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Measurement of α_s in e^+e^- Annihilation at $E_{cm} = 29$ GeV[1]

TPC/Two-Gamma Collaboration

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Abstract

A measurement of the strong coupling constant α_s using the event-shape variable y_3 (the differential two-jet rate) in the reaction $e^+e^- \to hadrons$ is presented. The analysis is based on data from the *TPC/Two-Gamma* detector at the PEP e^+e^- storage ring taken between 1984 and 1986 at a center-of-mass energy of $E_{cm} = 29$ GeV. A value of $\alpha_s(29\,\mathrm{GeV}) = 0.160 \pm 0.012$ is obtained, where the error is the quadratic sum of experimental and theoretical uncertainties. The procedure for determining α_s is the same as that used by the ALEPH and TOPAZ experiments, which allows for a consistent comparison of the α_s values obtained at different center-of-mass energies. The observed energy dependence "running" of α_s is found to be in good agreement with the QCD prediction, and is clearly incompatible with a constant value.

1. Introduction

Quantum chromodynamics (QCD) has been well established in recent years as the theory of strong interactions, in which interactions of quarks and gluons (partons) are characterized by the coupling strength α_s. Renormalization of ultraviolet divergences in QCD leads to an effective "running" coupling, which is predicted to decrease with an increasing energy scale of the process leading to asymptotic freedom [3]. A recent review of measurements in electron-positron annihilation of α_s using distributions of event-shape variables can be found in [4].

Significant progress in the theoretical predictions of event-shape distributions for the reaction $e^+e^- \to hadrons$ has been made since the end of the data taking at the PEP and PETRA e^+e^- storage rings in the late 1980s. For example, the QCD prediction for the distribution of the event-shape variable y_3 (defined below) using the Durham jet algorithm [5, 6] has become available, and has been used by experiments at LEP and SLC [1, 7, 8] and at TRISTAN [2] to measure the strong coupling constant α_s. In particular, the analyses carried out by the ALEPH collaboration [1] at a center-of-mass energy of $E_{cm} = 91.2$ GeV and by TOPAZ [2] at $E_{cm} = 58$ GeV use the same analysis technique and similar treatment of systematic uncertainties, allowing for a consistent comparison. In this note, the same analysis is carried out using data from the *TPC/Two-Gamma* experiment at PEP ($E_{cm} = 29$ GeV). An attempt is made to identify systematic errors common to all three of the measurements, thus providing an accurate investigation of the energy dependence of α_s.

In order to measure the strong coupling constant one must define an observable sensitive to hard gluon radiation, whose probability density can be computed using perturbative QCD as a function of α_s. In this analysis the quantity y_3, or equivalently $L_3 = -\ln y_3$, defined in section 2, is used to provide sensitivity to the three-jet character of an event and hence to the strong coupling of quarks and gluons. The theoretical prediction for the distribution of L_3 can be computed to order $O(\alpha_s{}^2)$ in perturbative QCD by an appropriate integration of the second-order matrix element, done numerically with the program EVENT [9]. In addition, improved predictions valid for the two-jet region (dominated by collinear gluon radiation) have recently become available, where the so-called leading logarithms are summed to all orders, and part of the next-to-leading order solution is computed as well [5]. The QCD prediction used is a combination of the fixed-order and leading-log solutions. The measurement of the L_3 distribution is discussed in section 3.

Before the QCD prediction can be compared to the measured distribution, it must be modified for the non-perturbative effects of hadronization. This is done with several Monte Carlo hadronization models, which first generate a system of partons according to perturbative QCD, and then convert these into hadrons by means of a phenomenological mechanism (e.g., cluster, string fragmentation). The theoretical uncertainties in the predicted L_3 distribution at hadron level stem both from higher-order perturbative corrections as well as non-perturbative effects. The procedures for estimating these uncertainties and the corresponding error in α_s, largely following the ALEPH [1] and TOPAZ [2] analyses, are discussed in section 4. In section 5 the resulting value for α_s from the *TPC/Two-Gamma* experiment is compared with the measurements from ALEPH and TOPAZ in order to investigate the energy dependence of the strong coupling.

2. Event Selection

The data were recorded from 1984-1986 with the *TPC/Two-Gamma* detector facility [10] at the PEP e^+e^- collider at SLAC. The total sample has an integrated luminosity of 66 pb^{-1} at an e^+e^- center-of-mass energy of 29 GeV. The detector, including the central time projection chamber (TPC) for charged particle reconstruction and identification, is described in detail in reference [10]. The measurements presented here are based only on the charged particles, which are reconstructed in the TPC over a solid angle of 87% of 4π with a momentum resolution of typically $(\Delta p/p)^2 = (0.0015)^2 + (0.0065 \cdot p(GeV/c))^2$.

A detailed description of the data reconstruction and event selection is given in reference [10]. The basic selection criteria are given below, where the z-axis is parallel and the xy-plane perpendicular to the beam axis. A good charged track is required to satisfy:

- Angle with respect to xy-plane, $|\lambda|, \leq 60°$
- $p \geq 0.15$ GeV
- Distance of closest approach to event vertex in xy-plane ≤ 3 cm
- Distance of closest approach to event vertex in z direction ≤ 5 cm
- Track's curvature error cut: $\Delta c \leq 0.15\, GeV^{-1}$ or $\Delta c/c \leq 0.15$.

Using the tracks selected in this way, the total charged energy, E_{ch} (assuming the pion mass), is computed. The sphericity algorithm [11] is used to determine an event axis and its angle with respect to the xy-plane λ_{sph}. Using the above track requirements, multihadronic events are selected which satisfy:

- Number of good tracks ≥ 5 (suppresses $\tau^+\tau^-$ events)
- $E_{ch} \geq 7.25$ GeV (suppresses two-photon events)
- $\lambda_{sph} \leq 45°$ (insures that event is well contained in detector)

- $|\sum p_z|/\sum |p| \leq 0.4$ (suppresses two-photon events)
- At least four non-electron tracks or an invariant mass greater than 2 GeV (suppresses $\tau^+\tau^-$ and Bhabha events) in at least one hemisphere.

The procedure yields a sample of 20247 hadronic events. Background levels are estimated to negligible, with 0.4% being $\tau^+\tau^-$ events and 0.5% being two-photon events [12].

3. Measurement of the L_3 distribution

The quantity y_3 is defined by means of the following algorithm. For each pair of particles in an event i and j, one computes

$$y_{ij} = \frac{2\,\min(E_i^2, E_j^2)(1 - \cos\theta_{ij})}{E_{vis}^2} \, , \tag{1}$$

where E_i and E_j are the energies of particles i and j, θ_{ij} is their opening angle, and E_{vis} is the total visible energy in the event. (If the algorithm is being applied to events in a Monte Carlo model in which all of the particles are available, or in a theoretical calculation, then E_{vis} is simply the center-of-mass energy E_{cm}.) One finds the pair of particles with the smallest y_{ij} and replaces them by a pseudo particle or *cluster*. The four momentum of the new cluster is given by the sum of the four momenta of particles i and j (the so-called E recombination scheme). This procedure is repeated until three clusters remain. The smallest value of y_{ij} in the three-cluster configuration is then y_3. In applying the clustering algorithm with equation (1), the energy of the charged tracks (computed assuming the pion rest mass) is used for the visible energy E_{vis}.

The measured distribution for the equivalent variable $L_3 = -\ln y_3$ is corrected for effects of geometrical acceptance, detector efficiency and resolution, decays, secondary interactions and initial-state photon radiation by the following procedure. A first set of hadronic events with flavor composition as predicted by the Standard Model was generated using the JETSET Parton-Shower (PS) model [13] including initial-state photon radiation. The events were passed through the detector simulation program to produce simulated raw data, which were then processed through the same reconstruction and analysis chain as the real data. A second set of Monte Carlo data without detector simulation was generated, in which all particles with mean lifetimes less than 1 ns were required to decay, the others were treated as stable, and initial-state radiation was turned off. These two data sets were used to derive bin-by-bin multiplicative correction factors for the measured quantities. The corrected value f_i^{corr} for bin i is obtained from the measured distribution f_i^{meas} by

$$f_i^{corr} = f_i^{meas} \cdot C_i \, , \tag{2}$$

where the correction factor C_i is

$$C_i = \frac{f_i^{MC\ generator\ only}}{f_i^{MC\ gen.+detector\ sim.}} \, . \tag{3}$$

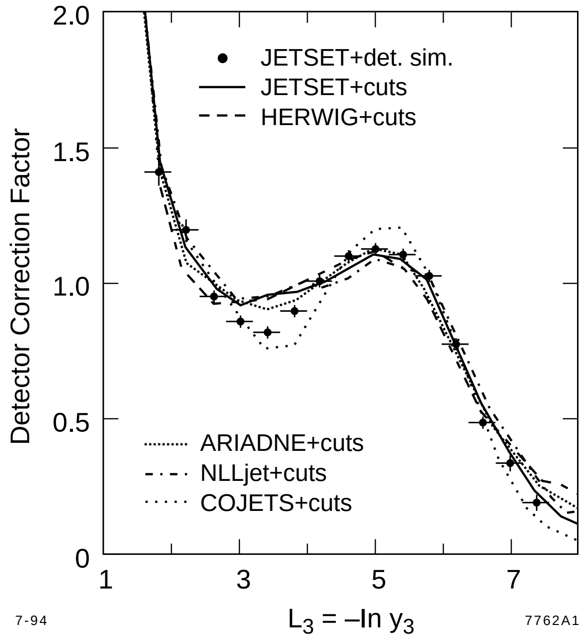

Figure 1:

This procedure corrects the measurements back to a fixed center-of-mass energy (free of initial-state radiation) and a well-defined, final-state particle composition that can be compared directly to theoretical predictions. The correction factors, typically in the range $0.8 \leq C \leq 1.4$, are shown for the L_3 distribution in Fig. 1. Based on the size of the experimental correction factors it was decided to require $L_3 > 1.6$ in the determination of α_s.

Also shown in Fig. 1 are simplified correction factors computed with various Monte Carlo generators without a full detector simulation. Instead only charged particles which passed the geometrical cut $|\lambda| < 60°$ and the momentum cut $p > 0.15$ GeV were accepted. The simulated momenta of the tracks were smeared according to a Gaussian resolution function with a width $(\sigma_p/p)^2 = (0.0015)^2 + (0.0065 \cdot p(GeV/c))^2$. From these simulated data sets one obtains simplified corrections:

$$C_i^{simp} = \frac{f_i^{MC\ generator\ only\ (all\ particles)}}{f_i^{MC\ gen. + cuts + p\ smearing (charged\ particles\ only)}} \ . \tag{4}$$

The simplified correction factor for the JETSET simulation, shown in Fig. 1, is in reasonably good agreement with that obtained from the full detector simulation indicating that the detector effects are dominated by the geometrical and momentum cuts. Since this does not require the full detector simulation, the simplified corrections can be easily computed for a variety of models. The relative spread in the simplified factors from model to model is a measure of the systematic uncertainty from generator dependence. In order to propagate the uncertainty in the L_3 distribution into an error for α_s, alternative versions of the corrected L_3 distribution were computed according to the formula

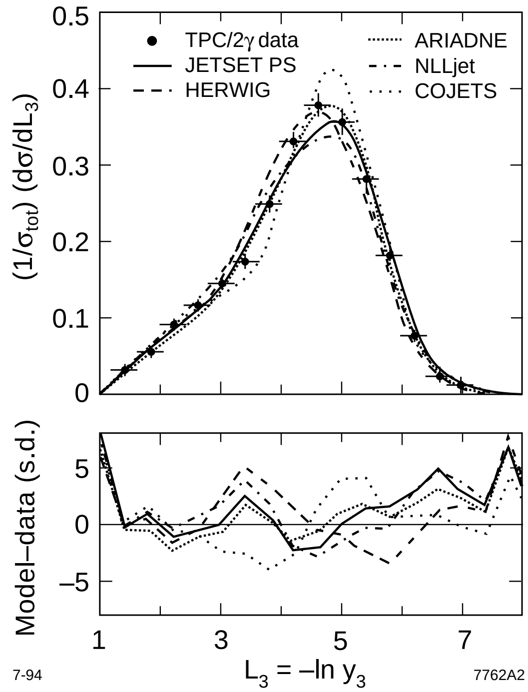

Figure 2:

$$f_i^{alt(MC)} = f_i^{corr} \cdot \frac{C_i^{simp(MC)}}{C_i^{simp(JETSET)}} \tag{5}$$

$$= f_i^{meas} \cdot C_i \cdot \frac{C_i^{simp(MC)}}{C_i^{simp(JETSET)}} \ , \tag{6}$$

where C_i is the correction factor using the full detector simulation according to Eq. (3), which is based on the JETSET PS model, and $C_i^{simp(MC)}$ is computed with the models HERWIG [15], ARIADNE [16], NLLjet [18], and COJETS [17]. The alternative distributions were then used in the fitting procedure for α_s as described in section 4 below, and the maximum difference between the resulting α_s values was included in the systematic uncertainty. Since the various models include different fragmentation schemes, the resulting error estimate includes the uncertainty arising from the correction for neutral particles, for which one relies on the Monte Carlo model. Figure 2 shows the corrected L_3 distribution compared to the predictions of several hadronization models. The models are consistent with the measured distribution.

Additional systematic uncertainties in the measured distribution were investigated by varying all of the track and event selection criteria listed above, redetermining the corrected L_3 distribution and repeating the fit procedure for α_s. In addition it was checked that the contribution to the correction factors from effects of initial-state photon radiation (ISR) in the region of the distribution used to determine α_s are small (less than several percent). Note that in comparing the results of this analysis with that from ALEPH, where the effects of ISR are greatly suppressed, a systematic error in this correction at $E_{cm} = 29$ GeV would not be common to the result from $E_{cm} = 91.2$ GeV.

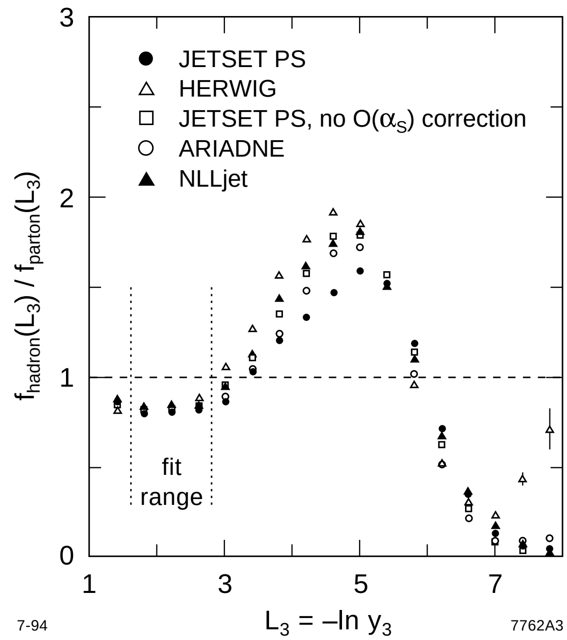

Figure 3:

4. Fitting procedure for α_s

The interval of the L_3 distribution used for determining α_s was restricted to a region where non-perturbative hadronization effects are expected to be small. This was determined by examining the hadron and parton level L_3 distributions from a number of parton-shower based Monte Carlo models: JETSET PS [with and without an $O(\alpha_s)$ correction for the first gluon emission], HERWIG, ARIADNE and NLLjet. The parameters of these models were tuned using data from the ALEPH experiment at a center-of-mass energy of $E_{cm} = 91.2$ GeV, where they were found to provide a good description of the data [14]. As can be seen in Fig. 2, the models also provide a good description of the L_3 distribution at $E_{cm} = 29$ GeV with the same model parameters, with some discrepancies visible for $L_3 > 4$. [Note that high L_3 or equivalently low y_3 corresponds to a more two-jet like configuration; see Eq. (1).] This agreement (at least in the three-jet region) allows for a consistent measurement of the energy dependence of α_s, without requiring a separate tuning of the model parameters at each energy. This procedure would not be possible with models based on $O({\alpha_s}^2)$ matrix elements, which have been found not to describe the energy dependence of the experimental data [see, e.g., [14]].

Figure 3 shows the ratio of parton-to-hadron level L_3 distributions from the above mentioned models. The ratios are all close to each other for $L_3 < 2.8$, so that in this range one expects the smallest uncertainty in α_s from hadronization effects. Based on these ratios and taking into consideration the detector correction factors, the range $1.6 < L_3 < 2.8$ was chosen for the determination of α_s.

Initially, several other event-shape variables such as thrust and heavy jet-mass were also investigated for purposes of determining α_s. From the ratios of hadron-to-parton level distributions it was found, however, that the uncertainty arising from hadronization effects was significantly smaller for the L_3 distribution, for which no published measurements were available at PEP/PETRA energies.

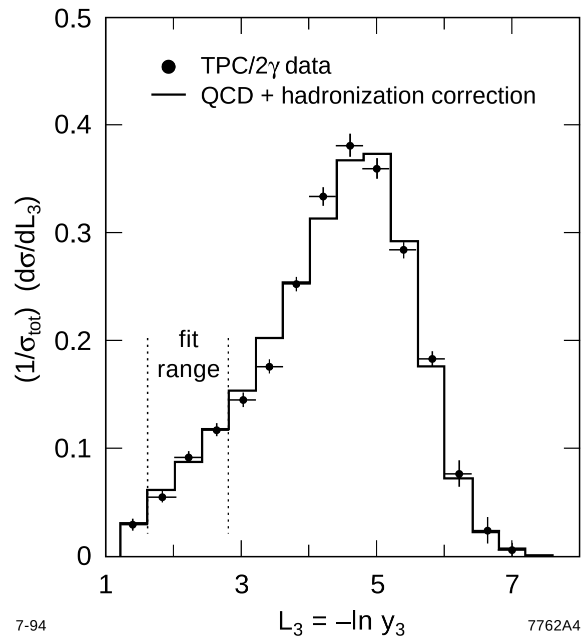

Figure 4:

In fitting, the parameter α_s is determined by minimizing the quantity

$$\chi^2 = \sum_{i=1}^{n} \frac{(f_i^{corr} - \sum_j P_{ij} f_j^{QCD}(\alpha_s, \mu^2/s))^2}{\sigma_i^2} \,, \tag{7}$$

where f_i^{corr} is the corrected measurement in bin i [as given by Eq. (2)], σ_i is the corresponding statistical error, $f_j^{QCD}(\alpha_s \, \mu^2/s)$ is the QCD parton level prediction for the L_3 distribution integrated over bin j, and P_{ij} is a matrix of hadronization correction factors based on one of the Monte Carlo hadronization models mentioned above. The hadronization correction matrix P_{ij} gives the probability that an event with L_3 in bin j at parton level obtains a L_3 value in bin i after hadronization. This correction is combined with the parton-level prediction $f_j^{QCD}(\alpha_s, \mu^2/s)$, where the sum over j in Eq. (7) covers the entire L_3 range, resulting in the hadron-level prediction for bin i.

The formula for $f_j^{QCD}(\alpha_s, \mu^2/s)$ combines the fixed-order $O({\alpha_s}^2)$ formula with the leading-log solution given in [5]. Terms from each solution must be matched in such a way that the $O(\alpha_s)$ and $O({\alpha_s}^2)$ parts of the leading-log formula are not counted twice. Two possible schemes, referred to as "R-matching" and "$\ln R$-matching" were proposed by ALEPH [1], the difference between the two being of order $O({\alpha_s}^3)$. Figure 4 shows a fit result using the R-matching scheme with the hadronization corrections based on the JETSET PS model. The fit has $\chi^2 = 2.79$ for two degrees of freedom, and the QCD prediction is in reasonably good agreement with the measured distribution even outside the fit range.

Following the convention of ALEPH [1], the nominal α_s value is given as the mean result of the two matching schemes for $\ln(\mu^2/s) = 0$. The maximum difference between this value and values obtained by varying the renormalization scale in the range $-1 < \ln(\mu^2/s) < 1$, using either R matching or $\ln R$ matching, is taken as the systematic uncertainty from the perturbative formula, $f^{QCD}(\alpha_s, \mu^2/s)$. This difference is illustrated

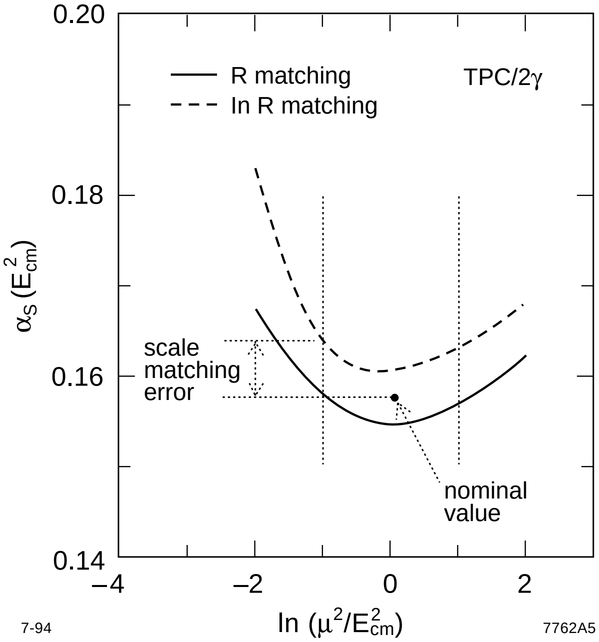

Figure 5:

in Fig. 5, where the JETSET PS model has been used for the hadronization correction. The resulting uncertainty of 0.0062 is conservatively taken to be symmetric.

Table 1 shows the values obtained using the various models for hadronization corrections for the two matching schemes. The hadronization mechanism in the HERWIG model uses cluster fragmentation, and the rest are based on the Lund string model. All of the models generate a system of partons based on QCD, an approach similar in physical content to the leading-logarithm formula for $f_j^{QCD}(\alpha_s, \mu^2/s)$. Although the models are equivalent at the parton level to leading order, they differ in their effective treatment of higher orders, e.g., angular ordering, $O(\alpha_s)$ corrections for the first emitted gluon, definitions of the parton-splitting variable, or in the case of NLLjet, explicit inclusion of next-to-leading order terms. Therefore the spread in the resulting α_s values reflects not only the uncertainty from the hadronization mechanism but also the theoretical uncertainty of the parton level of the model.

A final value may be obtained by taking the mean of the two extreme results obtained using the various hadronization models, as done in [1]. Table 1 shows that these results come from HERWIG and NLLjet, the average of which gives $\alpha_s = 0.1596 \pm 0.0033$ (*stat.*). The uncertainty from the hadronization correction is taken to be half the difference between the two extremes, or 0.0061. The resulting value for α_s is

$$\begin{aligned} \alpha_s(29\,\mathrm{GeV}) = 0.1596 \quad & \pm \quad 0.0033\ (\text{statistical}) \\ & \pm \quad 0.0074\ (\text{experimental systematic}) \\ & \pm \quad 0.0061\ (\text{hadronization model}) \\ & \pm \quad 0.0062\ (\text{scale/matching})\ . \end{aligned} \tag{8}$$

For purposes of the investigation of the energy dependence of α_s, the result based on hadronization corrections from JETSET PS ($\alpha_s = 0.1574$), rather than the average of NLLjet and HERWIG, will be used in order to have the same analysis technique at each energy.

5. Comparison with measurements at different energies

In order to investigate the running of α_s, it is a significant advantage to use the same process and same measured quantity at different center-of-mass energies, since many of the systematic errors are common to all energies. This type of approach has been done by experiments at PETRA in the energy range 8 GeV $< E_{cm} <$ 47 GeV [19, 20, 21] using the thrust distribution and jet rates, and by the Mark II experiment [22] in comparing the y_3 distributions measured at PEP ($E_{cm} = 29$ GeV) and at SLC ($E_{cm} = 91$ GeV). However, the hadronization uncertainties at the lowest energies of the PETRA range are large, and the theoretical predictions with resummed leading logarithms were not employed in the PETRA and Mark II measurements.

The primary goal of this analysis is not to provide the most precise measurement of α_s, but rather to investigate its energy dependence. In order to do this an attempt has been made by the *TPC/Two-Gamma*, ALEPH and TOPAZ collaborations to use a similar analysis technique, so that as many of the systematic errors as possible are common to all energies. The comparison of this analysis at $E_{cm} = 29$ GeV with the α_s measurements by TOPAZ at $E_{cm} = 58$ GeV and ALEPH at $E_{cm} = 91.2$ GeV takes advantage of the following common points:

- All analyses use the same event-shape variable, $L_3 = -\ln y_3$, with the same theoretical prediction, i.e., the mean of R matching and $\ln R$ matching with a renormalization scale equal to the the center-of-mass energy, i.e., $\ln(\mu^2/s) = 0$.
- Several models were used by each experiment for the hadronization corrections, and the discrepancies in the results given by the various models were used to estimate the systematic uncertainty. The conventions adopted differ slightly, since the hadronization corrections are significantly higher for lower energy. All experiments provide α_s values, however, using hadronization corrections based on the JETSET PS model with QCD and hadronization parameters from reference [14].
- The measurements were all made with charged particles detected by time-projection chambers with similar solid angle and momentum coverage, with dimensions that roughly scale with energy. The corrections for detector effects were all based on the JETSET PS model.

Figure 6 shows the α_s values obtained from this analysis and from ALEPH [1] and TOPAZ [2] as a function of the renormalization scale, for the two matching schemes, R and $\ln R$. The associated uncertainty is slightly smaller for ALEPH, since the smaller α_s value at higher E_{cm} leads to a reduced influence of higher-order terms in the L_3 distribution. Because of the larger non-perturbative effects at $E_{cm} = 29$ GeV, the fit range had to be restricted to $1.6 < L_3 < 2.8$, whereas TOPAZ used $1.2 < L_3 < 4.4$ and ALEPH

	R matching	$\ln R$ matching	average of R and $\ln R$ matching
Corrected with:			
JETSET PS	0.1546	0.1607	0.1574
HERWIG	0.1628	0.1695	0.1657
JETSET PS, no $\mathcal{O}(\alpha_s)$	0.1535	0.1597	0.1562
ARIADNE	0.1567	0.1631	0.1595
NLLjet	0.1504	0.1564	0.1534

Table 1: Fit results for α_s using different hadronization corrections and matching schemes, with the renormalization scale equal to the center-of-mass energy, i.e., $\ln(\mu^2/s) = 0$.

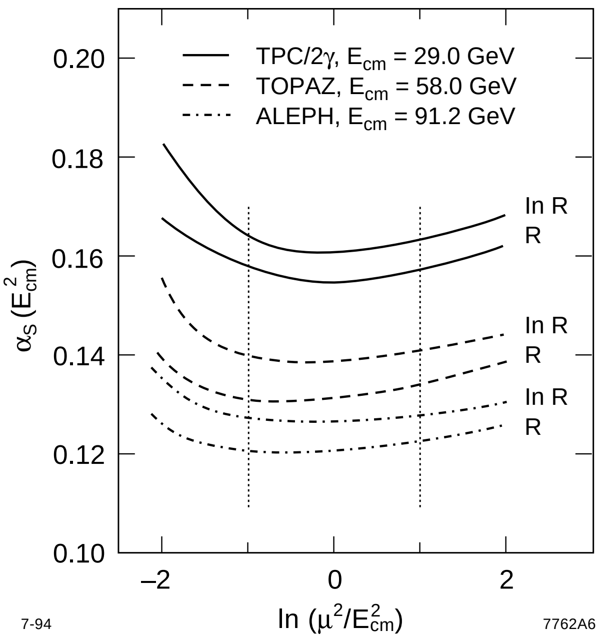

Figure 6:

used $1.6 < L_3 < 4.0$. Although this leads in principle to a different dependence on the renormalization scale, the results from Fig. 6 indicate that this effect is not large. The error from missing higher-order terms corresponds to a constant shift in the QCD scale parameter Λ to a good approximation in the energy range between 29 and 91.2 GeV. The somewhat larger dependence on matching and scale shown by the TOPAZ experiment is related to the larger fit range used [23].

The values of α_s from this analysis and from the TOPAZ and ALEPH analyses, obtained from the mean of R and $\ln R$ matching schemes, with $\ln(\mu^2/s) = 0$, and using hadronization corrections based on the JETSET PS model, are shown in Fig. 7. The theoretical uncertainties from the renormalization scale and matching scheme are not shown on the plot, since they are common for all energies to a good approximation. That is, the scale and matching errors correspond approximately to a common shift for all experiments in the QCD scale parameter Λ, and the uncorrelated part of the uncertainty is small compared to the hadronization error, for instance. The total error bars shown in Fig. 7 are the quadratic sum of the statistical, experimental systematic, and hadronization errors. Using the errors defined in this way, and neglecting possible correlations, the QCD scale parameter $\Lambda_{\overline{MS}}$ was fit to a value of 350 MeV, with $\chi^2 = 0.68$ for two degrees of freedom. (One should be cautioned against using the value of $\Lambda_{\overline{MS}}$ obtained in this way as an absolute measurement; the purpose of this study is to observe the energy dependence of α_s.) For an α_s independent of energy, one obtains $\alpha_s = 0.130$ and $\chi^2 = 15.0$ for two degrees of freedom.

The interpretation of χ^2 in terms of probabilities is not, strictly speaking, possible here so that χ^2 should be treated only as a qualitative measure of goodness-of-fit. First, the systematic errors have been estimated using necessarily arbitrary and somewhat conservative conventions, which do not correspond to errors of one standard deviation. In addition, the hadronization and detector-related systematic uncertainties are correlated

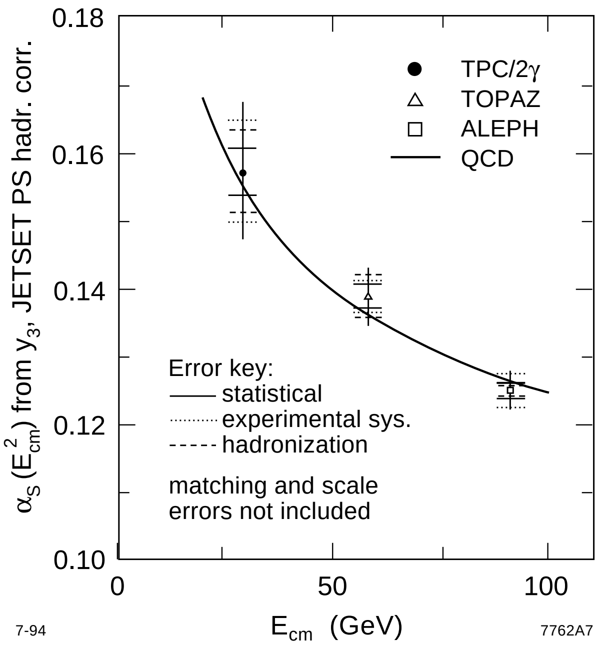

Figure 7:

to a certain extent, since the corresponding corrections were based on the same Monte Carlo model. It is plausible that these facts lead to the very small χ^2 value for the QCD prediction. Similarly, the χ^2 value for the constant α_s would presumably be larger if the correlations were correctly taken into account. The correlations from hadronization and detector corrections are difficult to estimate, however, and the errors are treated here as uncorrelated. The results, however, are in good agreement with QCD and are incompatible with a constant value.

6. Conclusions

The distribution of the event-shape variable $L_3 = -\ln y_3$ was used to determine the strong coupling constant α_s at a center-of-mass energy of 29 GeV. Although the result is not as accurate as similar measurements at higher energies, the main result of the present analysis is the observation of the energy dependence of α_s. This observation was made possible by coordinating the analysis efforts of three experiments at different center-of-mass energies—29, 58 and 91.2 GeV—so that some of the common systematic errors could be identified and removed. The three measurements constitute the clearest observation to date of the running of α_s based on a single physical process. A natural extension of this study will arise with the advent of the LEP II accelerator, which will allow measurements of α_s using the same technique at energies up to 170 GeV.

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