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Journal
Physical Review Letters, 49(8)

ISSN
0031-9007

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Publication Date
1982-08-23

DOI
10.1103/physrevlett.49.521

Measurement of Energy Correlations in $e^+e^- \to$ Hadrons

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(Received 29 April 1982)

Energy correlations have been measured with the MARK II detector at the PEP storage ring (Stanford Linear Accelerator Center) at c.m. energy of 29 GeV and are compared to first-order QCD predictions. Fragmentation processes are significant and limit the precision with which the first-order strong-coupling constant can be determined.

PACS numbers: 13.65.+i, 12.35.Eq

We present a measurement of energy correlations[1] of hadrons produced in high-energy e^+e^- annihilations. This kind of measurement probes the general structure of hadronic events in a simple way and can be used to test QCD, the candidate theory of the strong interactions. It has several advantages over other techniques[2] of testing QCD: It does not require either the selection of specific event topologies, such as three-jet events, or the definition of a jet axis. It uses a simple parametrization to account for the fragmentation process[3] rather than detailed Monte Carlo simulations. In particular, to first order, the backward-forward asymmetry in the correlation function is proportional to the strong-coupling constant α_s and is assumed to be independent of fragmentation processes.[4] Good statistics allows us to make the first experimental test of the validity of this assumption. We find a significant nonperturbative contribution to the asymmetry in the data which could be due to the fragmentation in three-jet events. This has to be taken into account in a determination of the strong-coupling constant.

The data reported here were taken at a center-of-mass energy of 29 GeV with the MARK II detector at the PEP storage ring of the Stanford Linear Accelerator Center and correspond to an integrated luminosity of 15 000 nb^{-1}. The essential features of the MARK II detector have been described previously.[5]

Charged tracks are used in the analysis if they have a momentum greater than 100 MeV/c and appear to come from within 10 cm of the interaction point along the beam direction. Photons are used if they are measured to have an energy greater than 200 MeV in the lead–liquid-argon calorimeters and are further than 10 cm from any charged track at the entrance of the calorimeters. Events are accepted if there are at least five charged tracks and at least one photon passing the above criteria, if the total visible energy is larger than 15 GeV, and if the event vertex is within 7 cm of the interaction point in the beam direction and within a radial distance of 5 cm from the beam axis. The total visible energy is the sum of the energies of photons as measured in the liquid-argon modules and of the energies of charged particles as measured in the drift chamber. Since we do not distinguish between particle masses, a pion mass has been assigned to all charged particles.

The fiducial volume for this measurement is taken to be $-0.7 < \cos\theta < 0.7$, where θ is the angle with respect to the incident beams, and the entire azimuthal acceptance with the exception of eight gaps of 6° width corresponding to the edges of the lead–liquid-argon calorimeter modules. With the above selection criteria, 3000 events have tracks inside the fiducial volume.

The energy-weighted cross section for observing the energy E in the solid angle $d\Omega$ and the energy E' in the solid angle $d\Omega'$ is defined by

$$\frac{1}{\sigma_0}\frac{d\Sigma}{d\Omega\, d\Omega'}=\frac{1}{N\, d\Omega\, d\Omega'}\sum\sum\frac{EE'}{s}. \qquad (1)$$

The first sum is over all pairs of particles in the solid angles $d\Omega$ and $d\Omega'$ while the second sum runs over all N events. The total hadronic cross section is denoted by σ_0, and the center-of-mass energy is $\sqrt{s}$. In this Letter we will study this cross section as a function of the angle χ between $d\Omega$ and $d\Omega'$. In order to obtain the cross section given in Eq. (1), corrections for the effects of resolution, detection inefficiency, initial-state radiation, and weak decays have been made by a Monte Carlo simulation. The sum of these corrections is small inside the fiducial volume and in the range of $20° < \chi < 160°$. They amount to 20% at $\chi = 20°$ and 5% at $\chi = 90°$.

The sum over all external angles keeping the opening angle χ fixed gives the following cross section:

$$\frac{1}{\sigma_0}\frac{d\Sigma}{d\cos\chi}=\frac{1}{N\Delta\cos\chi}\sum\sum\frac{EE'}{s}. \qquad (2)$$

This corrected cross section summed over all pairs of particles inside the fiducial volume is shown in Fig. 1 as a function of $\cos\chi$.[6] The peaks at $\cos\chi = +1$ and -1 show the tendency of the events to form into two back-to-back jets. Studying the deviations of the data from a two-jet structure requires comparison with a detailed theoretical calculation. The cross section as defined in Eq. (1) has been calculated for partons in the framework of first-order perturbative QCD.[1,7] The explicit form is

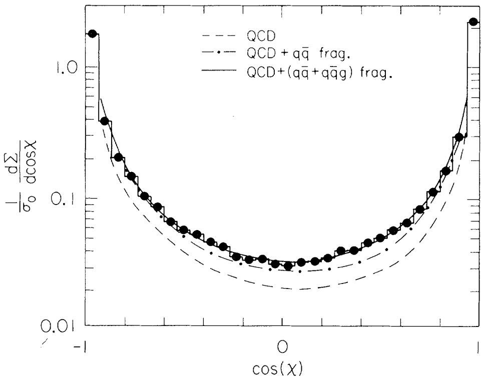

FIG. 1. $(1/\sigma_0)\, d\Sigma/d\cos\chi$ as a function of $\cos\chi$. The size of the dots corresponds to the statistical errors. The dashed line is the QCD prediction of Ref. 1. The dash-dotted line is the QCD result plus the $q\bar{q}$ fragmentation term [Eq. (4)]. The solid line is the sum of the QCD prediction and the two nonperturbative contributions from Eqs. (4) and (5).

$$\frac{1}{\sigma_0}\frac{d\Sigma}{d\Omega\, d\Omega'}=\frac{3}{16\pi}\left[A(\chi,\alpha_s)(2+\cos^2\theta+\cos^2\theta')+B(\chi,\alpha_s)(\cos\chi+\cos\theta\cos\theta')\right]. \qquad (3)$$

The direction of a particle with respect to the beam is given by the polar angle θ. The functions A and B have been calculated in the framework of perturbative QCD to first order in α_s and they depend only on χ and α_s. They describe the energy correlation of a quark, an antiquark, and a gluon, according to the two external angular terms. In the partonic picture quark-antiquark ($q\bar{q}$) contribute only at $\chi = 0°$ and $\chi = 180°$ to the energy correlation. The first-order perturbative cross section has singularities at $\chi = 0°$ and $\chi = 180°$, where the gluon, quark, and antiquark become collinear. In the intermediate angular range ($20° < \chi < 160°$) there is a very pronounced asymmetry around $\chi = 90°$. Only those terms of the cross section proportional to α_s contribute to this asymmetry.

In order to compare the theory with an experiment, in which hadrons are observed instead of partons, a nonperturbative correction has to be added to account for the fragmentation of partons into hadrons.[1] The fragmentation of the $q\bar{q}$ process is in leading order symmetric around 90° and is accounted for by an additional term added to A. This term has been estimated to first order in $1/\sqrt{s}$ as

$$A_{q\bar{q}f}(\chi)=A_f{}^0/(\sqrt{s}\,\sin^3\chi). \qquad (4)$$

A second fragmentation term for events with a gluon radiated off a quark or an antiquark ($q\bar{q}g$) has to be added to A. The dominant effect due to this fragmentation is to spread the correlation at 0° to larger values of the angle χ. This term is asymmetric with respect to 90° since for these three-jet events there is no jet at 180°. Following the description of fragmentation of a quark according to Eq. (4) we tried the following *Ansatz* to account for the fragmentation from $q\bar{q}g$ events[8]:

$$A_{q\bar{q}gf}(\chi)=\begin{cases}\alpha_s A_f{}^1/(\sqrt{s}\,\sin^3\chi) & \text{for } \chi<90°, \qquad (5a)\\ \alpha_s(A_f{}^1/\sqrt{s})(1+\cos\chi) & \text{for } \chi>90° \text{ (Ref. 9)}. \qquad (5b)\end{cases}$$

Equation (5) is only an estimate of the net contribution from $q\bar{q}g$ fragmentation, but it agrees well with a Monte Carlo simulation in the angular range $0° < \chi < 80°$. For angles $> 80°$ the actual shape of the fragmentation term is less important since it is small there. As will be shown below, the addition of a fragmentation term like Eq. (5) is necessary in order to describe the data. Note that all terms which are asymmetric about $\chi = 90°$ come from three-parton processes and are thus proportional to α_s in this model.

The solid curve in Fig. 1 is the result of a fit of Eqs. (3)–(5), integrated over the MARK II solid angle. For the parameters we obtained $\alpha_s = 0.19 \pm 0.02$, $A_f^{\,0} = 0.7 \pm 0.2$ GeV, and $A_f^{\,1} = 2.6 \pm 0.5$ GeV with a χ^2 of 25 for 22 degrees of freedom. The errors are statistical only. The fragmentation terms account for $\simeq 40\%$ of the observed correlation at $\chi = 90°$. The $q\bar{q}g$ fragmentation term is important in order to describe the observed energy correlation. A fit without this term ($A_f^{\,1} = 0$) increases χ^2 by a factor of 2 while the value of α_s changes to 0.14.

The measurement of the asymmetry

$$D(\chi) = \frac{1}{\sigma_0}\left[\frac{d\Sigma}{d\cos\chi}(\pi - \chi) - \frac{d\Sigma}{d\cos\chi}(\chi)\right],$$

which is given in Fig. 2, shows a change of nearly 2 orders of magnitude from $\chi = 20°$ to $\chi = 90°$. The sum of the perturbative and the $q\bar{q}g$ fragmentation component with parameters as determined from the full cross section is shown together with the pure perturbative prediction. The fragmentation of $q\bar{q}g$ events reduces the asymmetry by about a factor of 2.

The systematic error in α_s has been estimated to be 0.03. The major source of this error is the uncertainty in the form for the fragmentation terms, particularly Eq. (5). We have estimated the uncertainty by trying alternative forms of Eq. (5) that are roughly consistent with the shape predicted by the Monte Carlo simulations. The uncertainties from the fragmentation terms dominate the ones introduced by the Monte Carlo corrections.

There are two other sources of uncertainty which are not included in the error estimate because, in some sense, they are beyond the level of approximation we are considering. First, it is possible that the $q\bar{q}$ fragmentation has a second-order ($\propto 1/s$), asymmetric component. Monte Carlo simulations indicate that such components exist and, if included, would reduce the value of α_s by about 10%. Second, no correction has been made for second-order perturbative terms in the cross section, because the calculation of them has not yet been done.

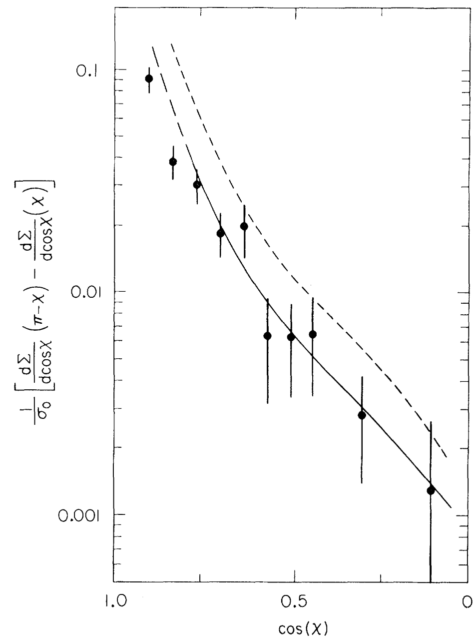

FIG. 2. The asymmetry $D(\chi)$ as a function of $\cos\chi$. The solid line is the QCD prediction with $\alpha_s = 0.19$ and the $qq\bar{g}$ fragmentation term with $A_f^{\,1} = 2.6$ GeV. The dashed line is perturbative QCD alone.

Our result is in reasonable agreement with several determinations of α_s made at PETRA[10-13] (Deutsches Elektronen Synchrotron) at $\sqrt{s}$ around 30 GeV.[14] The values of α_s vary between 0.15 and 0.20. The systematic uncertainties in these measurements come not only from different experimental methods but also from different treatment of the fragmentation. The energy-correlation method treats the fragmentation with a global parametrization, whereas the other methods rely on Monte Carlo simulations.

In conclusion, the energy-correlation cross section is a rather unbiased measure of the hadronic final state and allows a comparison with theoretical predictions with, in principle, minimal use of a Monte Carlo model. Quantitative tests of perturbative QCD predictions, however, depend on additional assumptions on the nonperturbative hadronization process, even in the opposite-side to same-side asymmetry, in contrast to previous expectations. With inclusion of the fragmentation terms the strong-coupling constant as defined in the first-order QCD calculation of Basham *et al.* is in good agreement with results from other experiments.

We wish to acknowledge stimulating discussions with L. Brown and S. Ellis.

This work was supported primarily by the U. S. Department of Energy under Contracts No. DE-AC03-76SF00515, No. W-7405-ENG-48, and No. DE-AC02-76ER03064. Partial support came from the listed institutions plus Ecole Polytechnique, Palaiseau, France, Der Deutsche Akademische Austauschdienst, Bonn, Germany, The Miller Institute for Basic Research in Science, Berkeley, California, The Institute of High Energy Physics, Academia Sinica, Beijing, China, The Swiss National Science Foundation, and the National Science Foundation.

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[4]The first use of this general method of analysis was by the PLUTO group at PETRA; Ch. Berger *et al.*, Phys. Lett. 99B, 292 (1981).

[5]R. H. Schindler *et al.*, Phys. Rev. D 24, 78 (1981), and references therein.

[6]Note that the cross section is for the fiducial volume and not extrapolated to the full solid angle.

[7]G. Fox and S. Wolfram, Z. Phys. C 4, 237 (1980).

[8]In the original work of Basham *et al.*, the $qq\bar{g}$ fragmentation term has been neglected.

[9]In order to avoid a discontinuity at 90°, we have added a linear extrapolation to zero for $\chi > 90°$.

[10]S. Yamada, in Ref. 2.

[11]D. P. Barber *et al.*, Phys. Lett. 89B, 139 (1979); H. Newman, in Ref. 2.

[12]R. Brandelik *et al.*, Phys. Lett. 94B, 437 (1980).

[13]Ch. Berger *et al.*, Phys. Lett. 97B, 459 (1980).

[14]Another type of determination of α_s, using the data of the Υ decay, yields a value of 0.16 ± 0.01 [P. B. Mackenzie and G. P. Lepage, Phys. Rev. Lett. 47, 1244 (1981)] which gives a relatively small value of α_s at $\sqrt{s} = 30$ GeV. As a result of the very different analysis, this difference may reflect the systematic uncertainties in the theoretical assumptions.