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Results on Hadronic Events from the MAC Detector at PEP*

I. Direct Photon Production

II. Precision R Measurement and Energy-Energy Correlations

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DIRECT PHOTON PRODUCTION IN e^+e^- ANNIHILATION INTO HADRONS

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on behalf on the MAC Collaboration†

Direct photon production in hadronic events from $e^+e^- \to$ hadrons has been studied at $\sqrt{s}$=29 GeV using the MAC detector at PEP. Both the charge asymmetry in the final state jets and total yield have been used to determine values of quark charges, which are in good agreement with the predictions of the fractionally charged quark-parton model. Limits have been established for anomalous sources of direct photons.

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

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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. Measurements of the photon energy spectrum and angular distribution are presented and compared to standard predictions. The parent data sample consists of about 100k multi-hadron events collected with the MAC detector[6] at the PEP storage ring at SLAC. The sample corresponds to an integrated luminosity of 220 pb^{-1} at $\sqrt{s}$=29 GeV.

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 $35° \leq \theta \leq 145°$. The lower energy cut is chosen to reduce the background coming from meson decays (mostly $\pi^0 \rightarrow \gamma\gamma$). 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 $e^+e^- \rightarrow q\overline{q}\gamma$, two jets are reconstructed as follows. A Lorentz transformation of the event is made into the hadronic center of mass system, using the measured photon energy and direction. This is done for all charged particles with momentum greater than 250 MeV/c, assigning each the pion mass. Since two jets are back-to-back in the $q\overline{q}$ 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 $>55°$.

A Monte Carlo method has been used in order to estimate backgrounds and to study the direct photon signal. A Monte Carlo program[8] was used to calculate the predictions for $e^+e^- \rightarrow q\overline{q}$ and $e^+e^- \rightarrow q\overline{q}\gamma$ 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: the reconstructed jet axes determined the quark direction with an uncertainty of 4°; about 68% of the jets in the data were found to be charged, in excellent agreement with the prediction; and approximately 70% of the charged jets are predicted to have the same sign as the parent quark. These conclusions are the same for string or incoherent jet fragmentation.

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±29, where the error includes statistical and systematic contributions, the latter due primarily to the uncertainty in the parameters of the Lund Monte Carlo. An additional background 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.

Fig. 1(a) shows the energy distribution of the background-subtracted direct photon signal of 808±43 events 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, in good agreement with the data. Fig. 1(b) 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

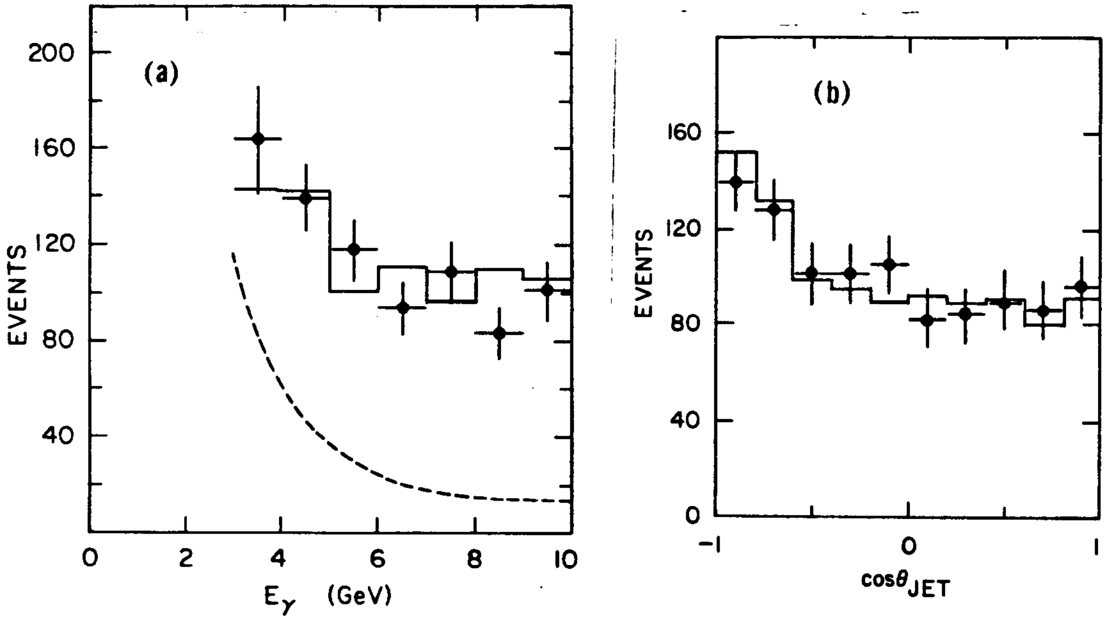

Fig. 1. (*a*) The energy distribution of the background-subtracted direct photon sample. The histogram is the Monte Carlo prediction for fractional charges. The meson decay background is indicated as a dashed curve. (*b*) The polar angle distribution of the jet axes. The histogram is the Monte Carlo prediction for fractional charges.

asymmetry about $\cos\theta=0$ is evident. The average charge asymmetry, defined in Ref. 2, is $\overline{A} = (-12.3 \pm 3.5)\%$. The angular distribution predicted by the Monte Carlo analysis for five fractionally charged flavors of quarks is shown as the histogram in Fig. 1(*b*) and yields $\overline{A} = (-11.7 \pm 2.6)\%$. Weak interaction effects are negligibly small.

As a check for false asymmetries resulting from π^0 decay background or possible detector biases, a control sample was created from the parent hadron events by applying the photon candidate requirements to charged particles, effectively replacing the photon with a charged pion. For this sample, $\overline{A} = (+1.8 \pm 3.5)\%$, consistent with the expectation that it should be negligible.

Since the charge asymmetry and the final state radiation contribution of 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. The Han-Nambu predictions for the total number of events

	Events	Asymmetry (%)	$3\sum\langle e_q^2\rangle^2$	$3\sum\langle e_q\rangle\langle e_q^2\rangle$
Data	808±43	−12.3±3.5	1.75±0.57	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

Table 1. Results and predictions for direct photon signal.

and the average jet charge asymmetry together with the experimental results are shown in Table 1. The total yield and charge asymmetry may be interpreted as 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.[10] 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, and are 3.5 and 2.8 standard deviations, respectively, away from the integer charge prediction.

A limit has been placed on anomalous photon production. The result can be expressed as the product of the cross section (scaled to the point μ-pair rate of 103.3 pb at $\sqrt{s}$=29 GeV) 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.

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RESULTS ON QCD FROM THE MAC DETECTOR AT PEP

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Measurements of the total cross section and energy-energy correlations for $e^+e^- \rightarrow$ hadrons at $\sqrt{s}$=29 GeV with the MAC detector are presented. Two complementary event selections for the precision R measurement are described, one accepting events over nearly the entire 4π solid angle (minimizing extrapolation to unseen phase space), and the other restricted to wide angles (reducing two-photon backgrounds). The two methods agree, yield $R = 3.93 \pm 0.10$ (which includes the effects of higher order radiative corrections), and give $\alpha_S = 0.19 \pm 0.07$, independent of fragmentation. The asymmetry in the energy-energy correlation cross section yields different results for α_S in different models, 0.185 in the string model and from 0.105 to 0.140 for incoherent jet formation, depending on the gluon fragmentation and momentum conservation algorithms. The string fragmentation model provides a satisfactory description of the measured correlation cross section, whereas incoherent jet fragmentation does not.

PRECISION R MEASUREMENT

A precise measurement of the total cross section for $e^+e^- \rightarrow$ hadrons provides one of the cleanest tests of the theory of quantum chromodynamics (QCD). In the quark-parton model $q\overline{q}$ pairs are produced with the QED fermion-antifermion cross section and then undergo fragmentation into hadrons. Normalized to the lowest-order cross section for μ-pair production, the lowest order total cross section is $R_0 = 3\sum_{\rm udscb} e_q^2 = 3\frac{2}{3}$, where the factor of 3 accounts for the 3 colors of each quark, and e_q signifies the charge for each of five quark flavors. The effect of gluon emission has been computed in perturbative QCD as $R = R_0\,[1 + C_1\left(\frac{\alpha_S}{\pi}\right) + C_2\left(\frac{\alpha_S}{\pi}\right)^2]$. For massless quarks $C_1 = 1$, but for standard mass assignments $C_1 = 1.065$. In the $\overline{\rm MS}$ renormalization scheme C_2=1.4.[1)] Weak interaction effects on R at this energy are negligible.

The MAC detector[2),3)] consists of a 1-meter-diameter solenoid coil containing a drift chamber, surrounded by electromagnetic shower detectors, trigger

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†For the complete author list please see the other article in these Proceedings by B.K. Heltsley, "Direct Photon Production in e^+e^- Annihilation into Hadrons".

scintillators, magnetized iron hadron calorimeters, and muon tracking drift chambers, all covering about 97% of the solid angle. Events trigger the apparatus on the basis of scintillator hits, energy deposition, tracking information, or combinations of these, resulting in high detection efficiency for multi-hadrons.

R is computed as $R = N\big(1 - \delta_{2\gamma} - \delta_\tau\big)/(\mathcal{A}\,\sigma_0 \int \mathcal{L}dt)$, where N is the number of events in the data passing a set of cuts, $\delta_{2\gamma}$ and δ_τ are the fractional backgrounds from two-photon and τ-pair production, respectively, $\int \mathcal{L}dt$ is the measured integrated luminosity, $\mathcal{A}$ is the calculated acceptance of the cuts including detector effects and radiative corrections, and σ_0=103.3 pb is the point cross section for muon pair production at this energy. Two independent analyses (Methods I and II) have been made to determine the background-subtracted number of events corrected to full acceptance. Table 1 shows all the results and errors going into the computation of R for the two techniques.

The integrated luminosity for both methods has been determined using four reactions with calculable weak-electromagnetic cross sections. Bhabha events in the detector ($|\cos\theta| < 0.9$) and in a small angle luminosity monitor (θ=30 mrad) are used, as well as events with two real photons or μ-pairs[4] in the final state. The distributions pertaining to these events are all in good agreement with the predictions and are consistent with one another. Their weighted average is used.

The criteria for Method I[2] exploit the large solid angle coverage of the detector while minimizing background contamination. First, three cuts based on the calorimeter energy hits $\vec{E}_i = (E_i, \theta_i, \phi_i)$ reject topologies characteristic of backgrounds. An event remains in the sample only if the visible energy $E_{\mathrm{vis}} \equiv \sum|\vec{E}_i|$>12 GeV, the transverse energy component $E_\perp \equiv \sum|\vec{E}_i|\sin\theta_i$>7.5 GeV, and the net imbalance $|I| \equiv (|\sum\vec{E}_i|/E_{\mathrm{vis}})$<0.65. Next, $\geq$5 charged tracks must be reconstructed in the central drift chamber, and the momenta $\vec{p}_i$ of all such tracks must sum to $P_{\mathrm{vis}} \equiv \sum|\vec{p}_i|$ >2 GeV/c. Visual scanning of the ~10% of the events with marginal event characteristics eliminates some remaining backgrounds, such as cosmic rays and Bhabha events with extra tracks. Two-photon rejection is enhanced by discarding events which fail at least two of the more restrictive requirements: $E_{\mathrm{vis}} > 15$ GeV, $E_\perp > 9.1$ GeV, or $I < 0.55$.

The largest potential background in R arises from two-photon production of hadrons which peak at small angles to the beam. Therefore, Method II[5] is based on events with thrust axes at large angles to the beam. In addition,

Value I	Value II	Quantity	Error I (%)	Error II (%)
36 642	17 767	Event Count N	0.5	0.8
100%	100%	Trigger Efficiency	0.2	0.2
		(Cuts	1.1	1.5
1.114	0.564	Acceptance $\mathcal{A}$ (Model	0.5	1.1
		(QED	1.2	1.2
2.3%	0.5%	2γ Background $\delta_{2\gamma}$	0.7	0.2
0.9%	0.4%	$\tau^+\tau^-$ Background δ_τ	0.3	0.1
77.7 pb^{-1}		Luminosity $\int \mathcal{L}dt$	1.5	
3.97	3.89	R value	2.5	2.8

Table 1. The components and errors of the two R measurements.

more emphasis on the modeling of the drift chamber is made than in Method I, which relies more on calorimetry, thus increasing the complementarity of the two techniques. The event selection criteria are as follows: the thrust direction, as determined from tracks in the central drift chamber, must be in the angular range from 55° to 125° from the beam line; at least 5 charged tracks must be reconstructed to the primary vertex in the central drift chamber; and the visible calorimetric energy must satisfy $E_{\mathrm{vis}}>16$ GeV.

The acceptance $\mathcal{A}$ is defined as the ratio of the accepted, radiatively-corrected cross section to the total point cross section. $\mathcal{A}$ has been evalutated using Monte Carlo computer programs[2] modeling $e^+e^- \rightarrow$ hadrons[6] with initial state radiation[7] and detector response. Application of the event selection of Method I (II) to the resulting Monte Carlo events yields $\mathcal{A}$=1.114 (0.564). For comparison, the acceptance for non-radiative events is 0.93 (0.47). The agreement between the data and Monte Carlo distributions of variables used in the cuts is excellent; even large variations in cut values result in small changes in R. Two such distributions of events passing Method I cuts are shown in Fig. 1. Notice the larger model and cut dependence of Method II in Table 1. Also included in the acceptance, as well as the luminosity, is the effect of higher order than α^3 radiative corrections.[8] Without these effects R would be about 1.5% larger.

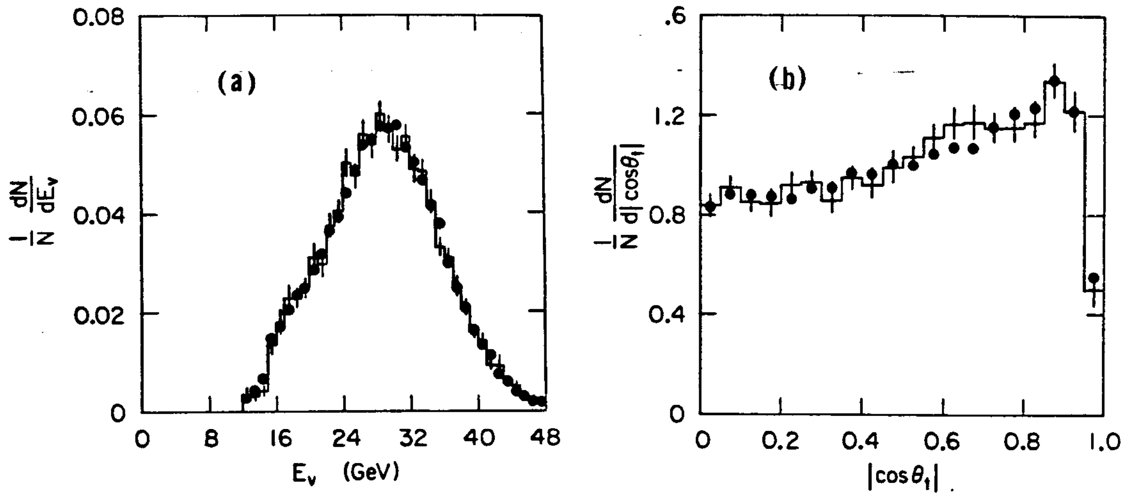

Fig. 1. Distributions of (*a*) the total energy $E_{\rm vis}$ and (*b*) thrust axis direction $|\cos\theta_t|$, for the data (points) and Monte Carlo (histogram), which includes backgrounds.

The fractional background contaminations from high-multiplicty τ-pairs and two-photon production of hadrons (including hard scattering[9] and vector dominance[10] contributions) has also been calculated with Monte Carlo technique, with results shown in Table 1. Notice the larger backgrounds and corresponding errors in Method I, a consequence of its less restrictive acceptance.

The R values from Methods I and II are consistent with each other, and the final value is taken as their arithmetic mean, R=3.93±0.03(stat)±0.10(sys), which implies α_S=0.19±0.07, independent of fragmentation. This value is consistent with previous measurements[11] at or near this energy.

ENERGY-ENERGY CORRELATIONS

The energy-energy correlation cross section for $e^+e^- \to$ hadrons provides a valuable tool for quantitative studies of QCD and fragmentation. The correlation cross section $\frac{d\Sigma}{d\chi}$ describes the energy-weighted angular correlation, averaged over many events, as a function of the angle χ between pairs of energy flow parcels. Specific predictions for $\frac{d\Sigma}{d\chi}$ have been made in the context of first[12] and second[13] order perturbative QCD, which neglect fragmentation contributions. The effects of gluon emission are emphasized and those of fragmentation are minimized in the asymmetry $A(\chi)$ of $\frac{d\Sigma}{d\chi}$ about χ=90°. However, various Monte Carlo models differ on the importance and precise contribution of fragmentation to the observed correlation and its asymmetry, and hence on how the strong coupling constant α_S should be extracted from the data. This situation has led to a variety of approaches to analysis in previous experiments.[2),14)–17)]

The energy-energy correlation cross section is given by[12)]

$$\frac{d\Sigma}{d\chi}(\chi_k) = \frac{1}{\Delta\chi}\ \frac{1}{N_{\text{evts}}} \sum_{\text{evts}} \ \sum_{l \geq m} \epsilon_l\, \epsilon_m\, (2 - \delta_{lm}) \tag{1}$$

where the $\vec{\epsilon}_i$ represent the normalized energy flow vectors of the hadrons in any event, satisfying $\sum|\vec{\epsilon}_i| = 1$ (energy conservation). The first summation in Eq. (1) averages over the N_{evts} hadronic events in the sample, and for each event the second summation includes all unique pairs of $\vec{\epsilon}_i$'s with $\angle(\vec{\epsilon}_l, \vec{\epsilon}_m) = \chi_k \pm (\Delta\chi/2)$, where χ_k are central values of bins with width $\Delta\chi$. The final factor with the Kronecker δ correctly treats self-correlation terms, ensuring the normalization $\int_0^\pi \frac{d\Sigma}{d\chi}(\chi)\, d\chi = 1$. The asymmetry $\mathcal{A}(\chi)$ is defined as $\mathcal{A}(\chi) \equiv \frac{d\Sigma}{d\chi}(\pi - \chi) - \frac{d\Sigma}{d\chi}(\chi)$.

For this analysis, requirements in addition to those of the large acceptance R measurement are made to reduce systematic uncertainties. To ensure nearly full containment of all particles within the detector's angular acceptance, the thrust axis is required to be more than 40° away from the beam. To discriminate against events with hard initial state radiation leaving the detector at small angles to the beam (which have large radiative corrections) the component along the beam line of the imbalance vector $\vec{I}$ must have magnitude$<$0.25. About 65 000 events pass these tighter cuts from a data set of 215 pb^{-1}.

The data will be compared to predictions of the Lund Monte Carlo[6)] (version 5.2) for $e^+e^- \to$ hadrons, which first generates $e^+e^- \to q\bar{q}(g)(g)$ events using the perturbative QCD matrix elements,[18)] and then simulates the fragmentation of these states into hadrons according to either the Lund model[19)] for string fragmentation (STR) or an incoherent jet (ICJ) models.[20),21)] In ICJ models a gluon is treated as a $q\bar{q}$-pair, with its momentum either given entirely to one quark (g=q) or shared between both ($g = q\bar{q}$) according to some distribution, e.g. the Altarelli-Parisi function.[22)] Momentum conservation needs to be imposed on an ICJ final state in a *ad hoc* way: in the "Boost" technique,[20)] all particles undergo a Lorentz transformation into the zero momentum frame whereas the "Jet" method[21)] attempts to equalize the ratios of jet to parent-parton momentum by rescaling the longitudinal components of individual hadron momenta separately within each jet. Different choices for gluon fragmentation and momentum conservation lead to different predictions[23] for $\frac{d\Sigma}{d\chi}$. In particular, to account for a given measured asymmetry, larger values of α_S are required for softer gluon jets ($g = \mathrm{q\bar{q}}$ and/or Boost) than for harder ones (g=q and/or Jet).

In addition to α_S, the event generation reqires specification of: the infrared cutoff y_{min}[17),24)] on the invariant mass (scaled by $\sqrt{s}$) of any two partons; the variance $2\sigma_q{}^2$ of the secondary quark momenta transverse to the initial parton direction; and the two parameters (A and B) of the fragmentation function.[25] $\frac{d\Sigma}{d\chi}$ is very insensitive to the position (A, B) on the constant multiplicity curve in (A, B)-space, a curve that depends on y_{min}, α_S, and σ_q.

Fragmentation changes $\mathcal{A}(\chi)$ from the QCD prediction in all the models. However, for any one model at fixed $\sqrt{s}$, the asymmetry for $\chi > 40°$ has the general shape of the perturbative prediction, scales nearly linearly with α_S, and has a small sensitivity to variations in other model parameters. Therefore α_S can be determined within the context of each model from comparison with the measured asymmetry alone. The predictions for the full correlation differ substantially in shape from model to model, though, opening the possibility that measurement of $\frac{d\Sigma}{d\chi}$ might distinguish among the fragmentation models.

Distortions to the energy-energy correlation cross section arise due to radiation of photons by the initial state electrons, detector resolution in angle and energy, and the limited acceptance. Removing these effects facilitates direct comparisons of the data with theoretical predictions and results from other experiments. This unfolding is achieved by applying a χ-dependent correction factor, computed as the ratio of a specific hadron production model's prediction for $\frac{d\Sigma}{d\chi}$ to that obtained from folding the model with a Monte Carlo simulation[2] of initial state radiation[7] and detector response to hadronic events. In order to probe subtleties in the detector modeling and to establish a reliable estimate of systematic errors, $\frac{d\Sigma}{d\chi}$ is measured and corrected separately with both the calorimeters and the central drift chamber on the same event sample. For these two independent measurements either the calorimeter hits $\vec{E}_i/E_{\mathrm{vis}}$ or the charged particle momenta $\vec{p}_i/P_{\mathrm{vis}}$ are used as the $\vec{\epsilon}_i$. The corrections for both measurement techniques are identical for events generated with string fragmentation and with incoherent jet formation.

Interpreting the discrepancies (3-7%) between the corrected $\frac{d\Sigma}{d\chi}$ from the calorimetry and tracking as a gauge of the systematic errors, the best measure

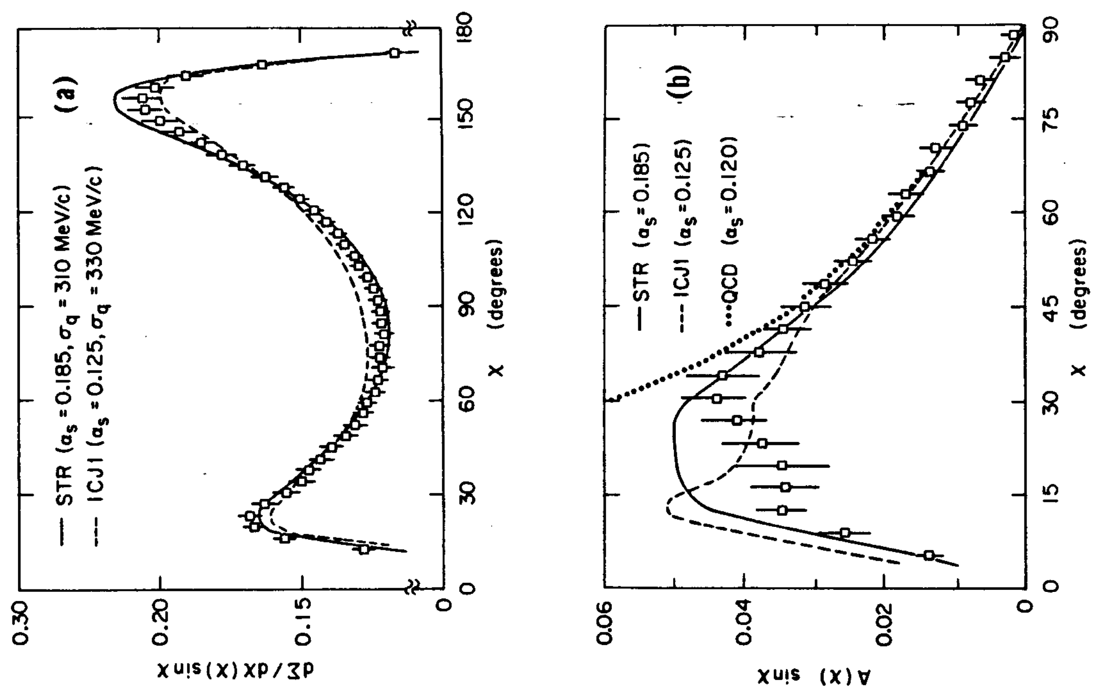

Fig. 2. The corrected data for (*a*) $d\Sigma/d\chi$ and (*b*) $\mathcal{A}(\chi)$, both multiplied by $\sin\chi$. The curves show the predictions (see Table 2) of perturbation theory (QCD), and the string (STR) and incoherent jet (ICJ1) fragmentation models.

of $\frac{d\Sigma}{d\chi}$ and $\mathcal{A}(\chi)$ is taken as the arithmetic mean of the calorimetry and tracking results. The total error in each χ-bin is computed by summing in quadrature the larger of the two statistical errors and a systematic uncertainty; the latter consists of a Monte Carlo correction error (1.5% for $\frac{d\Sigma}{d\chi}$ and 10% for $\mathcal{A}(\chi)$) added in quadrature with half the difference between the calorimetry and tracking values. The errors for the asymmetry $\mathcal{A}(\chi)$ are calculated separately to avoid symmetric errors in $\frac{d\Sigma}{d\chi}$. The results appear in Fig. 2.

An attempt has been made to vary the parameters in the Monte Carlo models discussed above to obtain agreement with the data. The procedure to do so is iterative and consists of adjusting (*i*) α_S, in steps of 0.005, to match the measured $\mathcal{A}(\chi)$ for $\chi > 40°$, with fixed y_{min}=0.015; (*ii*) the fragmentation function parameter B, in steps of 0.01, to yield the correct mean charge multiplicity, with fixed A=1.0; and (*iii*) σ_q, in steps of 10 MeV/c, to minimize the χ^2 for the fit of the model's $\frac{d\Sigma}{d\chi}$ to the data. The fit has 47 degrees of freedom. The best-fit parameters for five models are shown in Table 2 and two of the cross sections (STR and ICJ1) are plotted in Fig. 2. The row and curve labeled QCD is

Label	g Frag.	$\vec{p}$ Cons.	B	σ_q	α_S from $A(\chi)$	χ^2
QCD	none	...	...	...	0.120 ± 0.006	...
STR	string	...	0.67	310	0.185 ± 0.013	35
ICJ1	g=q	Boost	0.47	330	0.125 ± 0.009	136
ICJ2	g=q$\bar{q}$	Boost	0.60	320	0.140 ± 0.010	201
ICJ3	g=q	Jet	0.43	360	0.105 ± 0.007	98
ICJ4	g=q$\bar{q}$	Jet	0.50	350	0.110 ± 0.008	142

Table 2. The parameters resulting from fitting the data to five Monte Carlo models of QCD and fragmentation and to perturbative QCD (row 1). For all cases y_{min}=0.015 and A=1.0. For the g = q$\bar{q}$ cases, the quark and antiquark share the gluon momentum according to the Altarelli-Parisi function. The units of B are GeV^{-2} and for σ_q are MeV/c.

obtained from fitting the measured $A(\chi)$ to the perturbative prediction, yielding α_S(QCD)=0.120±0.006. The errors assigned to α_S for the five models include the measurement error of 5% added in quadrature with a 5% Monte Carlo contribution. The latter accounts for the finite step-size and slightly different values of α_S that would result with other compatible choices of the parameters.

The string model reproduces the measured $\frac{d\Sigma}{d\chi}$ with reasonable χ^2 (35 for 47 d.o.f.), but incoherent jet fragmentation fails to do so. Each ICJ model has a χ^2 more than 2.8 times larger, the equivalent of 6.5 standard deviations or more. All four ICJ models predict higher values near χ =90° than the data and lower near χ =30° or 150°. Any ICJ prediction for $\frac{d\Sigma}{d\chi}$ can be shifted slightly up or down (nearly uniformly over the range $20° < \chi < 160°$) by varying y_{min} and/or σ_q without significantly improving the fit to the data.

All the models represent the measured $A(\chi)$ well for $\chi > 30°$; the value of α_S for the string model is 0.185±0.013, and for ICJ jet models varies from 0.105 to 0.140 (±0.01), depending on the choice of gluon fragmentation and momentum conservation scheme. If only first order perturbative QCD were used in the Monte Carlo, the values of α_S would be larger by about 10% for ICJ models and by about 30% for the string model. This suggests that nontrivial corrections are likely to occur at higher orders than α_S^2, especially for string fragmentation. All the models predict a higher asymmetry for $\chi < 30°$ than observed. This is the region where the corrections are large and changing rapidly, an effect that is perhaps not properly included in the errors assigned to $\mathcal{A}(\chi)$.

The α_S values obtained from the asymmetry are consistent with measurements at $\sqrt{s}$=34 GeV of the same quantity by the CELLO[16] and JADE[17] collaborations when compared to the appropriate models, but are about 20% larger than those determined by the MARK J[15] group. The preference for the string model from comparison with $\frac{d\Sigma}{d\chi}$ seen in this experiment was also observed in the JADE analysis, but MARK J obtained equally good fits with the string model and an incoherent jet model (g=q and Boost, corresponding to ICJ2 in Table 2).

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