^* - p$ scattering and $m_1^2 = m_2^2 = M^2$ for $p - p$ scattering.

We note that due to the peculiar kinematics associated with virtual (imaginary) masses, the c.m. momenta q is not a single valued function of W. Our analysis is confined, thus, to $W^2 > Q^2 + P^2$ much the same as we have confined ourselves to $W^2 > Q^2$ in the single tag analysis [2]. For these values of W there is very little difference between our recipe and the standard fixed energy factorization relation. For further technical details of the fitting procedure, data handling etc., we refer the reader to [2].

The cut imposed on W, i.e. $W^2 > Q^2 + P^2$, provides a quantitative estimate of our requirement that W should be well above threshold. We shall return to this problem in some detail below.

In Fig. 2, we compare the results of both models

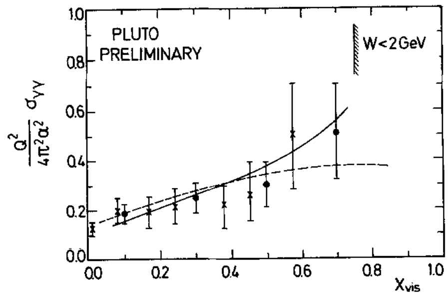

Fig. 2. Predictions of EVDM (solid line) and factorization (crossed points) for the virtual photon structure compared with PLUTO preliminary results (full circles) given in 3 as a function x_{vis} for $Q^2 = 6\,\mathrm{GeV}^2$ and $P^2 = 0.4\,\mathrm{GeV}^2$. Also shown QCD + VDM expectation (dashed line) taken from [3]. The error bars attached to the crossed points reflect the uncertainty present in the deep inelastic data and in the fitting procedure. Vertical shaded bars indicate the resonance region $W < 2$ GeV

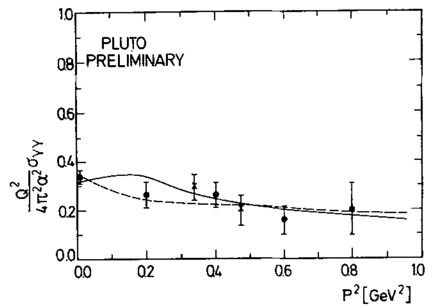

Fig. 3. Results of EVDM (solid line) and factorization (crossed points) for the virtual photon structure function as a function of P^2 averaged over Q^2 and x. Dashed line is QCD + VDM expectation from [3]. PLUTO experimental data (solid circles) from [3]. Factorization error bars are as in Fig. 2

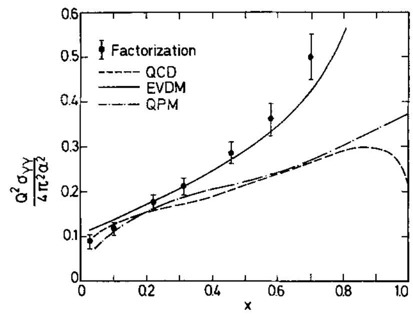

Fig. 4. Predictions for the virtual photon structure function. The EVDM, parton model and next-to-leading order QCD [8] calculations are for values of $Q^2 = 20\,\mathrm{GeV}^2$ and $P^2 = 0.5\,\mathrm{GeV}^2$, while the factorization calculation was made for $Q^2 = 22.5\,\mathrm{GeV}^2$ and $P^2 = 0.45\,\mathrm{GeV}^2$. Factorization error bars are as in Fig. 2

given as a function of x, with the preliminary data of the PLUTO collaboration [3] for $\sigma_{\gamma^*\gamma^*}$ at $\langle Q^2 \rangle = 6\,\mathrm{GeV}^2$ and $\langle P^2 \rangle = 0.4\,\mathrm{GeV}^2$ shown as a function of the true x value, whereas the data shown in Fig. 2 is given as a function of the measured x_{vis}, a quantity which is not corrected for the energy not seen in the detector. As in general $W_{vis}/W_{true} < 1$ and for the PLUTO detector in particular $W_{vis}/W_{true} \approx 0.8$, one has $x_{vis} > x_{true}$. The models are in agreement with the experimental data both as regards the magnitude and evolution in x. We note that the EVDM tends to lie above the data at large x. This is to be expected as large x corresponds to small W. It is obvious that the cross section parametrization of (1) cannot hold at threshold and a W_{min} cutoff is needed, corresponding to an x_{max} cutoff of $x_{max} = Q^2/(Q^2 + P^2 + W^2_{min})$. The EVDM results have been presented assuming $x = x_{true}$, so we expect these calculated values would decrease, if they had been calculated as a function of x_{vis}. For the actual values of Q^2 and P^2 of Fig. 2, we choose $W_{min} = 2$ GeV corresponding to $x_{max} = 0.57$. This is compatible with the choice $W^2 > Q^2 + P^2$ made in the estimates based on factorization.

In Fig. 2 we also show the predictions of the lowest order QCD calculations to which a VDM contribution has been added [3]. The added VDM structure function has the scale invariant form $F_2^{VDM} = 0.2\alpha(1 - x)$. In the first x bin, where most of the experimentally measured events lie, the VDM contribution accounts for approximately half of the measured cross section.

In Fig. 3, data from the same experiment is displayed as a function of the target mass (P^2), averaged over Q^2 and x. Again, the models suggested in this paper are in remarkable agreement with each other and very close to the data. We note that the data, as well as our estimates, show a much slower decrease in P^2 than the often assumed dipole form factor dependence [8]. In Fig. 4 we compare the predictions of EVDM for the virtual photon structure function for $Q^2 = 20\,\mathrm{GeV}^2$ and $P^2 = 0.5\,\mathrm{GeV}^2$, with the Rossi [8] results for the parton model and for the next to leading order QCD calculation. Also shown are the results of the factorization method, for $Q^2 = 22.5\,\mathrm{GeV}^2$ and $P^2 = 0.45\,\mathrm{GeV}^2$, the nearest values to the above for which experimental data on $\gamma^* - p$ is available [6]. Rossi [8] warns that one should view with due scepticism the QCD results at $P^2 = 0.5\,\mathrm{GeV}^2$, because of the possible breakdown of the perturbation expansion, for such low values of P^2. We have shown that both the factorization relation and EVDM are in good agreement with the data presently available on double tag $\gamma^* - \gamma^*$ collisions. These results, when combined with the conclusions of [1] and [2], which dealt with single tag events, provide a consistent overall picture. In that inclusive phenomena, associated with one or two virtual photons in $\gamma^* - \gamma^*$ reactions are well accounted for by factorizable models, such as ours, provided the virtual photon mass is not too large ($Q^2 \lesssim 25\,\mathrm{GeV}^2$), and W is above the threshold region.

From our analysis it is apparent that the validity of the models extend over a wider Q^2 domain than commonly believed. As the phenomena of hadron-like behaviour of the photon is assumed to take place through quantum fluctuations into hadron (vector) states with lifetimes of the order of $1/\sqrt{Q^2}$. We thus expect hadronic models to breakdown for sufficiently large Q^2, where the point-like coupling of the photon should be dominant.

It would be most rewarding, if somehow we could soon observe convincing experimental evidence of the point-like photon, which is expected to have two main signatures:

(i) A $\log Q^2$ dependence of $\sigma(Q^2, W)$ and $F_2^\gamma(x, Q^2)$ and

(ii) a $1/W^2$ cross section dependence which reflects itself in the unusual high x maxima of $F_2^\gamma(x, Q^2)$.

The point-like photon is devoid of quarks and gluons and is in principle easy to observe, however, in practice the situation is not as simple. As was noted in [1], the $\log Q^2$ dependence can also be simulated by hadronic models. Experimentally as well, there are problems, as presently available data is susceptible to kinematic uncertainties in the small W-high x region, which for the $\gamma^* - \gamma^*$ reactions is a domain where one cannot ignore the explicit threshold behaviour of $\sigma(Q^2, W)$.

We conclude with a remark concerning the range of validity of the two models discussed in the paper. As noted previously, EVDM cannot be extended to include cross section terms which are more singular than $1/W$. This is not necessarily the case for factorization, where the contribution is introduced through the deep inelastic scattering data. The problem here, however, is a practical one, i.e. the input data required is the $\sigma(\gamma^* - p)$ at low W-high x. This part is an unimportant small sector of the $e-p$ $(\mu - p)$ deep inelastic scattering, and is susceptible to all too many experimental uncertainties, and no accurate data is yet available.

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