Model-Independent Second-Order Determination of the Strong-Coupling Constant α_s

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With use of the MARK-J detector at $\sqrt{s} = 34.7$ GeV 21 000 $e^+e^- \to$ hadron events have been collected. By measurement of the asymmetry in angular energy correlations the strong coupling constant $\alpha_s = 0.13 \pm 0.01$ (statistical) ± 0.02 (systematic) is determined, in complete second order, and independent of the fragmentation models and QCD cutoff values used.

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Quantum chromodynamics (QCD)[1] is currently the leading candidate theory for the strong interaction. However, compared to QED our confidence in this theory is still restricted, because quantitative tests are few, particularly in higher order. To second order the process $e^+e^- \to$ hadrons can be visualized via the following sequence. (1) The production of a parton state:

$$\begin{aligned} e^+e^- + \gamma &\to q\bar{q} \\ &\to q\bar{q}g \\ &\to q\bar{q}gg \\ &\to q\bar{q}q\bar{q}\,. \end{aligned}$$

The partons interact with each other via exchange of gluons. The coupling strength between photon and quark is proportional to α $(=\frac{1}{137})$. The coupling strength between quark and gluon is proportional to α_s. (2) The partons fragment into hadron jets according to a phenomenological model. There are then three uncertainties in the calculation: (1) The strength of the strong-interaction coupling α_s; (2) the cutoff procedure employed to remove divergences in the QCD calculation due to soft or collinear partons; and (3) the fragmentation model used.

The discovery of three-jet events at PETRA[2] has been interpreted in terms of the emission of an energetic gluon, and α_s has been determined[3] to the leading order[4] of QCD to be ~0.15 to 0.20. Since this number is large, it is important to go to second order to check convergence of the perturbation series. In this report we present a complete second-order determination of α_s which is independent of cutoff parameters and fragmentation models.

It has been suggested that a sensitive test of QCD can be accomplished by measuring the correlations between the energy detected at a given solid angle with that energy at another angle.[5] This energy correlation function is defined as

$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\chi} = \frac{1}{N}\sum_{\text{event}}^{N}\sum_{i,j}\frac{E_iE_j}{E_{\text{vis}}^2}\,\delta(\cos\chi_{ij} - \cos\chi),$$

where the sum is over all hadronic events, E_i is the energy measured in a given solid-angle element i, E_{vis} is the total event energy, and χ_{ij} is the angle separating the directions of the en-

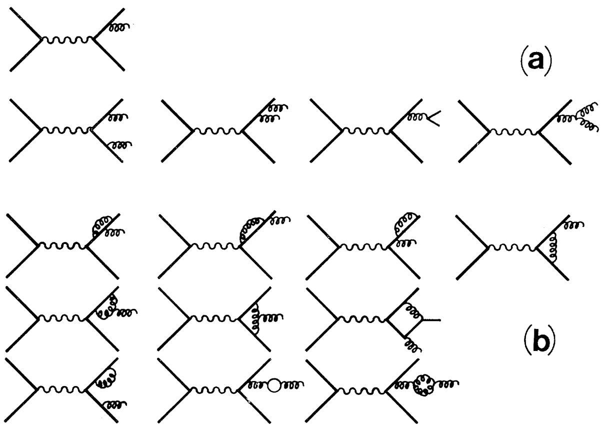

FIG. 1. (a) Tree-level diagrams for three- and four-parton final states. (b) Second-order virtual parton diagrams for three-parton final state.

ergy depositions. One expects that two-jet events predominate with peaks at $\cos\chi = \pm 1.0$. The nonzero correlation at other $\cos\chi$ arises from the transverse momentum which hadrons receive in the fragmentation as well as from the presence of large-angle energetic gluons. To isolate the effect due to gluon emission, one uses the asymmetry in $\cos\chi$:

$$A(\cos\chi) = \frac{1}{\sigma} \frac{d\Sigma}{d\cos\chi}(\pi - \chi) - \frac{d\Sigma}{d\cos\chi}(\chi) \quad .$$

Our Monte Carlo studies have shown that the region $|\cos\chi| < 0.72$ has only a small contribution from two-jet events, and thus allows a comparison with QCD calculations.

To calculate the hadronic cross section to second order in α_s we use the standard tree-level calculation[6] of three- and four-parton events [Fig. 1(a)] and complete the calculation by doing a Monte Carlo integration of the second-order virtual contributions computed by Ellis, Ross, and Terrano [Fig. 1(b)].[7] To ensure that our result is independent of the cutoffs[8,9] employed, we impose cuts on the minimum energy fraction of each of the partons and on the minimum angle between parton pairs, i.e., the Sterman-Weinberg[10] $\epsilon = \min E_i/s$ and $\delta = \min \chi_{ij}/2$. We have verified that the asymmetry in the energy-energy correlation does not depend on these cutoffs.[11] It is important to note that the commonly used procedures to determine α_s, such as comparing the data with thrust or oblateness distributions, produce values of α_s which depend strongly (30%) on the cutoff value used.[11]

To compare this calculation with data, the effects of fragmentation must be included. We have used two fragmentation models to test the model dependence of the result. In the first, implemented by Ali *et al.*,[6] the three (or four) partons fragment independently according to the Feynman-Field model.[12] In the second, known as the Lund model,[13] color strings connect quark to gluon and antiquark to gluon. The fragmentation is according to a Feynman-Field-type model, but it occurs along the directions of the color strings rather than along each parton direction. The two models are rather extreme with regard to the question of the effect of color strings; one assumes no effect while the other assumes that the two color strings in a three-jet event are preserved throughout the entire fragmentation process.

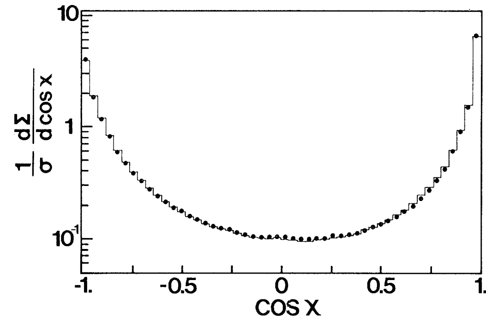

FIG. 2. Comparison of energy correlation data with Monte Carlo prediction, with $\alpha_s = 0.13$, for both fragmentation models, which are indistinguishable.

The data were collected with the MARK-J detector at PETRA, at an average center-of-mass energy $\sqrt{s}$ of 34.7 GeV. We have selected a sample of 21 000 hadron events from the one-photon annihilation process. A detailed description of

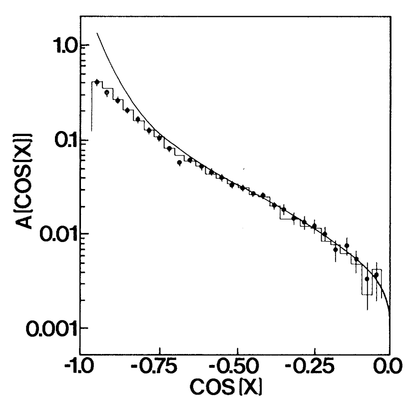

FIG. 3. Asymmetry data compared with predictions at parton level (curve) for $\alpha_s = 0.13$ and predictions for the two fragmentation models (Lund, Ali *et al.*; histogram) for the best-fit values of α_s. These two histograms are indistinguishable.

the detector and the event selection has been given elsewhere.[14]

The energy-energy correlation is shown in Fig. 2. Data are compared to a second-order QCD Monte Carlo prediction. The Monte Carlo prediction represents the data well for both fragmentation models, which are indistinguishable in the figure.

Figure 3 shows the asymmetry data compared with predictions at the parton level and best fits including fragmentation and detector simulation. As seen, detector and fragmentation effects are small for $|\cos\chi| < 0.72$.

By fitting the QCD asymmetry prediction to the data for $|\cos\chi| < 0.72$, we find $\alpha_s = 0.14 \pm 0.01$ for the Lund fragmentation model and $\alpha_s = 0.12 \pm 0.01$ for the model of Ali *et al.*

We make the following observations:

(a) We have performed many checks on the cutoff parameters, ϵ and δ, and find that our results are insensitive to their variation as seen for ϵ in Fig. 4. By using only the $|\cos\chi| < 0.72$ region, we are explicitly insensitive to the δ cut over a wide range.

(b) The difference in α_s between the Monte Carlo predictions using the fragmentation models of Lund and of Ali *et al.* is 0.02. Thus our results are insensitive to the fragmentation model used. This is a significant improvement over the model dependence that we find in first order.[11] In addition, our results are insensitive to variations of the transverse momentum of the partons in fragmentation by 40% in either model.

(c) α_s determined by this method is about 25% less in second order than in first order.

(d) By varying cuts in our data analysis such as those on the total visible energy and energy balance and by varying the τ background subtraction we have shown that the results are insensitive to our event selection.

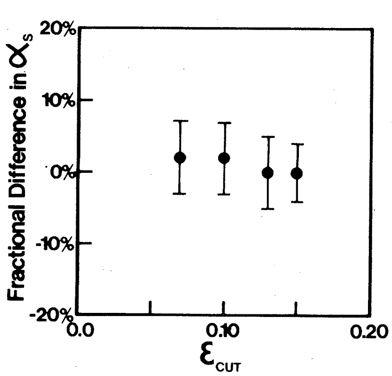

FIG. 4. Percentage change of α_s determined in second order as a function of the ϵ cut.

We obtain our best value of $\alpha_s = 0.13 \pm 0.01$ (statistical) ± 0.02 (systematic). This value[15] of α_s can be converted into a value of $\Lambda(\overline{MS})$, by use of the second-order formula: $\Lambda(\overline{MS}) = 180^{+60}_{-40}$ MeV.[16]

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