SLAC-PUB-3410
September 1984
(T/E)

Direct Photon Production in e^+e^- Annihilation*

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(Submitted to Physical Review Letters.)

*Work supported in part by the Department of Energy under contract numbers DE-AC02-81ER40025 (CU), DE-AC03-76SF00515 (SLAC), and DE-AC02-76ER00881 (UW); by the National Science Foundation under contract numbers NSF-PHY82-15133 (UH), NSF-PHY82-15413 and NSF-PHY82-15414 (NU), and NSF-PHY80-06504 (UU); and by I.N.F.N.

ABSTRACT

Direct photon production in hadronic events from e^+e^- annihilation has been studied at $\sqrt{s}$=29 GeV using the MAC detector at the PEP storage ring. A charge asymmetry $A = (-12.3 \pm 3.5)\%$ is observed in the final state jets. The cross section and the charge asymmetry are in good agreement with the predictions of the fractionally charged quark-parton model. Both the charge asymmetry and total yield have been used to determine values of quark charges. Limits have been established for anomalous sources of direct photons.

PACS numbers 12.20.Fv, 13.65.+i

The production of direct photons in e^+e^- annihilation into hadrons has been recognized as a powerful tool to explore the properties and interactions of quarks at short distances.[1] Quarks and gluons fragment into hadrons once they leave the short distance regime, whereas photons can leave without further interactions. If a photon radiated from a quark is detected with a large transverse momentum relative to the hadron jets, short distances are probed and it is possible to study properties of the quark-gluon system before the hadron fragmentation takes place. One of the consequences of photon emission is that the interference between photon radiation from initial state electrons and final state quarks generates a charge asymmetry proportional to the cube of the quark charge.[2] The charge asymmetry of the quarks in principle can be determined from the charge asymmetry of the resultant jets or the charge asymmetry of the inclusive hadron distribution. Measurements of both the jet charge asymmetry and the total photon yield can then be used to determine the color-averaged charge squared $\langle e_q^2 \rangle$ of the quark charges. This information may distinguish between fractional and integer charge schemes such as the Han-Nambu model.[3] These schemes have different charge assignments for colored quarks, keeping the average charge within a color multiplet fixed. It has long been realized that this distinction can not be made with experiments such as the measurement of the hadronic total cross section and the measurement of the average charge of leading hadrons in a quark jet.[4] Processes which have two photon couplings to the quark, such as the present experiment and two-photon annihilation jet production,[5] can in principle accomplish this distinction since they are sensitive to higher charge moments rather than the average charge. This experiment reports the first results on a high statistics analysis of multi-hadron final states containing a hard photon under conditions of maximal interference between initial and final state radiation.

The parent data sample consists of approximately 10^5 multi-hadron events collected with the MAC detector at the Stanford Linear Accelerator Center PEP storage ring. The sample corresponds to an integrated luminosity of 220 pb^{-1} at a center of mass energy of 29 GeV. A detailed description of the MAC detector has been given elsewhere.[6] We describe here only the elements essential to the present analysis. Charged particle tracks are analyzed in a solenoid magnet and central drift chamber with momentum resolution $\delta p/p \simeq 0.065 p(GeV/c) \sin\theta$ for $25° \leq \theta \leq 155°$. The total polar angle acceptance is $17° \leq \theta \leq 163°$. Photons are detected by a hexagonal barrel of electromagnetic shower calorimeters and by endcap calorimeters. For the present analysis only the central shower calorimeters are used for photon detection because of superior energy and angular resolutions, which average about $\delta E/E \simeq 20\%/\sqrt{E(GeV)}$, $\delta\phi \simeq 0.8^\circ$ and $\delta\theta \simeq 1.3^\circ$, respectively. The electromagnetic calorimeters are surrounded by hadron calorimeters. The calorimeter hits are used for multi-hadron event selection and jet axis reconstruction. The solid angle coverage of the entire calorimeter system is about 98% of 4π sr.

The hadronic event selection criteria have been described previously.[7] For the present analysis the direct photons are selected from the event sample with at least five charged particles. A photon candidate is defined as a shower detected in the central electromagnetic calorimeter with no significant energy deposition in the hadron calorimeter and separated by at least 30° from the nearest charged particle or other electromagnetic shower. The showers must have energy greater than 3 GeV and less than 10 GeV in the angular region $35^\circ \leq \theta \leq 145^\circ$. The lower energy cut is chosen to reduce the background coming from meson decays (mostly $\pi^0 \to \gamma\gamma$). The higher energy cut is applied because above 10 GeV: 1) initial state radiation is the dominant source of direct photons, thus lowering the fraction of events due to final state photon radiation; and 2) it becomes more difficult to calculate the true jet direction and to assign the jet charges properly.

Assuming that all events are $e^+e^- \to q\bar{q}\gamma$, two jets are reconstructed as follows. The event is Lorentz transformed into the hadronic center of mass system using the measured photon energy and direction. This is done for all calorimeter hits and all charged particles with momentum greater than 250 MeV/c, assigning each the pion mass. Since two jets are back-to-back in the $q\bar{q}$ rest system, the jet axis is obtained by calculating the thrust axis using the transformed calorimeter information. A net charge is then computed for both jets by summing over all the charged particles in the forward and backward hemispheres with respect to the thrust direction. The angle between the photon candidate and either jet axis, as transformed back into the laboratory system, is then required to be greater than 55°.

A Monte Carlo method has been used in order to estimate backgrounds and to study the direct photon signal. The Monte Carlo program of Berends, Kleiss, and Jadach[8] was used to calculate the predictions for $e^+e^- \rightarrow q\,\bar{q}$ and $e^+e^- \rightarrow q\,\bar{q}\,\gamma$ to order α^3 . The Lund Monte Carlo program was used to simulate QCD effects and parton fragmentation into hadrons.[9] The events generated by this program were then put through the MAC detector simulation program to trace in detail their interactions and the detector response. After subjecting these events to the same selection criteria used in the data sample, these Monte Carlo events provided the spectra for both signal and background studies. From these studies the reconstructed jet axes determined the quark direction with an uncertainty of 4°. The Monte Carlo was also used to study the mapping of quark charge into jet charge. About 68% of the jets were found to be charged, in excellent agreement with the predictions of the Monte Carlo, and approximately 70% of the charged jets are predicted to have the same sign as the parent quark.[10] Comparisons with the predictions of the Monte Carlo calulation are discussed further below.

There are 1049 direct photon candidates which pass the selection criteria, or about 1% of the parent sample. The meson decay background is estimated to be 226±40, where the error includes statistical and systematic contributions, the latter due primarily to the uncertainty in the parameters of the Lund Monte Carlo.[11] An additional background coming from $e^+e^- \rightarrow \tau^+\tau^-\gamma$ is estimated to be 15±3. Photons from final state hadron bremsstrahlung in the detector material are totally negligible. Subtracting these backgrounds, the direct photon signal is measured to be 808±51 events.

The results are shown in Figs.1 and 2. Fig.1 shows the energy distribution of the background-subtracted direct photon signal together with the calculated background coming from meson decays. Also shown is the Monte Carlo prediction for the direct photon signal assuming five flavors of fractionally charged quarks. The predicted yield is 762±39 events. The measured yield is thus in good agreement with the prediction of the fractionally charged quark model and shows no evidence of anomalous photon production. An upper limit for excess photon production from unknown sources is discussed below.

Fig. 2 shows the polar angle distribution of the jet axis for the charged jet subsample. The quantity $N^{+}(\cos\theta) + N^{-}(-\cos\theta)$ is plotted vs $\cos\theta$, where θ is measured relative to the e^{+} beam direction, and N^{+} (N^{-}) is the number of jets with positive (negative) net charge in each angular bin. Jets with zero net charge are not entered. A large asymmetry about $\cos\theta=0$ is evident. The average charge asymmetry, defined as

$$A = \frac{N^{+}(\theta < \frac{\pi}{2}) + N^{-}(\theta > \frac{\pi}{2}) - N^{+}(\theta > \frac{\pi}{2}) - N^{-}(\theta < \frac{\pi}{2})}{N^{+} + N^{-}},$$

is $A = (-12.3 \pm 3.5)\%$. The angular distribution predicted by the Monte Carlo analysis for five fractionally charged flavors of quarks is shown as the histogram in Fig. 2 and yields a charge asymmetry $A = (-11.7 \pm 2.6)\%$. The interference with weak interaction terms is expected to create an additional contribution to the asymmetry in the direct photon signal. However, due to the cancellations between contributions from charge 2/3 and −1/3 quarks and the reduced c.m. energy due to initial state photon radiation, this weak contribution is small and has been estimated to be $|\delta A| < 1\%$.

As a check for false asymmetries resulting from π^0 decay background or possible detector biases, a control sample was made from the parent hadron events by applying the photon candidate requirements to charged particles. The average charge asymmetry observed in this sample is $A = (+1.8 \pm 3.5)\%$. Another check was made with the direct photon sample by loosening the selection criteria, thus allowing the meson decay background to be dominant source of the events. The charge asymmetry observed in this sample is consistent with zero.

The charge asymmetry and total yield may be interpreted in terms of quark charges. The cross section is proportional to the incoherent sum of initial and final state photon radiation terms and depends on the charges as follows:

$$d\sigma \sim B_i \sum \langle e_q \rangle^2 + B_f \sum \langle e_q^2 \rangle^2.$$

The factors B_i and B_f represent the initial and final state radiation contributions respectively. Approximately 15% of the total yield is estimated to result from radiation of the final state quarks assuming the conventional fractional charge assignments. The jet charge asymmetry takes a simple form when expressed as a ratio to the corresponding asymmetry for $\mu^+\mu^-\gamma$ final states:

$$\frac{d\sigma(jet^+) - d\sigma(jet^-)}{d\sigma(\mu^+) - d\sigma(\mu^-)} = 3C \sum \langle e_q \rangle \langle e_q^2 \rangle.$$

C is a factor which includes all the efficiencies for a quark to be reconstructed as a charged jet of the same sign and has been calculated from the Monte Carlo events, e_q is the quark charge in units of the magnitude of electron charge, and $\langle e_q^n \rangle$ is the average value of e_q^n within a color multiplet. The sum is taken over all five quark flavors.

Since the charge asymmetry and the final state radiation contribution to the total yield are sensitive to the quark charge and probe the charge with two photons, it should be possible to test models which have different charge assignments for the quarks. In particular, the Han-Nambu model assigns integral charge to the quarks keeping the average charge for each flavor the same as the conventional fractional charge assignments. The predictions of the Han-Nambu model have been calculated using the Monte Carlo with Han-Nambu charge assignments. The Han-Nambu predictions for the total number of events and the average jet charge asymmetry, together with the experimental results, are shown in Table 1. The total yield and charge asymmetry may be used to calculate values for $3\sum\langle e_q^2 \rangle^2$ and $3\sum\langle e_q \rangle\langle e_q^2 \rangle$ of the quark charges respectively.[12] These results are also shown in Table 1. The $\langle e_q \rangle^2$ contribution to the total yield is assumed to be given by the usual fractional charge assignments as confirmed by the measurements of the total hadron production cross section.

Both the total yield and the charge asymmetry result favor the conventional fractional charge assignments for five quark flavors. The charge asymmetry result has the advantage of being directly sensitive to a two-photon probe of the quark charge. The result is about 2.8 standard deviations away from the integer charge prediction. The cross section is also sensitive to the quark charges but only the final state radiation contribution contains a two-photon probe of the charge. The total yield is about 3.0 standard deviations away from the integer charge prediction.

As mentioned above, a limit has been placed on anomalous photon production. The result can be expressed in terms of the product of the cross section (scaled to the point μ-pair rate) and branching ratio for any anomalous state which has been produced and subsequently decays into a hadron-photon final state. The 95% confidence level upper limit for this quantity varies as a function of the invariant mass M_H of the hadronic system recoiling against the photon, from 0.2% at M_H=16 GeV/c^2 to 0.9% at M_H=26 GeV/c^2.

We would like to thank S. Brodsky, K. Hagiwara, F. Halzen, and F. Herzog for useful conversations. We would also like to thank the PEP staff for all the effort that goes into operating the storage ring.

This work was supported in part by the Department of Energy under contract numbers DE-AC02-81ER40025 (CU), DE-AC03-76SF00515 (SLAC), and DE-AC02-76ER00881 (UW); by the National Science Foundation under contract numbers NSF-PHY82-15133 (UH), NSF-PHY82-15413 and NSF-PHY82-15414 (NU), and NSF-PHY80-06504 (UU); and by I.N.F.N.

Table 1.

Results and predictions for direct photon signal.

	Events	Asymmetry (%)	$3\sum\langle e_q^2\rangle^2$	$3\sum\langle e_q\rangle\langle e_q^2\rangle$
Data	808±51	−12.3±3.5	1.75±0.63	1.97±0.61
Fractional charge	762±39	−11.7±2.6	$\frac{35}{27}$=1.30	$\frac{19}{9}$=2.11
Integer charge	1006±50	−19.2±2.2	$\frac{11}{3}$=3.67	$\frac{11}{3}$=3.67

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10. The charge determination probability has been studied using both string and incoherent jet fragmentation models. The results of these studies show less than a 2% variation in this quantity for the different parameters and models.

11. The systematic contribution to this error has been estimated by varying the parameters of the Lund Monte Carlo over a wide range; $0.17 < \alpha_s < 0.21$, $0.29 < \sigma_q < 0.33$ GeV/c, $0.4 < \frac{V}{V+P} < 0.6$.

12. The quark mass effects have been studied with the Monte Carlo simulation program using masses $m_u = m_d$=0.3 GeV/c^2, m_s=0.5 GeV/c^2, m_c=1.6 GeV/c^2 and m_b=5.0 GeV/c^2. The corrections to the values of $3\sum\langle e_q^2\rangle^2$ and $3\sum\langle e_q\rangle\langle e_q^2\rangle$ are negligible.

FIGURE CAPTIONS

1. The energy distribution of the background subtracted direct photon sample. The histogram is the Monte Carlo prediction for fractional charges. The meson decay background is indicated as a dashed curve.
2. The polar angle distribution of the jet axes as described in the text. The histogram is the Monte Carlo prediction for fractional charges.

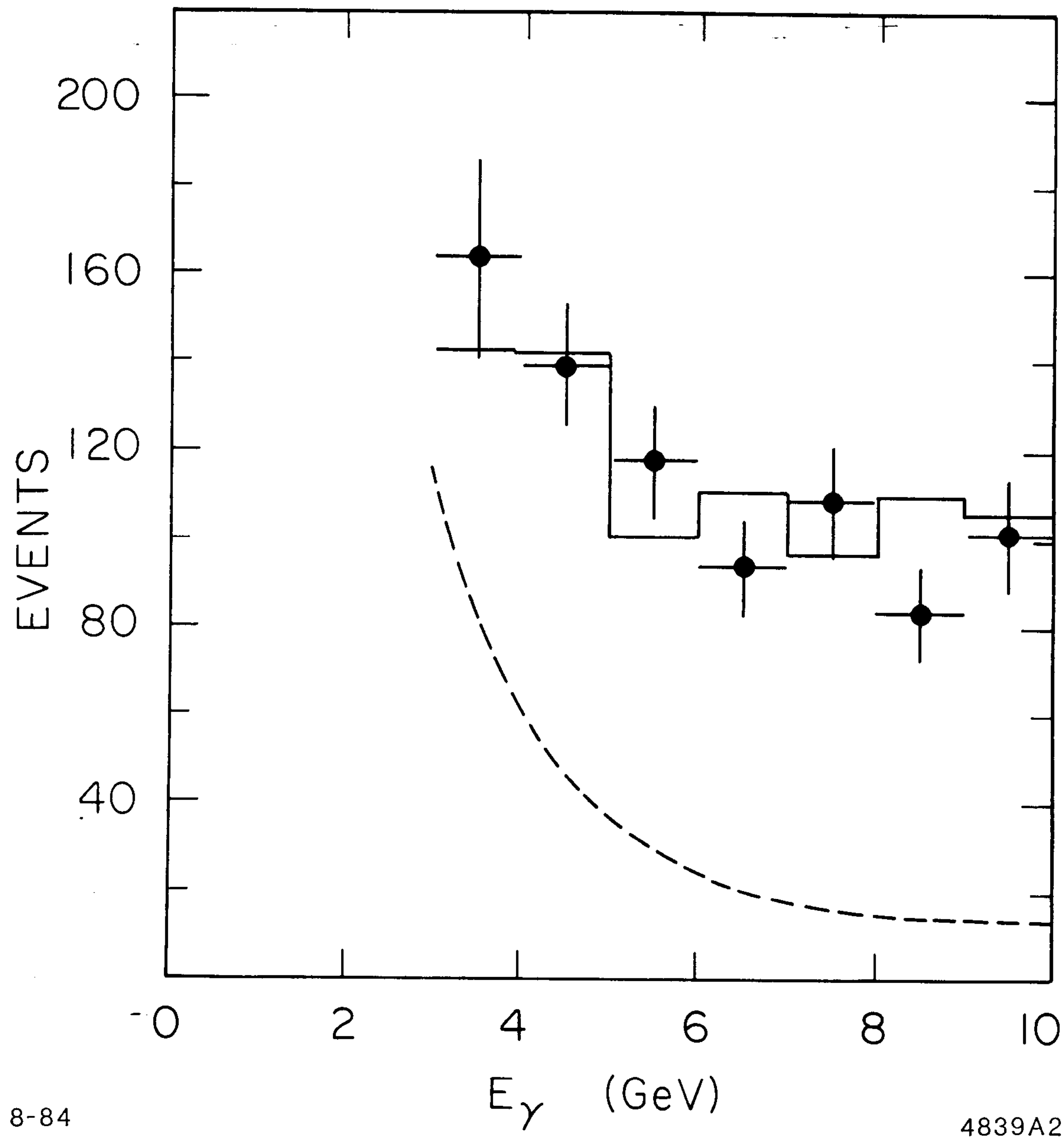

Fig. 1

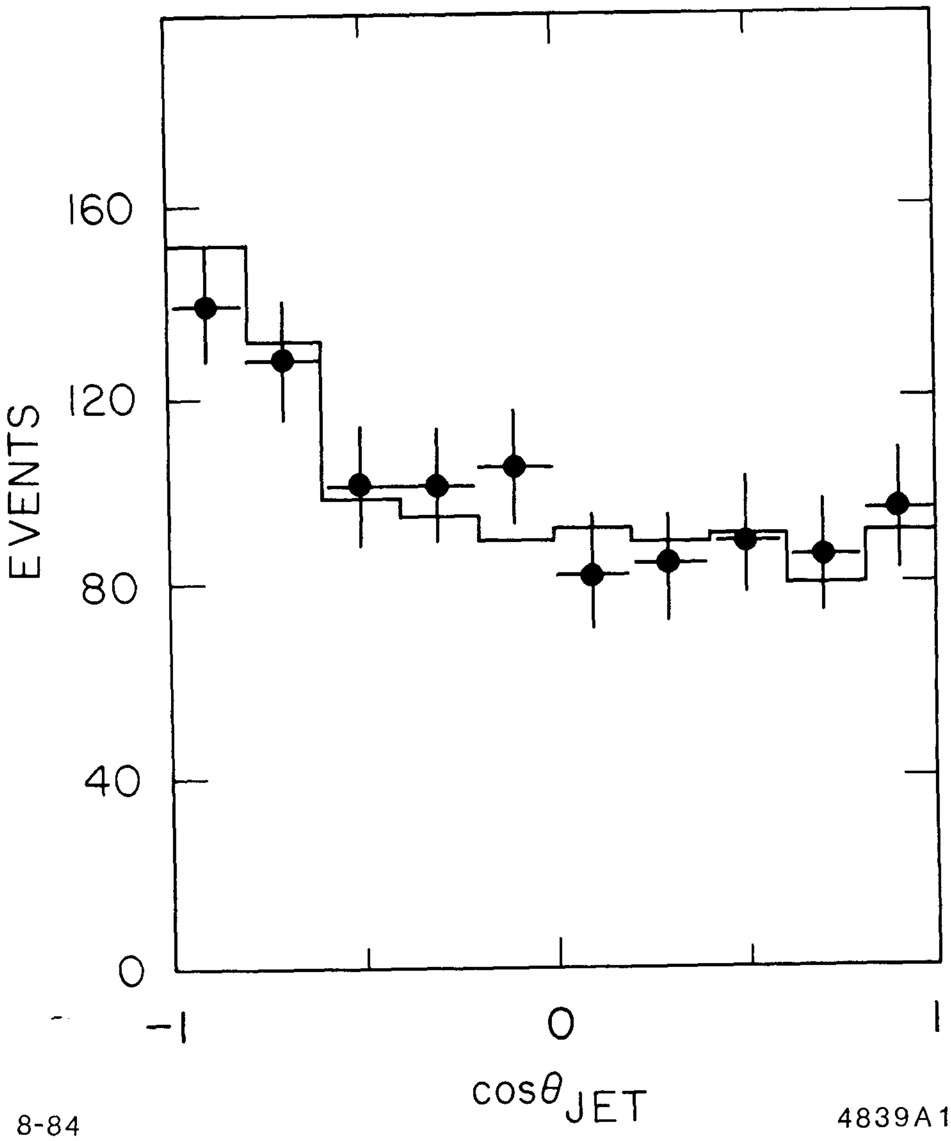

Fig. 2