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MEASUREMENT OF THE TOTAL PHOTON–PHOTON CROSS SECTION FOR THE PRODUCTION OF HADRONS AT SMALL Q^2

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The total photon–photon cross section for the production of hadrons, $\sigma_{\gamma\gamma}(W, Q^2)$, has been measured in the single-tag condition for $0.1 < Q^2 < 1.0\ \mathrm{GeV}^2$ and $1.5 < W < 10$ GeV. The results are based on 2929 multihadron events obtained with the PLUTO detector at PETRA. The Q^2 dependence of $\sigma_{\gamma\gamma}$ averaged over W can be described by GVDM. The dependence of $\sigma_{\gamma\gamma}$ on the mass W of the hadronic final state has been extracted at $Q^2 = 0.44\ \mathrm{GeV}^2$ by unfolding the effects of experimental resolution and acceptance. The cross section is found to rise at small W. The result is compared with VDM and the parton model.

High energy electron–positron storage rings allow the inclusive reaction $e^+e^- \to e^+e^- +$ hadrons to be measured. This type of process can be interpreted as hadron production by two interacting virtual photons ($\gamma_1\gamma_2 \to$ hadrons) radiated from the incoming leptons. Experimentally, two-photon reactions can be identified by detecting at least one of the final state leptons (tagging). If the second lepton is restricted to small angles $\Theta_2 < \Theta_2^{\max}$ (antitagging) the photon radiated from this lepton is nearly real. The reaction is then equivalent to the scattering of electrons off a real photon beam.

Under these conditions the inclusive cross section [1] $\sigma(e^+e^- \to e^+e^- +$ hadrons) can be written in terms of $\sigma(e\gamma \to e +$ hadrons) as

$$\mathrm{d}\sigma(e^+e^- \to e^+e^- + \text{hadrons}) = \mathrm{d}\sigma(e\gamma \to e + \text{hadrons}) N(z, \Theta_2^{\max})\, \mathrm{d}z$$

with

$$N_\gamma(z, \Theta_2^{\max}) = (\alpha/\pi) z^{-1} \times \{[1 + (1-z)^2] \ln[E(1-z)\Theta_2^{\max}/m_e z] - (1-z)\},$$

describing the flux of quasi-real target photons with fractional energy $z = E_\gamma/E$ (E = beam energy). The relation between $\sigma_{e\gamma}$ and $\sigma_{\gamma\gamma}$ is given by

$$\mathrm{d}\sigma(e\gamma \to e + \text{hadrons}) = \Gamma_T \sigma_{\gamma\gamma}(W, Q^2)\, \mathrm{d}\Omega,$$

where $-Q^2$ is the mass squared of the virtual photon (the probe photon) radiated by the tagged lepton and W is the invariant mass of the hadronic final state. The quantity Γ_T describing the flux of transversely polarized virtual photons is related to the measured kinematic parameters (E_1, Θ_1) of the tagged lepton

$$\Gamma_T = \alpha E_1 [1 + (1-y)^2]/2\pi^2 Q^2 y, \quad y = 1 - (E_1/E)\cos^2(\Theta_1/2).$$

The total cross section $\sigma_{\gamma\gamma}(W, Q^2)$ measured for single tag events can be written as

$$\sigma_{\gamma\gamma}(W, Q^2) = \sigma_{TT}(W, Q^2) + \epsilon\sigma_{TL}(W, Q^2),$$

where σ_{TT} is the cross section for interaction between a transversely polarized photon and a real photon, and σ_{TL} is the cross section for interaction between a longitudinally polarized photon and a real photon. The ratio of the respective photon fluxes is

$$\epsilon = \Gamma_L/\Gamma_T = 2(1-y)/[1 + (1-y)^2].$$

For the conditions of this analysis ϵ differs little from unity ($\langle\epsilon\rangle = 0.98$).

Only one measurement [2] of the W and Q^2 dependence of the total photon–photon scattering cross section $\sigma_{\gamma\gamma}(W, Q^2)$ has been published. This measurement was made in the kinematic region $0.1 < Q^2 < 1.0\ \mathrm{GeV}^2$ and $1.5 < W < 10$ GeV. In the present paper we report on a measurement of $\sigma_{\gamma\gamma}$ in the same kinematic region but with significantly increased statistics using an apparatus with improved acceptance for photon–photon interactions. The cross section $\sigma_{\gamma\gamma}$ has been determined as a function of W and Q^2 using 2929 single-tagged hadronic events which correspond to an integrated luminosity of 19 pb^{-1}. The events were obtained with the PLUTO detector at the e^+e^- storage ring PETRA at an e^+e^- center of mass energy of 34.6 GeV.

Details of the PLUTO detector have been given elsewhere [3,4], so we briefly discuss only those components relevant to this study. Charged particles are detected and their momenta are measured in either the central detector, which consists of cylindrical proportional chambers in a 1.65 T solenoidal magnetic field, or two forward spectrometers, which are each composed of arrays of drift and proportional chambers and a 0.2 T m septum magnet. The central detector covers the polar angular range $25^\circ \lesssim \Theta \lesssim 155^\circ$ and the full azimuth. The forward spectrometers cover the region $5^\circ \lesssim \Theta \lesssim 15^\circ$ (and symmetrically, $165^\circ \lesssim \Theta \lesssim 175^\circ$) and 85% of the full azimuth. The momentum resolution of both the central detector and the forward spectrometers is $\sigma_p/p = 3\% \cdot p$ (p in GeV/c). Photons are measured in the barrel, endcap and forward (LAT) lead-scintillator shower counters, which cover 99% of the full solid angle.

The scattered electrons are measured in small-angle taggers (SAT's) which cover the polar regions from 30 to 55 mrad. The SAT's are lead-scintillator shower counters with energy resolution $\sigma_E/E = 16.5\%/\sqrt{E}$, ($E$ in GeV). Each SAT is azimuthally segmented into twelve 30° modules, the signal from each of which is read out at the inner and outer radial edges using wavelength shifter bars. These signals, together with energy sharing between modules, provide a good measurement of the shower position. Proportional tube chambers in front of the SAT's improve the position resolution and distinguish between charged particle and photon showers. The Q^2 resolution in the SAT is $\sigma(Q^2)/Q^2 = 10\%$.

The experimental trigger for single-tagged events was made as loose as possible. The trigger required a SAT shower energy of at least 6 GeV in conjunction with at least one track in the central detector. This track trigger condition was fully efficient for tracks at $|\cos(\vartheta)| < 0.8$ and with momenta transverse to the e^+e^- beam axis greater than 150 MeV/c.

The following event selection criteria were defined in order to optimize the acceptance and minimize the background contamination:

(1) Tag definition. One isolated energy cluster in the SAT with $E > 8$ GeV was required to be associated with a hit in the tube chambers in front of the SAT. To avoid edge effects the position of the shower was restricted to a fiducial area corresponding to an angular range $32 < \Theta < 55$ mrad.

(2) Antitag condition. To keep the mass of the target photon small, a veto against double-tag events was applied. No additional energy cluster of more than 4 GeV was allowed in the SAT or in the LAT opposite to the tag.

(3) Hadronic final state. A multihadronic final state was required to have either 2 charged particles with momenta transverse to the beam $p_T > 150$ MeV/c (tracks) and at least 1 photon ($E > 150$ MeV) or at least 3 tracks. At least one inner detector track with $p_T > 200$ MeV/c was required. To reduce the background from leptonic QED processes, particles identified as electrons by the correlation between momentum and shower energy were not included in the track count. The visible invariant mass W_{vis}, reconstructed from the measured charged and neutral particles in the final state, was required to be between 1.2 and 10 GeV to maintain a good acceptance and to eliminate e^+e^- annihilation events.

To determine the background contamination in the selected event sample the following sources were considered:

(a) Beam–gas events.

(b) 1γ events: $e^+e^- \to ee, \mu\mu, \tau\tau$, hadrons.

(c) 2γ QED events: $\gamma\gamma \to ee, \mu\mu, \tau\tau$.

The beam–gas background was determined from the data using the side bands of the event vertex distribution along the beam, and found to be small (4%). Backgrounds (b) and (c) were studied in detail by Monte Carlo (MC) calculations. The 1γ annihilation background is calculated to be less than 0.3% mainly because of the requirement of a high energy electron identified by the SAT. The most important background in category (c) is $\tau\tau$ production (1.5%). The sum of all background sources (a)–(c) amounts to 6.7% of the selected event sample and was subtracted from it.

The resulting data sample covers the Q^2 range $0.1 < Q^2 < 1$ GeV^2 with an average Q^2 of 0.44 GeV^2. The antitag condition (with $\Theta_2^{\max} \approx 30$ mrad) restricts the target photon mass to be small ($\langle P^2 \rangle = 0.017$ GeV^2). The event acceptance in the Q^2 range considered rises from 15% at $W = 2$ GeV to 50% for $W > 4$ GeV.

The evaluation of $\sigma_{\gamma\gamma}(W, Q^2)$ is difficult for several reasons. Firstly, in contrast to e^+e^- annihilation processes, the hadronic final state mass W is variable in $\gamma\gamma$ processes; W is therefore not a priori known, but has to be reconstructed from the observed hadrons. Due to particle losses and the finite resolution of the detector, the measured invariant mass W_{vis} is on average 27% lower than the true mass W, with an RMS resolution $\sigma_W/W_{\text{vis}} = 26\%$. Secondly, the evaluation of the multihadron acceptance after data selection depends on the assumed fragmentation of the $\gamma\gamma$ system into hadrons. In the following we outline the procedure used to obtain the dependence of $\sigma_{\gamma\gamma}$ on the true value of W.

Monte Carlo events were generated according to the photon fluxes described above with $\sigma_{\gamma\gamma}$ set to a constant. A model for the fragmentation of the $\gamma\gamma$ system into hadrons was developed. In this model a multipion final state was generated with mean charged and neutral multiplicities given by

$$\langle n^{\pm}\rangle = 2.0\sqrt{W}, \quad \langle n^{0}\rangle = 1.3\sqrt{W} \quad (W \text{ in GeV}) .$$

For a given mean multiplicity the event multiplicities were generated according to KNO distributions [5] similar to those found in e^+e^- annihilation [3]. The distribution of the transverse momenta p_T of the pions relative to the $\gamma\gamma$ axis was best described by a W dependent mixture of isotropic phase space (IPS) and limited p_T phase space (LPS). From pure IPS, generated below 3 GeV, the fraction of LPS was increased to 90% above 5 GeV. LPS events were generated in the same way as IPS events but with an additional weight factor of $\exp(-5p_T^2)$ for each pion.

In an unfolding procedure the mapping from W to W_{vis} was determined by a MC simulation which included both the $\gamma\gamma$ fragmentation and the detector response. This mapping was then inverted [6] in a way which enforced smoothness of $\sigma_{\gamma\gamma}(W)$ and thus avoided the enhancement of the random fluctuations which usually occurs in the matrix inversion in such a procedure.

The reliability of the unfolding procedure for the PLUTO detector was verified by simulating events with an assumed photon–photon cross section and then extracting $\sigma_{\gamma\gamma}$ using the unfolding procedure described above. Good agreement between the input cross section and the cross section determined in the unfolding procedure was achieved.

To adjust the fragmentation parameters and to test the fragmentation model, various experimental distributions were compared with the MC simulation (which used the cross section finally obtained from the unfolding procedure). Figs. 1a and 1b show as examples the inclusive p_T^2 distribution of charged particles and the charged multiplicity distribution for the full W_{vis} range. In both cases the fragmentation model describes the data well. Similar good agreement was found in sub-regions of W_{vis}. The W_{vis} distribution (fig. 1c) is also well reproduced.

The sensitivity of the unfolded $\sigma_{\gamma\gamma}$ to the details of the hadron fragmentation was studied by varying the fragmentation parameters with respect to their optimal values described above. By varying the fragmentation parameters in such a range that the measured final state particle distributions were still well reproduced, the systematic uncertainty in the event acceptance was estimated. The resulting systematic error on $\sigma_{\gamma\gamma}$ was found to be 15% for $2 < W < 8$ GeV and 25% for $W < 2$ GeV and $W > 8$ GeV. These systematic errors in-

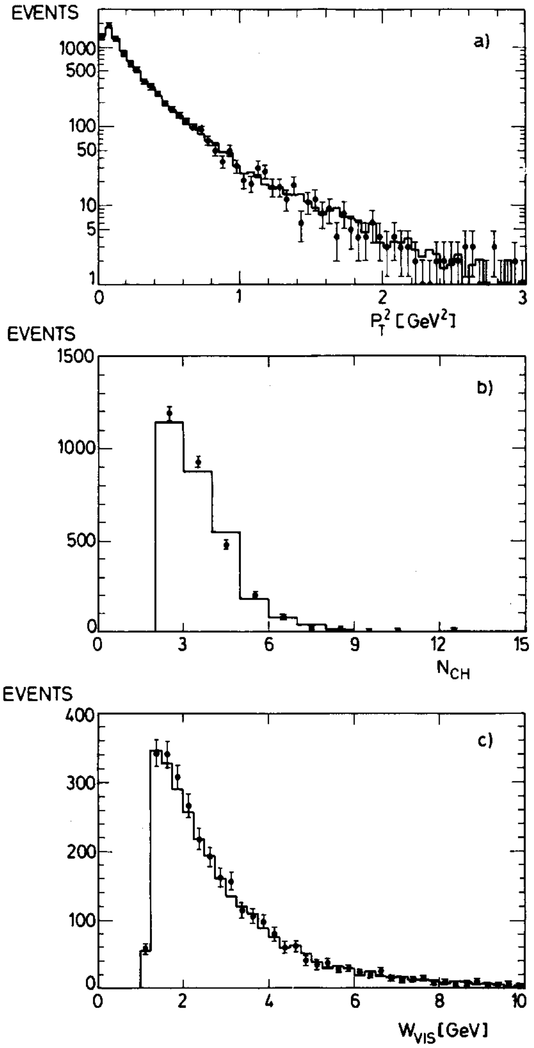

Fig. 1. Uncorrected experimental data (points) compared with the Monte Carlo calculation (histogram) obtained with the extracted cross section $\sigma_{\gamma\gamma}$ and the fragmentation model described in the text; (a) inclusive charged particle p_T^2 (transverse momentum relative to the beam axis), (b) charged particle multiplicity and (c) measured invariant mass W_{vis}.

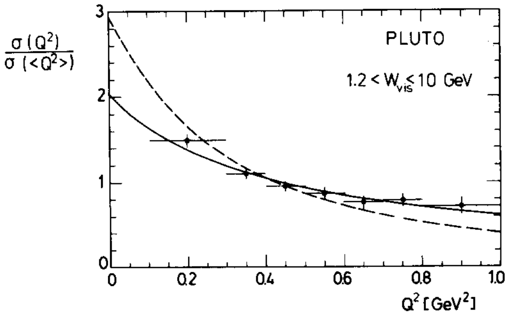

Fig. 2. The Q^2 dependence of the total photon–photon cross section averaged over 1.2 GeV $< W_{\text{vis}} <$ 10 GeV. The full curve describes a fit of the GVDM function, the dashed one of the ρ propagator ansatz.

Table 1
W dependence of $\sigma_{\gamma\gamma}$ measured at Q^2 = 0.44 GeV^2 and extrapolated to Q^2 = 0 GeV^2 using GVDM. For Q^2 = 0.44 GeV^2 the first and second errors are the statistical and systematic errors, respectively. For Q^2 = 0 GeV^2 the errors are the statistical and systematic errors added in quadrature.

W (GeV)	$\sigma_{\gamma\gamma}$ (nb)	
	Q^2 = 0.44 GeV^2	Q^2 = 0 GeV^2
1.5 – 2	309 ± 21 ± 77	627 ± 163
2 – 3	241 ± 11 ± 24	489 ± 54
3 – 4	182 ± 14 ± 27	369 ± 62
4 – 6	144 ± 17 ± 22	293 ± 56
6 – 8	107 ± 24 ± 21	218 ± 66
8 – 10	125 ± 39 ± 31	254 ± 102

clude also variations found in $\sigma_{\gamma\gamma}$ when applying different event selection criteria (e.g. excluding events with two tracks and a shower in the final state).

The Q^2 dependence of $\sigma_{\gamma\gamma}$ was obtained by determining the ratio of data and MC event yields, where the MC sample had been generated with a cross section $\sigma_{\gamma\gamma}$ independent of Q^2. Fig. 2 shows the dependence of $\sigma_{\gamma\gamma}$ on Q^2 averaged over the whole accepted region in the hadronic final state masses (1.2 $< W_{\text{vis}} <$ 10 GeV). We compare the Q^2 dependence of the data with two commonly used functions. As a first approximation it has been assumed that the Q^2 dependence of the cross section is given by the ρ propagator squared

$$F_\rho(Q^2) = [1/(1+Q^2/m_\rho^2)]^2 .$$

This ansatz, motivated by the Vector Meson Dominance model (VDM), neglects contributions from higher mass vector mesons and assumes that the cross section for longitudinal polarized photons vanishes. An alternative form, without these assumptions, is the generalized vector meson dominance model (GVDM) [7]:

$$F_{\text{GVDM}}(Q^2) = \sum [r_v(1+Q^2/4m_v^2)/(1+Q^2/m_v^2)^2] + 0.22/(1+Q^2/m_0^2) ,$$

with $v = \rho, \omega, \varphi$ and $r_\rho = 0.65$, $r_\omega = 0.08$, $r_\varphi = 0.05$, $m_0 = 1.4$ GeV.

In fig. 2 fits of the form $\sigma_{\gamma\gamma}(Q^2) = a \cdot F(Q^2)$ to the data are shown. Under the assumption that the data can be entirely described by VDM-like models, it is evident that the data fit the GVDM function (χ^2/n_{D} = 5/6) better than the ρ ansatz (χ^2/n_{D} = 33/6). We have investigated whether the Q^2 dependence of $\sigma_{\gamma\gamma}$ varies with W. We found that both low ($W_{\text{vis}} <$ 3 GeV) and high ($W_{\text{vis}} >$ 3 GeV) W events have Q^2 distributions that are consistent with $F_{\text{GVDM}}(Q^2)$.

The function $F_{\text{GVDM}}(Q^2)$ was used to interpolate the cross section within the accepted Q^2 range to determine $\sigma_{\gamma\gamma}(W)$ at our central value of Q^2 = 0.44 GeV^2. Using other functions (flat or ρ propagator) for the purpose of interpolation yielded indistinguishable results. The cross section $\sigma_{\gamma\gamma}(W, Q^2 = 0.44\ \text{GeV}^2)$ is shown in table 1 and fig. 3. The inner error bars in fig. 3 describe the statistical errors only, whereas the full error bars show the systematic and statistical errors added in quadrature. Table 1 shows also the cross section extrapolated to Q^2 = 0 GeV^2 using the GVDM function. These measurements agree with those of ref. [2] within errors provided the same function is used for extrapolation to Q^2 = 0 GeV^2.

Theoretical predictions for $\sigma_{\gamma\gamma}$ have been derived within the Regge pole model using factorization and the high energy behaviour of photon–nucleon and nucleon–nucleon scattering. An early attempt [8] to evaluate $\sigma_{\gamma\gamma}$ in this VDM motivated approach has given $\sigma_{\gamma\gamma}(W, Q^2 = 0) = [240 + 270/W(\text{GeV})]$ nb. The dashed line in fig. 3a shows this prediction evaluated at Q^2 = 0.44 GeV^2 using $F_{\text{GVDM}}(Q^2)$. It is evident that this model is in disagreement with the data at low W. Recently this VDM motivated method has been extended [9] to include in the factorization procedure phase space and flux corrections, which are not negligible at low W values. The band in fig. 3a shows the corresponding prediction. The measured cross section

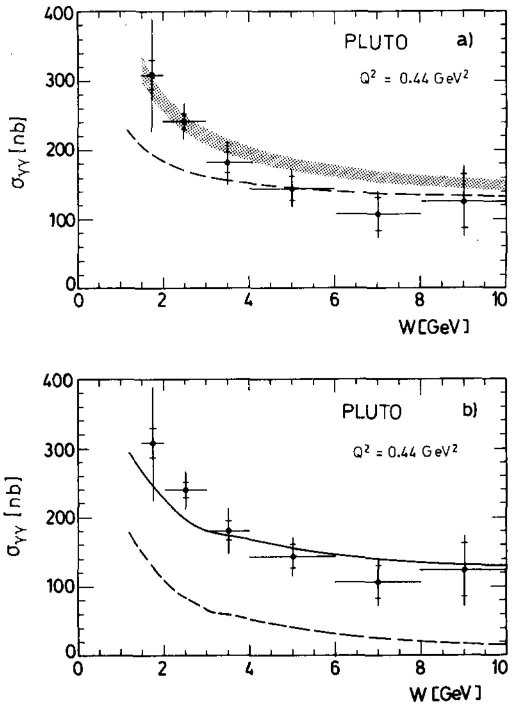

Fig. 3. The total photon–photon cross section as a function of the true value of the final state hadronic mass W at Q^2 = 0.44 GeV^2. The inner error bars show the statistical errors only, whereas the full error bars include the systematic errors added in quadrature. (a) The dashed line represents the cross section [240 nb + 270 nb/W (GeV)] $\cdot F_{\mathrm{GVDM}}(Q^2)$. The band represents the prediction of ref. [9]. (b) The dashed line shows the QPM prediction, while the full line describes a sum of QPM and a W-independent cross section of (120 ± 14) nb.

is described satisfactorily overall, although at high W the data tend to lie below the prediction.

We have investigated whether all the rise of $\sigma_{\gamma\gamma}$ at low W could be explained by a point-like photon–quark coupling. The point-like contribution to $\sigma_{\gamma\gamma}$ (dashed line in fig. 3b) has been calculated for the quark–parton model (QPM) using the formula given in ref. [1] for the production of u, d, s and c quarks in $\gamma\gamma$ scattering. The u and d quark masses were both taken to be 300 MeV, the s quark mass 500 MeV and the c quark mass 1.6 GeV. The full line in fig. 3b corresponds to a fit in which the QPM contribution is added to a constant term ($\sigma_{\gamma\gamma} = \sigma_{\mathrm{QPM}} + A$) with A = (120 ± 14) nb. Although the fit describes the data well (χ^2/n_{D} = 4/5), the systematic deviation of the data from the fit might suggest a somewhat steeper W dependence than expected from QPM alone.

In conclusion, we have measured the total photon–photon cross section $\sigma_{\gamma\gamma}(W, Q^2)$ for Q^2 values up to 1 GeV^2 over a range of W between 1.5 and 10 GeV. The Q^2 dependence averaged over W can be described by GVDM. The W dependence of $\sigma_{\gamma\gamma}$ has been determined at Q^2 = 0.44 GeV^2. The cross section rises at small W. The W dependence of the data is compatible with a prediction [9] motivated by VDM or with QPM plus a W independent hadronic component.

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