HIGH p_T HADRON PRODUCTION IN PHOTON–PHOTON COLLISIONS

TASSO Collaboration

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We have studied the properties of hadron production in photon–photon scattering with tagged photons at the e^+e^- storage ring PETRA. A tail in the p_T distribution of particles consistent with p_T^{-4} has been observed. We show that this tail cannot be due to the hadronic part of the photon. Selected events with high p_T particles are found to be consistent with a two-jet structure as expected from a point-like coupling of the photons to quarks. The lowest-order cross section predicted for $\gamma\gamma \to q\bar{q}$, $\sigma = 3 \Sigma e_q^4 \cdot \sigma_{\gamma\gamma \to \mu\mu}$, is approached from above by the data at large transverse momenta.

Photon–photon scattering is a new field which can be explored particularly well with high energy e^+e^- storage rings. First results on multihadron production with quasi-real photons [1,2] indicated that the size of the total cross section at energies above 3 GeV is in qualitative agreement with that expected from the scattering of the hadronic part of the photon (vector dominance model, VDM). Preliminary analyses of the distribution of p_T, the particle momentum transverse to the beam, indicated the presence of a tail of high p_T particles [2,3]. Such a tail can arise from the point-like coupling of the photon to quarks. However, a major experimental problem in connection with the high p_T tail is the background from one-photon annihilation, which also produces events with high p_T particles.

In this paper we present an analysis of our data on $\gamma\gamma$ production of high p_T hadron events and a detailed evaluation of the background processes. We show that the high p_T particles observed in this experiment are indeed predominantly produced by two photon scattering. We have analyzed the shape of events with high p_T particles in order to investigate a possible two-jet structure and have compared the cross section for two-jet production with that expected for the process $\gamma\gamma \to q\bar{q}$ [4], and with the lepton-pair cross section, $\gamma\gamma \to$ lepton$^+$lepton$^-$, measured in this experiment.

We have analyzed tagged two-photon events observed with the TASSO detector at the e^+e^- storage ring PETRA. The data were collected at beam energies from 13.7 to 18.3 GeV with a total integrated luminosity of 9008 nb^{-1}.

In this analysis we have included only charged particles observed in the central part of the detector, the features of which have been described previously [5]. Charged tracks were accepted for polar angles $|\cos\Theta| < 0.87$ and for momenta transverse to the beam of $p_T > 0.1$ GeV/c. The rms momentum resolution including multiple scattering was $\sigma_p/p = 0.02 \times (1 + p^2)^{1/2}$ (p in GeV/c) and the track finding efficiency was 97%. The trigger required at least one track in the central drift chamber, with a polar angle $|\cos\Theta| < 0.82$ and with p_T of more than about 0.3 GeV/c. In addition, an energy of at least 3.5 GeV had to be deposited by a charged particle in the forward detector (tag). The forward detector covered a narrow angular region between 24 and 60 mrad relative to the beam direction. Identical forward detector modules surrounded the beam pipe at either side of the central detector about 6 m away from the center of the interaction region. Each consisted of an array of 36 lead-glass Čerenkov counters, about 12 radiation lengths thick, preceded by an azimuthally segmented scintillator hodoscope. The average q^2 of the tagged photon was 0.35 GeV^2.

Candidates for two-photon produced multihadron events were selected requiring in the forward detector a tag energy $E > 4$ GeV together with a hit in the scintillator hodoscope and in the central detector one track with $p_T > 0.3$ GeV/c, $|\cos\Theta| < 0.84$ and two or more tracks with $p_T > 0.2$ GeV/c, $|\cos\Theta| < 0.84$, all coming from the interaction point. The invariant mass of the particle system seen in the central detector, W_{vis}, had to be smaller than 70% of the beam energy. A total of 1125 events satisfied these selection criteria with an average $\gamma\gamma$ cms energy of $\langle W_{\gamma\gamma}\rangle = 6.1$

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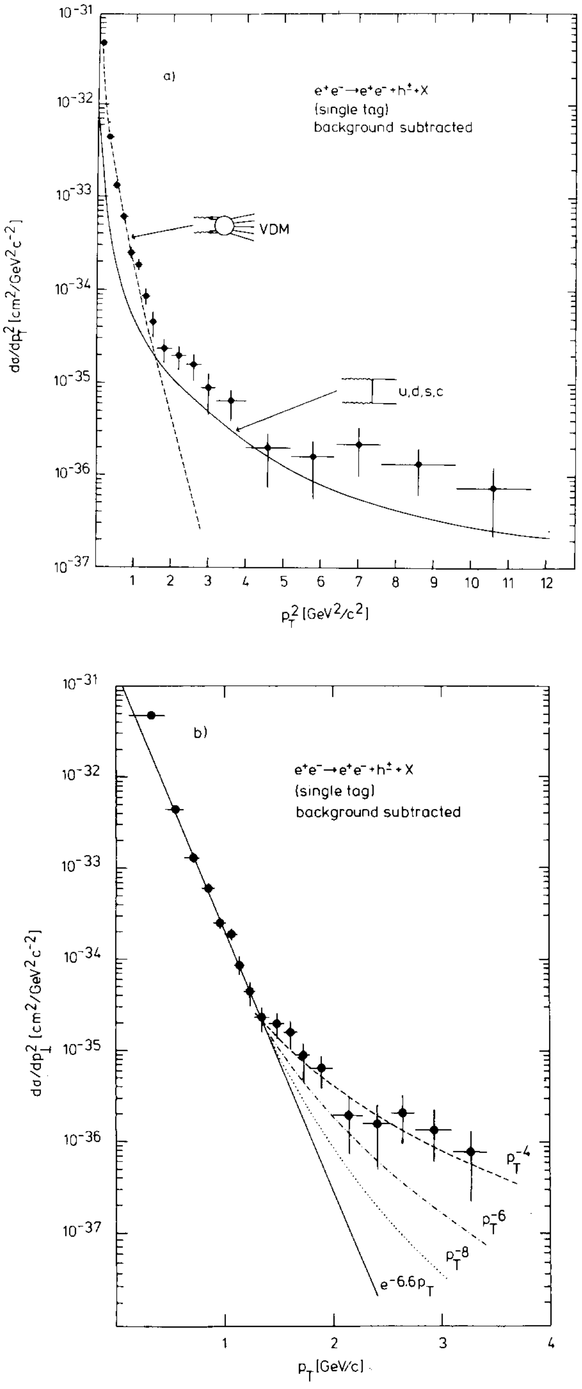

Fig. 1. Differential cross section $d\sigma/dp_T^2$ plotted against (a) p_T^2, (b) p_T. Also shown in (a) are the predictions from VDM (dashed line) and from $\gamma\gamma \to q\bar{q}$ with subsequent quark fragmentation as described in model (a) of the text (full line).

GeV as determined by Monte Carlo simulation. For these events fig. 1a shows the differential cross section $d\sigma/dp_T^2$ versus p_T^2 of the charged particles corrected for acceptance of the central detector. The acceptance is constant for $p_T > 0.7$ GeV/c. In this analysis p_T is taken with respect to the beam axis which is in general close to the direction of motion of the $\gamma\gamma$ system. The data exhibit a steep fall-off at low p_T^2 and a long tail at higher p_T^2 values.

To make sure that the high p_T tail is due to $\gamma\gamma$ production of hadrons we have investigated possible sources of background. Contributions not originating from e^+e^- reactions like beam–gas scattering have been determined from vertex distributions to be a total of 3%. Most of the background from QED processes is removed by the multiplicity requirement. Converted photons from bremsstrahlung in QED processes which could fake higher multiplicites have been removed by kinematical cuts. The QED process $\gamma\gamma \to \tau^+\tau^-$ has been calculated using the program of Vermaseren [6] and the tau decay branching ratios given in ref. [7]. Its contribution to the multihadron data sample is 2%.

A serious background for the production of high p_T events comes from one-photon annihilation (1γ) events when either the incoming electron or positron radiates a hard photon. This background is considerably reduced by requiring a tag in the event selection. However a tag in 1γ events may be produced by a charged particle interacting in the lead-glass of the forward detector or a photon with either converts in the beam pipe or simultes a charged particle in the forward detector by shower particles backscattered from the lead-glass into the hodoscope. In most 1γ background events, the tag is produced by the photon originating from initial state bremsstrahlung, rather than by a particle from the final hadronic state. The probability for a photon to be detected as a charged particle in the forward detector is given by the conversion probability in the beam pipe (11%) plus the probability that products from a shower in the lead-glass counters scatter back into the hodoscope (20 ± 4%). We have studied 1γ hadron production using a standard event generator for e^+e^- annihilation which included initial state radiation [8]. This generator has been used extensively in the analysis of 1γ annihilation processes in TASSO experiments [9]. All experimental distributions are found to be well described by this program down to detected charged particle energies of about 10 GeV and we have assumed its validity down to total cms energies of GeV. For kinematical reasons the actual invariant mass of the hadronic system for 1γ events accepted in our data sample was never smaller than 5 GeV. Since this is well above the resonance region the use of a $q\bar{q}$- jet model for the final state generation is justified. We have checked the absolute normalization of the 1γ background calculation in an energy range where this process dominates over two photon reactions, namely $W_{vis} > 10$ GeV. We observed 6 tagged events in this energy range, of which only 1.2 are expected to come from $\gamma\gamma$ reactions. The remainder of 4.8 ± 2.4 events agrees with the result of 4.1 ± 0.7 events from the MC calculation of 1γ annihilation. Going back in the kinematic range of our $\gamma\gamma$ data sample this calculation predicts a 1γ background contribution of 1% to the total sample.

All background processes mentioned above have been subtracted in fig. 1a. They amount to about 20% ($\frac{2}{3}$ from 1γ events, $\frac{1}{3}$ from $\gamma\gamma \to \tau^+\tau^-$) in the range of $p_T^2 > 4$ GeV$^2/c^2$. We conclude that the high p_T tail observed in our tag data is a feature of $\gamma\gamma$ production of hadrons.

Also shown in fig. 1a are the expectations from a vector dominance model of $\gamma\gamma$ scattering into hadrons (dashed line) and from a pointlike coupling $\gamma\gamma \to q\bar{q}$ with subsequent quark fragmentation (full line). This model is explained below. In VDM the photons couple directly to vector mesons and $\gamma\gamma$ scattering proceeds via vector meson–vector meson scattering. We used an $\exp(-5p_T^2)$ parametrization of the p_T^2 distribution of hadrons with respect to the $\gamma\gamma$ axis and a total cross section for $\gamma\gamma \to$ hadrons of $\sigma_{\gamma\gamma}(W_{\gamma\gamma}) = (450 + 600/W_{\gamma\gamma})$ nb, where $W_{\gamma\gamma}$ is the total $\gamma\gamma$ cms energy. This model fits the multihadron data except for the high p_T tail in fig. 1a [‡1].

We present further evidence that the high p_T tail cannot be attributed to hadron–hadron-like scattering of the photons by plotting in fig. 1b $d\sigma/dp_T^2$ versus p_T which can be compared with the $Ed^3\sigma/dp^3$ distributions of proton–proton scattering [10]. The p_T distributions measured in p–p interactions show a steep exponential fall-off – $\exp(-ap_T)$, 6 GeV^{-1} $c < a < 7$ GeV^{-1} c for pions – at low p_T. In the p_T range below 4 GeV/c, $Ed^3\sigma/dp^3$ always falls faster than p_T^{-8} and reaches this power only for large s. Our two-photon data above 2 GeV/c however are about 10 times larger than expected from a p_T^{-8} behaviour, although our values for $\sqrt{s}$ are only around 10 GeV. The experimental distribution above $p_T = 1.5$ GeV/c is in agreement with p_T^{-4}. A fit of the type $c_1 \exp(ap_T) + c_2 p_T^b$, p_T in GeV/c, to the p_T distribution yielded $a = -7.4 \pm 0.3$ GeV^{-1} c and $b = -3.87 \pm 0.6$. We conclude that the inclusive p_T distribution in $\gamma\gamma$ collisions is qualitatively different from that observed in hadron–hadron collisions.

If the production of high p_T hadrons in $\gamma\gamma$ collisions is the result of the point-like coupling of the photons to a quark–antiquark pair one should observe two jets of hadrons. The two jets are in general not collinear since in the laboratory system the two initial photons usually have unequal momenta.

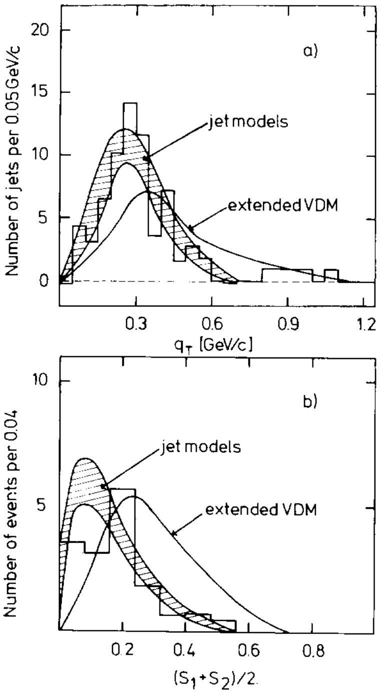

Fig. 2. Distributions of (a) transverse particle momentum averaged over each jet and (b) sphericity averaged over both jets for candidate jet events in comparison to a $\gamma\gamma \to q\bar{q} \to$ jet + jet model with four different types of fragmentation (shaded area) and to an extended vector dominance model (line).

‡1 The asymptotic value of $\sigma_{\gamma\gamma}$ has been estimated from πp scattering data via vector dominance and the additive quark model to be about 250 nb [11]. Using this value instead of our best fit to the low p_T multihadron data, the contribution of VDM to the high p_T tail would be even smaller than shown in fig. 1a.

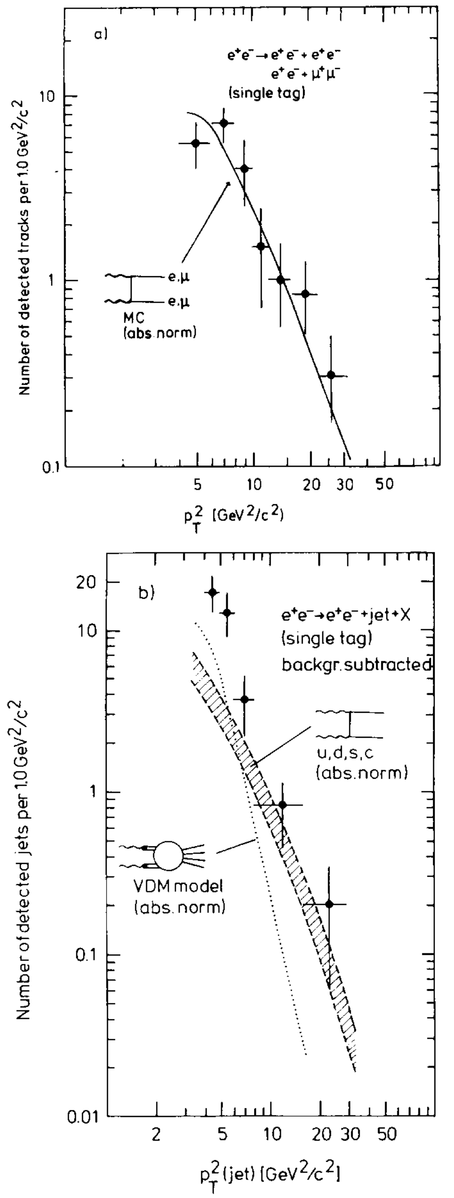

Fig. 3. The p_T^2 distribution for (a) $e^+e^- \to e^+e^-$ + lepton$^+$lepton$^-$ compared to a QED calculation and (b) the $p_{T\,\mathrm{jet}}^2$ distribution for $e^+e^- \to e^+e^-$ + jet + X compared to $e^+e^- \to e^+e^-$ + $q\bar{q}$ model with four different types of fragmentation (shaded area) and to VDM (dotted line).

In order to search for a possible two-jet structure we selected events with at least four tracks. Then we defined two jets as those two groups C_1, C_2 of particles which maximize $|\Sigma_{C1}\boldsymbol{p}| + |\Sigma_{C2}\boldsymbol{p}|$. We required at least two tracks per jet and at least one jet with a p_T greater than 2 GeV/c. The visible energy had to be between 3.0 GeV and 70% of the beam energy. After these cuts we were left with 43 jet candidate events with an average $W_{\gamma\gamma}$ of 9.5 GeV. Distributions of these jet candidate events, corrected for acceptance, are shown in figs. 2 and 3. The background of 7 events, 1.5 of which come from beam–gas scattering, 1 from $\gamma\gamma \to \tau^+\tau^-$ production and 4.5 from 1γ processes, has been subtracted.

In the jet picture it is expected that hadrons arising from jet fragmentation have limited momenta k_T transverse to the jet axis and that these k_T averaged over each jet have a mean value of about 0.3 GeV/c. In fig. 2a we show the distribution of $q_T = \Sigma_{\mathrm{jet}} |k_T| / N_{\mathrm{jet}}$, where N_{jet} is the number of particles in the jet. The average value is $\langle q_T \rangle = 0.32 \pm 0.02$ GeV/c. Fig. 2b shows the mean of the sphericities S_1, S_2 of the jets, independently determined for each jet.

The selected events were compared with a model where hard $\gamma\gamma$ scattering proceeds through $q\bar{q}$ production via quark exchange:

$$e^+e^- \to e^+e^- + q\bar{q} \to e^+e^- + 2 \text{ jets} .$$

This process was computed using the Monte Carlo program of Vermaseren [6] which generates events according to $e^+e^- \to e^+e^- + q\bar{q}$. The cross section for this process is given in terms of [4]

$$R_{\gamma\gamma} = \sigma_{\gamma\gamma\to q\bar{q}}/\sigma_{\gamma\gamma\to\mu\mu} = 3 \sum_{\mathrm{udsc}} e_q^4 = 34/27 ,$$

where e_q is the quark charge and the factor 3 comes from the sum over all colour indices.

Some uncertainty may be introduced by the choice of mass in the propagator for the exchanged quark. We used for u, d, s, c masses of 300, 300, 600, 1500 MeV, respectively. Changing the masses to 10, 10, 150, 1500 MeV had no noticeable effect. This is due to the selection of high p_T events which suppresses the influence of the quark mass assigned to the propagator.

Several models are available to describe the fragmentation of the quarks. Jet production as observed in 1γ annihilation at PETRA energies is well described by the Field–Feynman fragmentation model [8]. At low energies (5 to 7 GeV) the observed features of jets are best described by a longitudinal phase space model [12]. The limited statistics of the present analysis did not allow us to discriminate between the models or different sets of parameters. We therefore have compared our data to four different types of fragmentation models:

(a) a Field–Feynman model [13] with fragmentation parameters as determined by this experiment for e^+e^- annihilation [8],

(b) a Field–Feynman model using the original parameters,

(c) a longitudinal phase space model involving only pions with the neutral pion fraction set to 1/3,

(d) as model (c), but with the neutral pion fraction set to 1/2. This higher neutral fraction was required to fit the lower energy charged particle data and compensates for the absence of heavy particles in the model.

We also compared our results to a model which is in a simple extension to the VDM. Events were generated according to $d\sigma/dp_T^2 \propto \exp(-5p_T^2)$ and $\propto \exp(-1p_T)$ in the proportions 0.85/0.15. This fits the $d\sigma/dp_T^2$ distribution in fig. 1a.

In figs. 2a, b we have compared our results with the predictions from the jet model (the results from the 4 different types of fragmentation are indicated by the shaded area) and the extended vector dominance model (line). The data show a stronger collimation than the extended VDM predicts. This shows that the presence of a high p_T tail in the single particle p_T distribution is not sufficient to explain the collimation of the particles into distinct jets. In addition, we have compared our data to the standard VDM discussed above and to a phase space model. Neither model can explain all distributions shown in figs. 1 and 2.

As a check of our procedure we have also analysed lepton-pair production in $\gamma\gamma$ reactions. Fig. 3a shows the p_T distribution of the sum of e^+e^- and $\mu^+\mu^-$ production compared to the prediction of the same QED Monte Carlo program which we use for the generation of $\gamma\gamma \to q\bar{q}$. The theoretical prediction and the data agree in shape and magnitude.

In fig. 3b the number of observed jets is given as a function of the square of the total transverse momentum of each jet, $p_{T\,jet}^2$. The background contributions have been subtracted. They amount to about 30% of the signal above $p_{T\,jet}^2 = 8$ GeV$^2/c^2$. We have compared the data with the same estimate of the VDM as used in fig. 1a and with the $\gamma\gamma \to q\bar{q}$ model including acceptance effects. As shown by the dotted line the VDM contribution is not negligible particularly at lower $p_{T\,jet}^2$ values. The prediction from the $\gamma\gamma \to q\bar{q}$ model as shown by the shaded band lies below the data for $p_{T\,jet}^2$ less than 6 GeV$^2/c^2$. For higher $p_{T\,jet}^2$ the prediction approaches the observed number of events. However, other hard processes and higher order QCD corrections [14–16] are not ruled out by the data.

In summary we have demonstrated that $\gamma\gamma$ collisions produce hadrons with large p_T. This high p_T tail is not due to the hadronic part of the photon. Furthermore, events with high p_T particles are found to be consistent with a two-jet structure as expected from $\gamma\gamma \to q\bar{q}$. At large transverse momenta the data approach the expected cross section for this process.

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