Measurement of Strong-Coupling Constant α_s to Second Order for $22 \leqslant \sqrt{s} \leqslant 46.78$ GeV

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Using the Mark-J detector at the high-energy e^+e^- collider PETRA, we compare the data from hadron production with the complete second-order QCD calculation over the energy region 22 to 46.78 GeV. We determine the QCD parameter $\Lambda = 100 \pm 30^{+60}_{-45}$ MeV which yields the strong-coupling constant $\alpha_s = 0.12 \pm 0.02$ for $\sqrt{s} = 44$ GeV.

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In the last half century, there have been many experiments to study the validity of quantum electrodynamics (QED), particularly the measurement of the fine structure constant α. Since the discovery of the three-jet events, much effort has been spent in recent years to measure the corresponding constant in strong interaction, α_s, the coupling strength between a quark and a gluon. Unlike α, however, α_s is running appreciably, that is, it decreases with energy, and the first-order measurement shows that α_s is still large: $\alpha_s \sim 0.2$ at $\sqrt{s} = 35$ GeV. To date, there have been many efforts[1-3] to measure α_s to second order. Unfortunately, these measurements have yielded results for α_s values ranging from 0.1 to 0.2.

The purpose of this experiment is to perform a systematic study of α_s measurements at different energies and to understand the source of this large discrepancy. The second-order measurements of α_s are complicated because of the following:

(1) Since the first-order α_s is large and QCD is non-Abelian, the second-order contribution is not small. All the second-order diagrams must be included in a proper calculation.

(2) Contrary to QED where one measures the electrons and photons directly, in QCD we do not detect quarks and gluons directly. Instead, we measure the hadrons which result from complicated fragmentation processes where the original quarks and gluons combine with additional quarks and gluons from the vacuum to form hadron jets. Thus, to measure α_s, the effect of the fragmentation process must be properly understood.

(3) Since $\alpha_s > \alpha$, the infrared-divergence problem in QCD becomes much more serious than in QED. Therefore, the proper choice[4] of dynamical variable is important so that the variables are not dependent on the infrared cutoffs.

Electron-positron annihilation into hadrons provides a fruitful testing ground for quantum chromodynamics (QCD). Indeed, it was the discovery of the three-jet events and planar events at PETRA[5,6] and the identification of this phenomenon with the process of gluon bremsstrahlung from the quark or the antiquark that has provided one of the stronger justifications for the acceptance of QCD.

In second-order QCD, α_s is given in the $\overline{\text{MS}}$ scheme by[7]

$$\alpha_s = 2\pi\left[\frac{(33-2N_F)}{6}\ln\left(\frac{s}{\Lambda^2}\right) + \frac{(153-19N_F)}{(33-2N_F)}\ln\left(\ln\frac{s}{\Lambda^2}\right)\right]^{-1}. \tag{1}$$

N_F is the number of quark flavors at a particular energy (e.g., $N_F=5$), and Λ is a scale parameter of the theory. In this study we determine Λ directly using the large energy range available.

We study the energy dependence of α_s from 14 to 46.78 GeV using two fragmentation models, the Ali[8] "independent jet model" and the Lund[9] "string model." The high-energy data are collected from a continuous scan of c.m. energies $39.79 \leq \sqrt{s} \leq 46.78$ GeV with a total integrated luminosity of 31 pb^{-1}. The other data have 88 pb^{-1} at $\langle\sqrt{s}\rangle = 35$ GeV, 3.2 pb^{-1} at 22 GeV, and 2 pb^{-1} at 14 GeV.

The essence of this analysis is the use of data over a wide range of energies and at much higher $\sqrt{s}$ values. The advantage here does not lie in the s dependence of α_s which is weak [for $\Lambda = 100$ MeV, $\alpha_s(\sqrt{s}=22\text{ GeV}) = 0.154$, and $\alpha_s(\sqrt{s}=46\text{ GeV}) = 0.118$]; rather, the range of energies permits a separation of the phenomenon described by perturbative QCD from the "soft" hadronization effect. The latter, estimated[10] to have $1/\sqrt{s}$ dependence, should be less important at the highest energies and their description at all energies is facilitated by measurements over a large energy range.

Other analyses have attempted to use lower-energy data to separate QCD phenomena from the soft hadronization effects.[11] In contrast this experiment covers a large range at high energies, far from all known resonances, and above the region where the soft hadronization effects are dominant.

We measure the energy deposited in the various calorimeter elements for a hadronic event and compute the pairwise products of these measurements versus the spatial angle, χ_{ij}, between the pair. We use the energy-energy correlation function[12]

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

The sum is over all hadronic events; E_i is the energy measured in the solid angle element i; and E_{vis} is the measured total event energy. This measurement is expected to be symmetric about $\cos\chi = 0$ for the back-to-back two-jet events arising from $q\bar{q}$ production. However, hard gluon bremsstrahlung will yield an asymmetry in $\cos\chi$ whose magnitude depends upon the quark-gluon coupling constant. To enhance the effect arising from gluon emission we use the asymmetry in $\cos\chi$:

$$A(\cos\chi) = \frac{1}{\sigma}\left[\frac{d\Sigma}{d\cos\chi}(\pi-\chi) - \frac{d\Sigma}{d\cos\chi}(\chi)\right]. \quad (3)$$

Monte Carlo studies show that the region $|\cos\chi| < 0.72$ has only a small contribution to the asymmetry from the two-jet events, allowing a sensitive comparison with QCD calculations.

The procedure of calculating the hadronic cross section to second order in α_s has been described[13] in detail. We have investigated the behavior of several variables in terms of their dependence on the details of this calculation, particularly the cutoff parameter(s) needed for a perturbative calculation. We have found that the rate of low-thrust events versus the parton-pair mass cutoff, expressed as the fraction $x = m^2/s$, varies $\approx 20\%$ over the experimentally revelant region $0.02 < x < 0.05$ and varies $\approx 20\%$ for $0 < x < 0.02$. Therefore, thrust cannot be used to determine α_s.

The integrated asymmetry

$$\int_{-0.72}^{0} A(\cos\chi)\, d\cos\chi, \quad (4)$$

on the contrary, is stable over the full range of the cutoff parameters ϵ (the minimum parton energy fraction) and δ (the minimum parton-parton angle), including the limit of vanishing ϵ (e.g., $\epsilon \approx 10^{-3}$) and δ.

Figure 1 shows the measured asymmetry as a function of $\cos\chi$ for the high-energy (39.7 to 46.78 GeV) and lower-energy (35 GeV) data. The histograms are Monte Carlo simulations using a complete second-order QCD calculation ($\Lambda = 100$ MeV) and the Ali fragmentation model. The effects of QED radiative corrections,[14] finite detector acceptance, and resolution are imposed upon the model to facilitate direct comparison with the data. The asymmetry function, integrated over $|\cos\chi| < 0.72$, is shown in Fig. 2 as a function of $\sqrt{s}$. The predictions of the Ali and Lund fragmentation models with $\Lambda = 100$ MeV are shown to be good descriptions of the data. The fragmentation contribution from quark-antiquark final states alone, shown as the dashed curve in Fig. 2, decreases rapidly with energy. For $\sqrt{s} > 35$ GeV, the asymmetry function is almost constant showing that QCD effects dominate.

In Fig. 3 we plot α_s as a function of $\sqrt{s}$, obtained from fitting the energy-energy correlation asymmetry data in 3-GeV bins by a full second-order QCD calcualtion including fragmentation models. The curves are

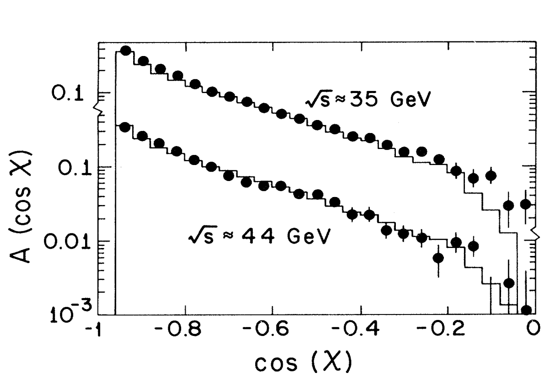

FIG. 1. Energy asymmetry data (circles) as a function of $\cos\chi$, at 35 and 44 GeV. The histograms are full Monte Carlo simulations using the Ali fragmentation model with $\Lambda = 100$ MeV.

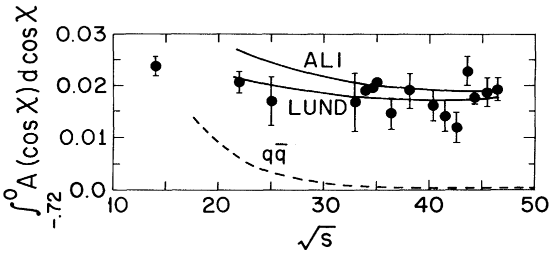

FIG. 2. The integrated energy asymmetry data (circles) as a function of c.m. energy. The calculated $q\bar{q}$ contribution is shown as the dashed curve. The other curves are for $\Lambda = 100$ MeV for both the Ali and the Lund models.

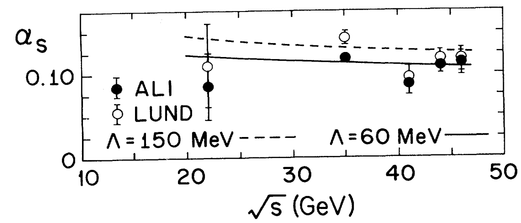

FIG. 3. The strong-coupling constant α_s, from the energy asymmetry measurement, as a function of c.m. energy $\sqrt{s}$. Solid circles are obtained from the Ali model and open circles from the Lund model. Curves for $\Lambda = 60$ and 150 MeV are shown.

from Eq. (1) with $\Lambda = 60$ and 150 MeV, respectively. The fragmentation effects at low energy hinder the QCD analysis there; α_s determinations are not meaningful with these techniques for $\sqrt{s} = 14$ GeV, and are less accurate at $\sqrt{s} = 22$ GeV than at higher energies.

In order to fully exploit the data and the energy dependence of the fragmentation effects, we fitted data at all energies simultaneously with the energy asymmetry. We obtain $\Lambda = 60 \pm 12^{+25}_{-20}$ MeV for the Ali model and $\Lambda = 150 \pm 30^{+50}_{-40}$ MeV for the Lund model, where the systematic errors include the acceptance cuts, QCD calculation parameters, and the regions (in the asymmetry angle) over which we perform the fitting.

Our present result from the asymmetry function yields $\Lambda = 100 \pm 30^{+60}_{-45}$ MeV, or $\alpha_s = 0.12 \pm 0.02$ at 44 GeV. The error is dominated by systematic errors due to the fragmentation models. This value of α_s is obtained with use of the complete second-order QCD calculation[15] together with a rigorous Monte Carlo method which includes radiative effects, jet dressing, fragmentation, and detector resolution.[16]

This value of α_s could be compared with other results,[2] which used approximate calculational methods,[17] only after the latter are properly renormalized.[18] Our results on α_s disagree with the conclusion of Althoff *et al.*[3] This value of α_s is in agreement with that of Adeva *et al.*[1] who used identical methods at lower energies. The value of Λ is in agreement with those obtained from measurements of the upsilon decays.[19] Our data are consistent with a logarithmic s dependence of the coupling constant α_s, as expected from QCD.

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[1]B. Adeva *et al.*, Phys. Rev. Lett. **50**, 2051 (1983).

[2]W. Bartel *et al.*, Phys. Lett. **119B**, 239 (1982), and Z. Phys. C **25**, 231 (1984); H. J. Behrend *et al.*, Phys. Lett. **138B**, 311 (1984); G. Wolf, Deutsches Elektronen Synchrotron Report No. DESY 83-96, 1983 (unpublished); P. Soeding, in *Proceedings of the International Europhysics Conference on High Energy Physics, Brighton, England, 1983,* edited by J. Guy and C. Costain (Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire, England, 1983), p. 567; E. Fernandez *et al.*, Stanford Linear Accelerator Center Report No. SLAC-PUB-3385, 1984 (unpublished).

[3]M. Althoff *et al.*, Z. Phys. C **26**, 157 (1984). The values of α_s obtained here, e.g., with the Lund model, are 15% to 36% higher than our values at 35 GeV.

[4]G. Kramer, Deutsches Elektronen Synchrotron Report No. DESY 83-068, 1983 (unpublished). Linear quantities such as the asymmetry functions and the oblateness are less sensitive to the details of the Monte Carlo (such as multiplicity) than quadratic variables such as $\langle p_T^2 \rangle$. The latter depends strongly on the multiplicity of the gluon jet which is poorly known.

[5]D. P. Barber *et al.*, Phys. Rev. Lett. **43**, 830 (1979). It was established here that the angular width of each jet is much smaller than the separation between the jets.

[6]R. Brandelik *et al.*, Phys. Lett. **86B**, 243 (1979).

[7]In this paper we use the $\overline{\mathrm{MS}}$ scheme for the definition of Λ. M. Dine and S. Sapirstein, Phys. Rev. Lett. **43**, 688 (1979); A. Buras, Rev. Mod. Phys. **52**, 199 (1980); W. J. Marciano, Phys. Rev. D **29**, 580 (1984).

[8]A. Ali *et al.*, Phys. Lett. **93B**, 155 (1980), and Nucl. Phys. **B168**, 409 (1980); see also R. D. Field and R. P. Feynman, Nucl. Phys. **B136**, 1 (1978). Our data are best described by this model with the fragmentation parameter $\sigma_q = 300$ MeV.

[9]B. Andersson, G. Gustafson, and T. Sjostrand, Z. Phys. C **6**, 235 (1980), and Nucl. Phys. **B197**, 45 (1982). Likewise, in this model we find $\sigma_q = 420$ MeV. Our results are insensitive to the exact values of σ_q used in either model of Ref. 8 or 9.

[10]T. F. Walsh, in *Proceedings of the International Europhysics Conference on High Energy Physics, Brighton, England, 1983,* edited by J. Guy and C. Costain (Rutherford Appleton La-

boratory, Didcot, Oxfordshire, England, 1983), p. 545.

[11]Ch. Berger *et al.*, Z. Phys. C **12**, 297 (1982).

[12]G. L. Basham, L. Brown, S. Ellis, and S. Love, Phys. Rev. D **19**, 2018 (1979).

[13]B. Adeva *et al.*, Phys. Rep. **109**, 133 (1984); R. Y. Zhu, Ph.D. thesis, Massachusetts Institute of Technology, 1983, unpublished.

[14]F. A. Berends and R. Kleiss, Nucl. Phys. **B178**, 141 (1981).

[15]R. K. Ellis *et al.*, Nucl. Phys. **B178**, 421 (1981).

[16]A complete second-order QCD calculation for the energy-energy correlation has been carried out by S. D. Ellis *et al.*, Nucl. Phys. **B229**, 317 (1983), and by A. Ali *et al.*, Phys. Lett. **118B**, 155 (1982), and Nucl. Phys. **B236**, 269 (1984), who include parton fragmentation within the Ali model.

[17]F. Fabricus *et al.*, Phys. Lett. **97B**, 431 (1981); F. Gutbrod *et al.*, Z. Phys. C **21**, 235 (1984).

[18]M. Chen, Massachusetts Institute of Technology, Laboratory for Nuclear Science Report No. 137 (unpublished), and in Proceedings of the International School of Subnuclear Physics at Erice, Sicily, August 1983 (to be published); T. D. Gottschalk and M. P. Schatz, Phys. Lett. **150B**, 451 (1985). These studies conclude that the approximate formulae commonly used (Ref. 17) will yield α_s values about 10% to 30% too high. We emphasize that the calculation used here and in our previous work (Refs. 1 and 13) does not involve the mentioned approximations.

[19]P. B. Mackenzie and G. P. Lepage, Phys. Rev. Lett. **47**, 1244 (1981); P. Franzini, private communication.