Z. Phys. C – Particles and Fields 29, 499–503 (1985)

Zeitschrift für Physik C Particles and Fields

Jet Production at High Transverse Momenta by Interactions of Two Quasi-Real Photons

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Received 1 October 1985

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Abstract. An experimental study of two jet production by interactions of two quasi-real photons is presented. The data for production of jets with high transverse momentum squared, $p_T^2 > 10\,\mathrm{GeV}^2$, are found to be consistent with the fractionally charged quark-parton model. If gauge integer charged quark models are considered, then the gluon mass is less than 5 MeV at the 95% confidence level.

The two photon production of quark jets can be studied via the interaction of high energy e^+e^- beams in the reaction

$$e^+e^- \to e^+e^- \gamma^* \gamma^*, \qquad \gamma^* \gamma^* \to q\bar{q} \tag{1}$$

where γ^* represents a virtual photon. The final quark-antiquark ($q\bar{q}$) system is detected as a pair of hadronic jets. For small electron scattering angles the photons are quasi-real with Q^2, the photon mass squared, ≈ 0.

Reaction (1) allows the possibility of distinguishing models with fractional quark charges [1] (FCQ) from those with integer charges [2] (ICQ) by measurement of the ratio for two photon interactions

$$R_{\gamma\gamma} = \frac{\sigma(e^+e^- \to e^+e^- + \text{hadrons})}{\sigma(e^+e^- \to e^+e^- \mu^+\mu^-)} = \frac{1}{3} \sum_{nf} \left(\sum_{nc} q(f,c)^2\right)^2 \tag{2}$$

where $nf(nc)$ is the number of flavors (colors ($=3$)), and $q(f,c)$ is the quark charge for flavor f and color c in units of electron charge. This is to be contrasted with single photon reactions, where, assuming the hadrons are produced as color singlets, such differentiation is not possible. In e^+e^- annihilation, for example, the ratio

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = \frac{1}{3} \sum_{nf} \left(\sum_{nc} q(f,c)\right)^2. \tag{3}$$

is identical for both FCQ and ICQ models, since for a given flavor the quark charge summed over color is necessarily the same in each case. The ratio (2) must be measured for jets produced at high transverse momentum (p_T) so that reaction (1) dominates over hadron production by other processes such as the vector meson dominance mechanism [3] (VMD).

One method to study the reaction $e^+e^- \to e^+e^-$ + hadrons is when at least one of the scattered electrons is detected (tagged mode) with consequent reduction of backgrounds. In an earlier study [4] results have been reported for single tagged events in which one photon was off-shell ($Q > 0.1$ GeV), which, in particular at high jet p_T, agree with the prediction of the FCQ model. However, gauge models with integer charge quarks (gauge ICQ) have been proposed [5] in which color $SU(3)$ is broken and gluons acquire both mass and electric charge. In this case equation (2) must be modified [6] and such models can be distinguished from the unbroken fractional charge model, in practice, only when quasi-real photons are used. For this reason results on jet production by quasi-real photons, using anti-tagging, are of interest.

The data presented here were obtained at the PETRA storage ring (at DESY, Hamburg) with a beam energy of 17.3 GeV ($\sqrt{s} = 34.7$ GeV) using the PLUTO detector which has been described in previous publications [7]. The central detector measures charged particles for angles at >25 degrees to the beam axis with cylindrical proportional chambers in 16.5 Kgauss magnetic field. Photons are detected in lead-scintillator shower counters for angles >15 degrees. In addition, two forward spectrometers [8] measure charged particles between 90 and 260 mr and photons between 23 and 260 mr. Charged particles are measured with resolution $\sigma_p/p = 3\% \cdot p(\mathrm{GeV})$ and showers with energy resolution of $(16.5\% - 28\%)/\sqrt{E}$.

The photon-photon interactions of reaction (1) are characterised by a total hadronic mass, W, much less than the e^+e^- center of mass energy, $\sqrt{s}$, since energy is carried off by the scattered electrons. In the present analysis predominantly quasi-real photon interactions are selected by using the forward spectrometers to reject events with detected electrons, retaining mainly those events where the scattered electrons are at angles less than 23 mr.

Accepted events are required to satisfy the following conditions:

a) No electron detected in the forward spectrometers with energy greater than 5 GeV.

b) Measured hadronic vertex <30 mm from beam crossing point to reduce beam-gas bakground.

c) Number of charged tracks in each jet $\geqq 2$ in order to reduce background due to τ production. Since a two jet analysis is performed, the total number of charged tracks observed is $\geqq 4$.

d) Absolute value of charge of detected hadrons $|\Sigma q| \leqq 2$.

e) Total transverse momentum of the detected hadronic system less than 1.5 GeV/c. This limit preferentially selects interactions of quasi-real photons and reduces background due to badly measured annihilation events.

f) Only events with total observed hadronic mass, W_{vis}, less than 12 GeV were used in order to maximise the signal relative to the annihilation background which peaks at $W \approx \sqrt{s}$. A cut of $W_{vis} > 6\,\mathrm{GeV}$ is applied to allow a reliable determination of the jet axis using a thrust algorithm. The value of W_{vis} is calculated from charged track momenta (assuming pions) and the energies of the showers.

With the above cuts the data sample consists of 3203 events. The corresponding integrated luminosity is $18.7\,\mathrm{pb}^{-1}$.

Beam-gas interactions, as determined from the event vertex distribution, contribute a background of 0.25% to the final data sample and can be ignored. Additional background events arise from the following processes:

$$e^+e^- \to e^+e^-\tau^+\tau^-, \tag{4}$$

$$e^+e^- \to \tau^+\tau^-, \tag{5}$$

$$e^+e^- \to \text{hadrons} \tag{6}$$

and have been studied by Monte Carlo simulations and included in the calculated background. Reaction (4) gives a negligible background contribution, while reaction (5) gives a small contribution which is discussed later.

The annihilation process (6) is the most important source of background for high p_T jets produced in untagged photon-photon interactions, since for some events W_{vis} has a small value either due to high particle loss (charged or neutral) or due to hard radiation off one or other initial state electron. The contribution of this background has been studied by generating annihilation events using the Lund jet Monte Carlo [9], and including first order initial state radiative corrections according to the method of Berends and Kleiss [10]. The resulting events are then processed through the PLUTO detector simulation program, after which they are treated identically to the data and used to perform the background subtractions. Similarly, Monte Carlo events for reaction (1) have been generated for comparison with the high jet transverse momentum (p_T) data in accordance with (2) and assuming that in the process

$$\gamma^*\gamma^* \to q\bar{q} \tag{7}$$

the photons couple directly to the fractionally charged quarks of unbroken color $SU(3)$. We will refer to this as the quark-parton model (QPM). Detailed information on this simulation is given in a previous PLUTO report [4].

We present our experimental results as observed distributions, uncorrected for acceptance, which are then compared with simulations which include the acceptance effects.

Each event has been analysed by using a thrust algorithm, in the rest frame of the observed hadrons, to define two hadronic jets. To isolate the reaction (7) we must consider data for jets produced at high p_T, where we have measured the transverse momentum relative to the electron beam direction. At lower p_T, multi-jet events and QCD corrections play a role. Jet production by the VMD mechanism dominates at small p_T. Figure 1a shows the rapidity distribution of the total hadronic system for events with $p_T^2 > 10\,\mathrm{GeV}^2$ and $6 < W_{vis} < 12\,\mathrm{GeV}$. The expected QPM contribution is shown as the lower histogram (an essentially flat distribution is expected for fixed W before acceptance effects) and the data are compared with the sum of QPM and annihilation simulations. The agreement between data and simulation is good. The figure indicates the importance of the background from annihilation events for high jet p_T, which can however be reduced by a cut excluding low rapidity events whose low W_{vis} is mainly due to track or shower loss. Consequently an additional cut requiring $|rapidity| > 0.15$ is used in

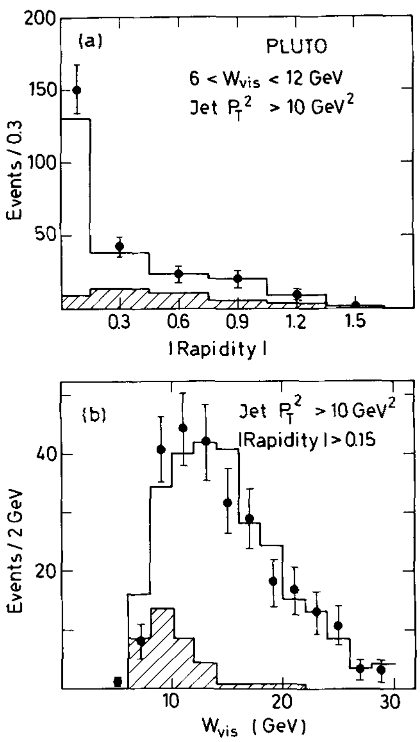

Fig. 1. a The absolute value of the total hadronic rapidity for events with $p_T^2 > 10\,\mathrm{GeV}^2$ and $6 < W_{vis} < 12\,\mathrm{GeV}$. The lower histogram indicates the QPM Monte Carlo prediction. The upper histogram is the prediction for the sum of QPM and annihilation background. The first bin includes an estimated 7 ± 2 events from the reaction $e^+e^- \to \tau\tau$. **b** The observed hadronic mass distribution for events with $p_T^2 > 10\,\mathrm{GeV}^2$ and $|Rapidity| > 0.15$. The upper and lower histograms as for **a**

what follows. At lower p_T such a peak at low rapidity is less prominent since track loss will also lead to change of observed rapidity. Figure 1b shows the W_{vis} distribution for the data with $p_T^2 > 10\,\text{GeV}^2$ and $|rapidity| > 0.15$ compared to the Monte Carlo simulation. The agreement is satisfactory. The Monte Carlo also describes the charge balance, charged particle multiplicity distributions and W_{vis} for $|rapidity| < 0.15$. The neutral multiplicity is slightly underestimated by the Monte Carlo. For $6 < W_{vis} < 12\,\text{GeV}$ and total hadronic transverse momentum $> 1.5\,\text{GeV/c}$, or for $12 < W_{vis} < 15\,\text{GeV}$, where the QPM contribution is expected to be small, the annihilation Monte Carlo gives an acceptable description of the data. These checks indicate that systematic uncertainties in the background simulation are no more than 20%.

Background from τ production by reaction (5) is due to undetected neutrals (e.g. neutrinos) resulting in a low value for W_{vis}. It is strongly suppressed by selection (f). The remaining background events tend to have low rapidity and the applied rapidity cut reduces this source of background to an insignificant level.

Figure 2 shows the observed jet transverse momentum squared (p_T^2) distribution for $6 < W_{vis} < 12\,\text{GeV}$ after subtraction of the annihilation background. The p_T of the two observed jets may differ by up to 1.5 GeV/c, the difference being limited by cut (e) above. The higher p_T jet has been used as the better approximation to the quark p_T as indicated by Monte Carlo studies. For comparison the QPM Monte Carlo prediction is also shown. The data for $p_T^2 > 10\,\text{GeV}^2$ are consistent with the QPM prediction (solid curve) but not with the naive ICQ model (factor 2.65 higher than QPM, dashed curve). The observed thrust distributions for these high p_T^2 events (not shown) are in good agreement with the Monte Carlo predictions. At small p_T^2 the VMD process is expected to dominate over the QPM contribution. The sudden rise of the data below 10 GeV^2 is a so far unexplained excess in the region $5 < p_T^2 < 10\,\text{GeV}^2$ over VMD, which was also observed for interactions of low Q^2 photons in our single-tag data [4]. This region of excess is associated with lower mean thrust than is expected for the QPM.

Figure 3 shows (upper data points) the charged

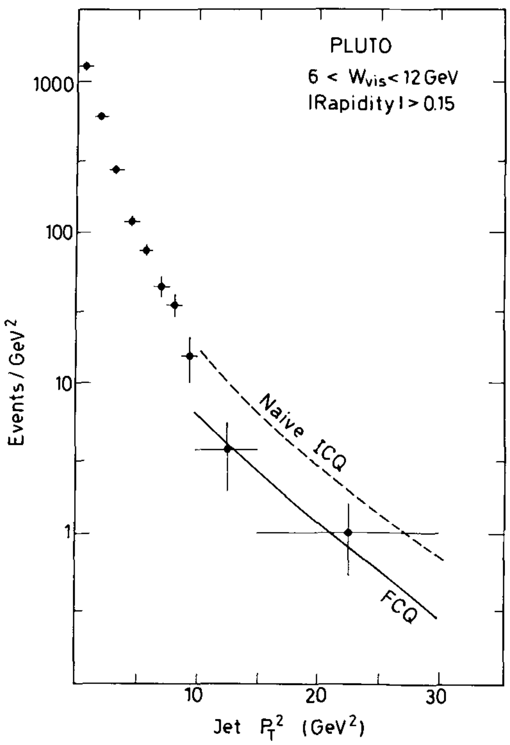

Fig. 2. The observed jet p_T^2 distribution for events with $6 < W_{vis} < 12$ GeV after subtraction of the annihilation background. The errors are statistical only. The solid (dashed) curve is drawn through the Monte Carlo prediction for fractional (integer) charged quarks and should be compared with data at the bin centers

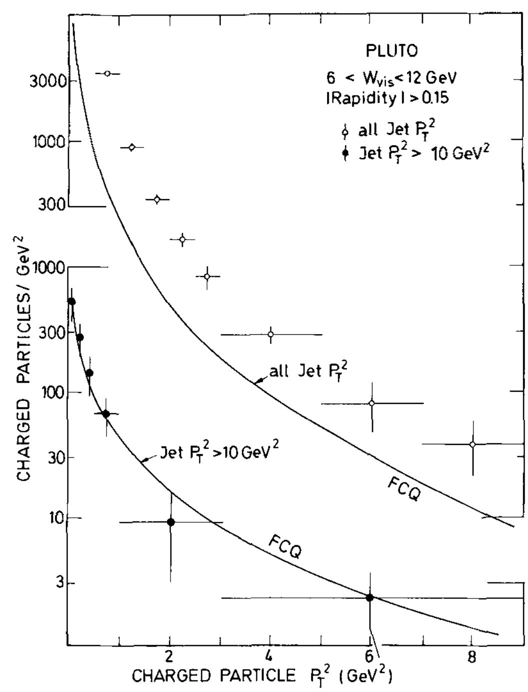

Fig. 3. The upper data points show the charged particle p_T^2 distribution for the events of Fig. 2 (annihilation background subtracted). The lower data points (note shifted scale) show the charged particle p_T^2 distribution for those events with the jet $p_T^2 > 10\,\text{GeV}^2$. The errors are statistical only. The curves are drawn through the QPM Monte Carlo predictions and should be compared with the data at the bin centers

particle p_T^2 distribution for the events shown in Fig. 2. For $p_T^2 > 3\,\mathrm{GeV}^2$ the data exceed the QPM Monte Carlo prediction (upper curve) by a factor of ≈ 3. This result is consistent with that of the TASSO Collaboration [11] who find data/QPM≈ 4 for $p_T^2 > 2.5\,\mathrm{GeV}^2$. The greater excess at low p_T^2 is due to the VMD contribution. However, if only events with jet $p_T^2 > 10\,\mathrm{GeV}^2$ are used, the lower set of data points is obtained. For this case, the data are in agreement with the QPM prediction (lower curve) again demonstrating the validity of the QPM model for events with jet $p_T^2 > 10\,\mathrm{GeV}^2$.

We now discuss the limits set on the gauge ICQ model by our data. For jet $p_T^2 > 10\,\mathrm{GeV}^2$ (data of Fig. 2), the ratio of the 33 observed events (after background subtraction) to the QPM prediction is 1.1 ± 0.4 (± 0.4 systematic) and the data are therefore consistent with the fractionally charged quarks of unbroken $SU(3)$ at the limit of high p_T. For integer charged quarks the expected ratio would be 2.65 for 4 quark flavors, deviating by more than 3 standard deviations from the observed value. This result is consistent with results on other processes involving two photons, such as $e^+e^- \to q\bar{q}\gamma$ [12] and $\gamma q \to \gamma q$ [13]. However, if color $SU(3)$ is broken as in the gauge ICQ model [5, 6], then (2) becomes

$$R_{\gamma\gamma} = \tfrac{1}{3} \sum_{nf} \Big(\sum_{nc} \big(q(f,c)^2 + 2/9\, D(1)\, D(2)\big)\Big)^2. \tag{8}$$

Here, $q(f,c)$ is the fractional (FCQ) quark charge and

$$D(i) = M_{\mathrm{gluon}}^2 / (M_{\mathrm{gluon}}^2 + Q(i)^2)$$

$Q(i)^2$ = absolute momentum transfer squared of i^{th} photon,

and the factor 2/9 arises from the octet contribution to the effective quark charge. In addition a large contribution to jet production arises from production of charged gluon pairs for which the cross section is given by a lengthy formula [6].

For the high jet p_T data sample we have computed the ratio,

$$R_{\gamma\gamma}(\text{gauge ICQ model}) / R_{\gamma\gamma}(\text{FCQ model})$$

including acceptance effects, and both quark and gluon production for a range of values of M_{gluon}. Comparing the calculated ratios with the measured ratio of 1.1 ± 0.4 (± 0.4) we obtain the following limit (including systematic error) for the gluon mass

$$M_{\mathrm{gluon}} < 5\,\mathrm{MeV} \quad \text{at} \quad 95\%\ \text{C.L.}$$

With $M_{\mathrm{gluon}} < 5\,\mathrm{MeV}$ the gauge ICQ model is indistinguishable from the FCQ model for tagged data where $Q^2 > 0.1\,\mathrm{GeV}^2$ for one of the photons. Thus single tag data is expected to be consistent with the FCQ model for $p_T^2 > 10\,\mathrm{GeV}^2$ as observed [4]. The single tagged data of the JADE [14] and TASSO [15] collaborations are also consistent with the FCQ model at high p_T.

In conclusion, we find that for jets produced by interaction of quasi-real photons the cross section is consistent with the expectation of the fractionally charged quark model for jet $p_T^2 > 10\,\mathrm{GeV}^2$ and $6 < W_{\mathrm{vis}} < 12\,\mathrm{GeV}$. If broken $SU(3)$ is considered then $M_{\mathrm{gluon}} < 5\,\mathrm{MeV}$ at the 95% confidence level.

Acknowledgements. The university groups thank the DESY directorate for their hospitality. We acknowledge the excellent performance of the PETRA machine group, the DESY computer center, and of all the engineers and technicians who participated in construction and maintenance of the apparatus.

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