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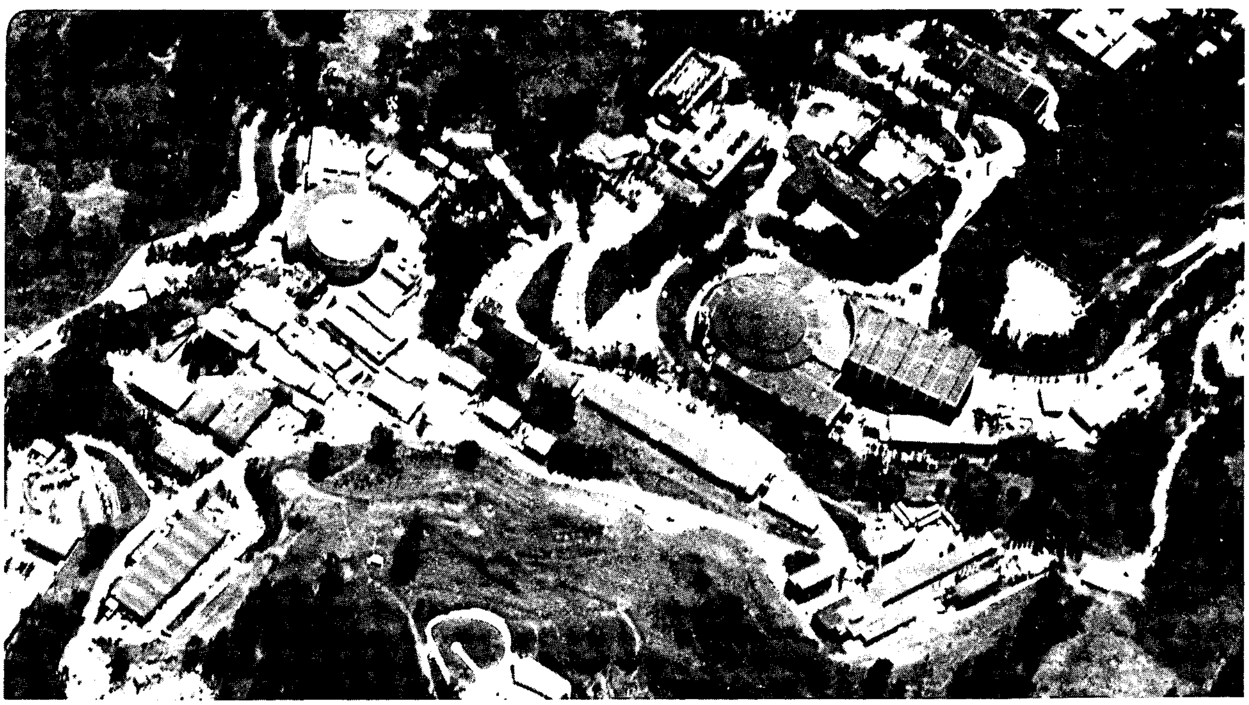

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JET PHYSICS IN e^+e^- ANNIHILATION: EVIDENCE FOR THE RUNNING OF α_s

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Abstract. The energy dependence of the relative production rate of 3-jet events is studied in hadronic e^+e^- annihilation events at centre of mass energies between 22 and 56 GeV, using the data of the JADE, MARK-II and AMY collaborations at PETRA, PEP and TRISTAN. Three jet events are defined by a jet finding algorithm which is closely related to the definition of resolvable jets used in $O(\alpha_s^2)$ perturbative QCD calculations, where the relative production rate of 3-jet events is roughly proportional to the strong coupling strength, α_s. The observed production rates of 3-jet events decrease significantly with increasing centre of mass energy. The results, which are independent of fragmentation model calculations, can be directly compared to theoretically calculated jet production rates and are in good agreement with the QCD expectations of a running coupling strength, while the hypothesis of an energy independent coupling constant can be excluded with a significance of 5 standard deviations. Based on these results, the presented jet analysis also provides the possibility to detect first signs of the production of new and heavy particles in the early stage of data taking at SLC and LEP.

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Introduction

Within the framework of Quantum Chromodynamics (QCD), the renormalizable gauge theory of the strong interactions between quarks and gluons [1], it is predicted that the strong coupling strength, α_s, decreases with increasing energy and quarks and gluons are quasi-free at large momentum transfers [2]. In second order perturbation theory, the energy dependence of α_s is calculated to be

$$\alpha_s(Q^2) = \frac{12\pi}{b_0 \cdot ln(Q^2/\Lambda^2_{\overline{MS}}) + \frac{b_1}{b_0} \cdot ln\ ln(Q^2/\Lambda^2_{\overline{MS}})}, \qquad (1)$$

where $b_0 = (33 - 2N_f)$, $b_1 = (918 - 114N_f)$ and N_f is the number of quark flavours produced. In e^+e^- annihilation , Q^2 is chosen to be the centre of mass energy of the hadronic system ($Q^2 \equiv E^2_{cm}$), and $\Lambda_{\overline{MS}}$ is the QCD scale parameter which has to be determined by experiment.

Although α_s has been determined in many different analyses (for reviews see [**3-5**]), the energy dependence of α_s, as the most characteristic feature and a "proof" of QCD, has not yet been established experimentally [**3**], due to the relatively large systematic errors that must be taken into account. These systematic errors are mainly caused by the fact that α_s cannot directly be measured and, due to the nonperturbative hadronization process, phenomenological fragmentation models are usually used to extract α_s from experimental observables [**6**].

In view of these systematic uncertainties, the energy dependence of experimental observables which are closely related to theoretical calculations is studied in this paper, rather than extracting individual values of α_s at different energies. Such an observable is e.g. the relative production rate R_3 of 3-jet events which, in second order perturbative QCD, is a simple function of α_s:

$$R_3 = C_1 \cdot \alpha_s \cdot (1 + C_2 \cdot \alpha_s). \qquad (2)$$

C_1 and C_2 denote the first order term and the second order virtual correction term, respectively, and can be precisely calculated. Using a suitable definition for resolvable jets, C_1 and C_2 are constants and the energy dependence of 3-jet event production rates is only determined by the energy dependence of α_s, providing the possibility for an illustrative test of the running of α_s without analysing individual values of α_s.

Theory and Experimental Method

Within perturbative QCD calculations, the cross sections for n-parton final states are singular for vanishing parton energies and for the case where two partons are collinear in space (infrared and collinear singularities). Since, after the assumed fragmentation of partons into jets of hadrons, such configurations are practically indistinguishable from (n-1)-jet events, a resolution cut-off is introduced in order to calculate finite production cross sections of n-parton events, where n indicates 2, 3 and 4 in second order perturbation theory. A commonly used resolution criterion is to require the square of the scaled invariant mass of any pair of partons i and j,

$$y_{ij} = \frac{M_{ij}^2}{E_{cm}^2}, \tag{3}$$

to satisfy the relation

$$y_{ij} \geq y_{min}, \tag{4}$$

where y_{min} is the cut-off parameter defining resolvable partons. Within a certain renormalization scheme (e.g. the $\overline{MS}$ scheme), C_1 and C_2 in Eq. 2 are constants for fixed values of y_{min}, and the energy dependence of the 3-parton event rate is only determined by the energy evolution of α_s.

The definition of resolvable jets by requiring minimum invariant jet pair-masses can be easily adopted to a jet finding algorithm. Such a jet finding algorithm was developed and extensively used in earlier studies of multijet event production rates [7]: The squares of the scaled invariant masses,

$$y_{kl} = \frac{M_{kl}^2}{E_{vis}^2}, \tag{5}$$

are calculated for all pairs of particles k and l, where E_{vis} is the visible energy of the event. The two particles i and j with the smallest invariant pair mass are replaced by a pseudoparticle or "cluster" with four-momentum $(\mathbf{p}_i + \mathbf{p}_j)$. This procedure is repeated until the invariant masses of all pair-combinations exceed a certain threshold value y_{cut} :

$$y_{kl} \geq y_{cut}, \tag{6}$$

and the remaining clusters are called "jets". To calculate the invariant pair mass M_{kl}, the expression $M_{kl}^2 = 2 \cdot E_k \cdot E_l \cdot (1 - cos\Theta_{kl})$ is used. Studies with Monte Carlo generated events show, that this choice of M_{kl} provides the closest agreement between jet- and parton-multiplicities at comparable values of y_{cut} (the experimental cutoff in the jet finding algorithm) and y_{min} (the QCD cutoff parameter for massless partons in the perturbative QCD calculations). While this agreement has been demonstrated in [7] for fixed centre of mass energy as a function of y_{cut}, the analysis of energy dependent effects requires that the agreement also holds as a function of energy at fixed values of y_{cut}.

To demonstrate that this requirement can be fulfilled, the ratio of reconstructed 3-jet event rates and original 3-parton rates, $q = \frac{R_3(rec.jets)}{R_3(partons)}$, is studied in model calculations for various values of $y_{cut} = y_{min}$. Ideally, this ratio should be close to one and should be constant over the entire energy range to be analysed. The ratio q is shown in Fig. 1 for $y_{cut} = y_{min} = 0.08$ and c.m. energies between 20 GeV and 60 GeV, using the Lund QCD shower model [8], based on leading logarithmic approximations[1], and the second order QCD

[1]The shower model produces multi-parton final states with minimum invariant pair masses down to 1 GeV. Therefore, the parton multiplicities for the desired values of y_{min} have been reconstructed using the same jet algorithm as for the final hadrons. It has been verified that this procedure is equivalent to terminating the parton generation at the higher cutoff values of $y_{min} = y_{cut}$.

Lund string model (Lund MA) [8], based on the complete second order QCD matrix elements of Gottschalk and Shatz [9]. The QCD- and fragmentation parameters of these models, which presently are the most successful candidates in view of a general description of the data [10], are described in [11]. For this study, however, the results do not depend on the detailed choice of parameter values.

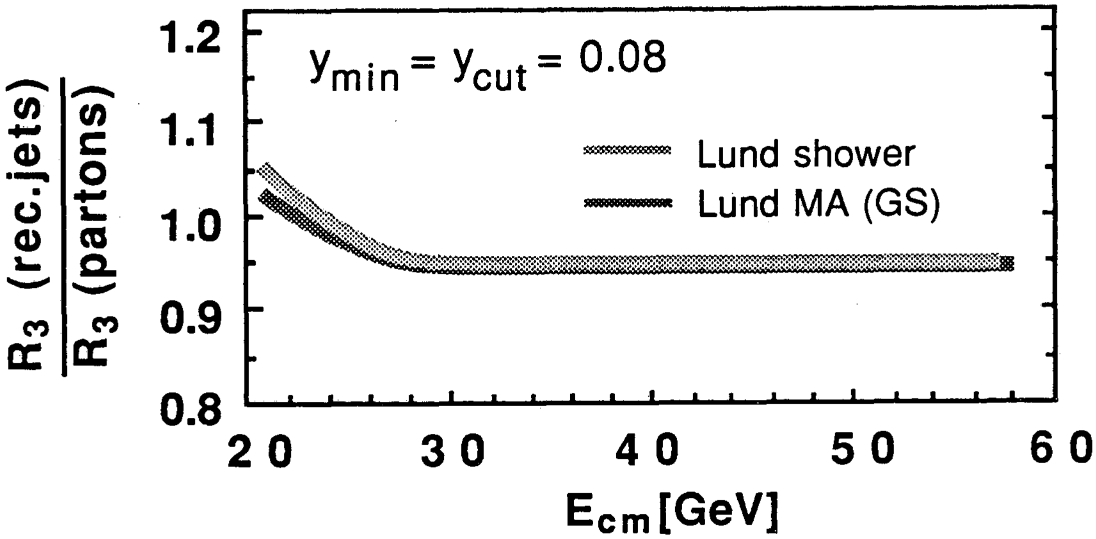

Fig.1: The ratio q of reconstructed 3-jet and 3-parton event rates for different QCD and fragmentation model calculations.

The ratio q is close to unity and is constant for centre of mass energies above 28 GeV for both types of model calculation. This behaviour has been verified to persist for energies up to 100 GeV. Below 28 GeV a slight increase in q is seen, as is expected in case the minimum required pair mass of jets gets too low to discriminate against fluctuations in the nonperturbative fragmentation region or the decays of heavy particles ($y_{cut} = 0.08$ corresponds to $M_{cut} = 6.2$ GeV at $E_{cm} = 22$ GeV). For higher values of y_{cut}, q starts to deviate from the same constant value at lower energies than seen in Fig. 2 : At y_{cut}=0.12 the constant region of q extents down to 22 GeV, while at y_{cut}=0.04 q is constant above 31 GeV. Thus, within the energy range where q is seen to be flat, the jet algorithm does not induce any energy dependent effects by itself and is therefore well suited to deduce the energy dependence of α_s from experimental jet production rates. Moreover, since q is close to unity, experimental jet rates can directly be compared with parton rates calculated in perturbative QCD[1], and no further fragmentation model calculations are needed to derive conclusions from the data themselves.

[1]The observed deviation of q from unity by about 6% can be explained by the phenomenological string fragmentation which tends to pull the original jet axes together and thereby soften the multijet structure of an event during fragmentation. This is, however, a purely kinematical effect and is not predicted by perturbative QCD. The question whether experimental jet rates should be corrected by these 6% cannot finally be answered, but is of minor importance for an analysis which concentrates on studying energy dependent effects. The experimental jet rates presented in this analysis will *not* be corrected by these 6%.

In the following, the experimental production rates of 3-jet events will be studied as a function of the centre of mass energy for *fixed* values of y_{cut}. The expectation, based on the theoretical motivations and the verification of the experimental method presented so far, is that these rates should decrease with increasing centre of mass energy in almost the same proportion as α_s is running with energy (cf. Eq.2). For the case of an energy independent coupling strength, the production rates of 3-jet events are expected to be constant.

Experimental Results

The energy dependence of 3-jet event production rates will be investigated, using the data taken with the JADE detector [**12**] around centre of mass energies of 22 GeV, 29.0 to 36.7 GeV and 38.0 to 46.7 GeV, and taken with the upgrade version of the Mark-II detector [**13**] at 29 GeV. After selecting well contained hadronic events as described in [**7**], the total event samples at 22, 29, 30, 34.6, 38 and 44 GeV centre of mass energy consist of 1666, 7482, 843, 13617, 1950 and 6636 events, respectively.

The 3-jet event rates of the JADE and Mark-II data are shown in Figure 2 for different values of y_{cut}, together with preliminary results from AMY [**14**] based on their first 1000 events recorded at TRISTAN around E_{cm} = 54 GeV [**15**]. The data are not explicitly corrected for the effects of detector resolution, acceptance and initial state photon radiation, since model calculations showed that these corrections are of negligible size: Due to the fact that E_{vis} rather than E_{cm} is used to calculate the y_{kl} and that, by the event selection chosen, only well contained events without hard initial state photon radiation are analysed, the sum of the correction factors deviates from one by less than $\pm 2\%$ (AMY uses slightly different selection cuts than JADE and Mark-II to achieve similarly small correction factors).

As can be seen in Fig. 2, the 3-jet production rates decrease significantly with increasing energy for all values of y_{cut}. The theoretical predictions of 3-parton event production rates as calculated from the complete second order perturbative QCD matrix elements from Gottschalk and Shatz (GS) [**9**] and from Kramer and Lampe (KL) [**16**], are also shown in Fig. 2 for fitted values of the QCD scale parameter, $\Lambda_{\overline{MS}}$, of 210 MeV and 205 MeV, respectively[1]. The theoretical curves describe the experimental data *both* in absolute normalisation and in the energy dependence for *all* values of y_{cut} larger than 0.04. Note that this is not a trivial point, since there is only one free parameter ($\Lambda_{\overline{MS}}$) in the theory.

Only for $y_{cut} = 0.04$ does theory overestimate R_3 at the higher PETRA energies. This effect can be explained by the earlier observation [**7**] that $O(\alpha_s^2)$ calculations underestimate the production rate of 4-jet events. In this paper, $\Lambda_{\overline{MS}}$ has been adjusted at the larger values of y_{cut}, where almost no 4-jet events are resolved separately, so that, by the normalization

[1]The slight differences in $\Lambda_{\overline{MS}}$ and in the detailed energy dependence of R_3 may be explained [17] by the different choice of 3-jet variables used in the theoretical calculations [9;16], and have no practical impact on the present study of the energy dependence of α_s. Within the statistical fitting error of $\Delta(\Lambda_{\overline{MS}}) = \pm 13$ MeV, the values of $\Lambda_{\overline{MS}}$ determined for individual values of y_{cut} ($y_{cut} \geq 0.06$) agree with each other.

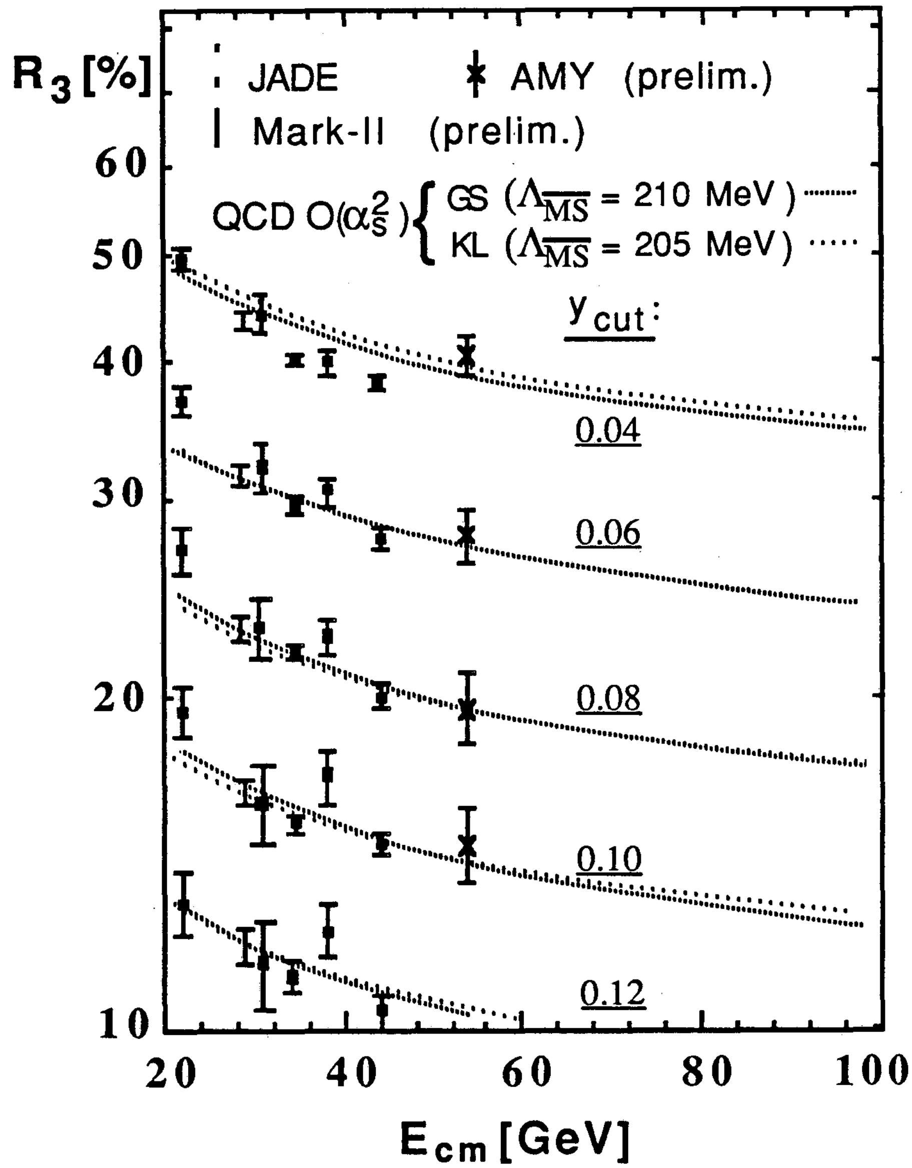

Fig.2: Three-jet event rates at different centre of mass energies for various values of y_{cut}, together with the direct predictions of the complete $O(\alpha_s^2)$ QCD calculations of Gottschalk and Shatz (GS) and of Kramer and Lampe (KL).

$\sum R_n = 100\%$, at lower values of y_{cut} discrepancies in R_4 also affect the description of R_3. If the sum of 3- and 4-jet production rates is analysed instead of R_3, theory provides a good description of the data also for $y_{cut} = 0.04$.

Expressing the agreement between data and QCD in terms of χ^2, the 22 GeV data points are not taken into account, since at this low energy hadronization effects may bias the results towards larger values (see Fig. 1). Using the data of Mark-II and JADE above 22 GeV, the χ^2 between the data and the QCD curves shown in Fig. 2 are always about 1 per degree of freedom for all y_{cut} larger than 0.04. Assuming an energy independent coupling strength (and therefore expecting a constant rate of 3-jet events at all energies) results in χ^2=24.7/4 d.f. and 18.4/4 d.f. at y_{cut}=0.06 and 0.08, respectively, corresponding to a 5 standard deviation effect in favour of the running α_s. At higher values of y_{cut} the significance reduces to 3 standard deviations and less, due to the smaller number of 3-jet events and larger statistical errors. Within the statistical errors shown, the results of the AMY collaboration are in good agreement with the expectations put forward by the QCD fits to the data of JADE and Mark-II, but do not yet contribute significantly to the presented values of χ^2.

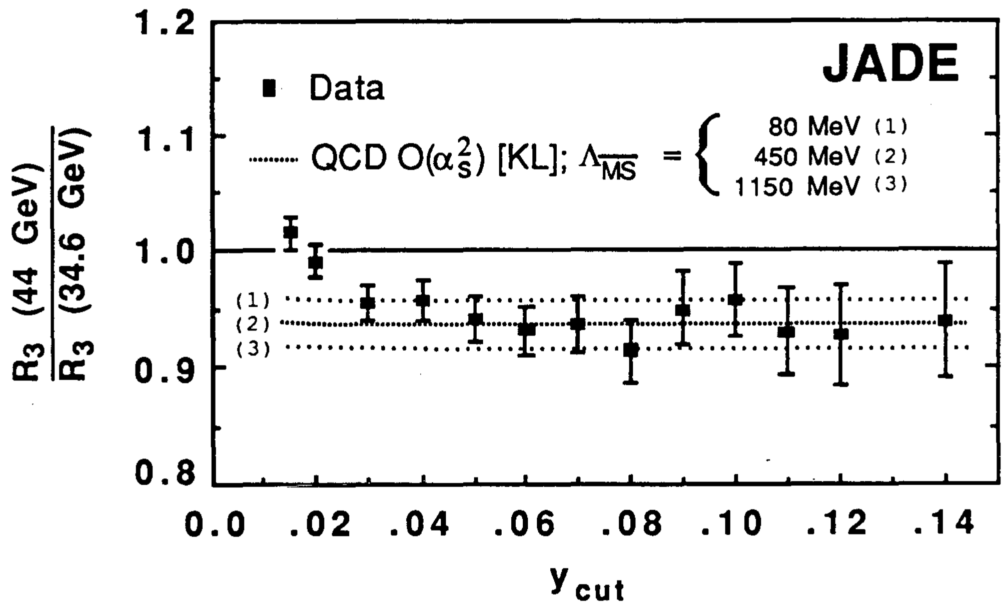

Fig.3: The ratio r of 3-jet event rates observed at E_{cm} = 44 GeV and 34.6 GeV.

An additional way to investigate the reliability of the analysis and its theoretical interpretation is to study the observed ratio r of 3-jet event production rates at different centre of mass energies, $r = R_3(E_{cm})/R_3(E'_{cm})$. Within the QCD calculations, this ratio is expected to be roughly proportional to $\alpha_s(E_{cm})/\alpha_s(E'_{cm})$, which should be less than unity for $E_{cm} > E'_{cm}$. More important for this test, r is expected to be independent of the common resolution cut-off y_{cut}. In order to verify whether the data are consistent with these expectations, the ratio r of the data at E_{cm} = 44 GeV and E'_{cm} = 34.6 GeV is presented in Fig. 3 for y_{cut} ranging from 0.015 to 0.140, together with the direct $O(\alpha_s^2)$ QCD predictions of Kramer and Lampe for different values of $\Lambda_{\overline{MS}}$. Within the statistical errors, r is significantly smaller than one and is consistent with being independent of y_{cut} for $y_{cut} \geq 0.040$. Note that the experimental errors are correlated since all values of r are calculated using the same data sample. This "self-consistency" check of the data shows, that the results of this study do not depend on the detailed value of y_{cut} (provided it is chosen to be large enough) and are in good agreement with the expectations of perturbative QCD and the energy dependence of α_s.

The ratio r also provides the possibility to determine $\Lambda_{\overline{MS}}$ from the *energy dependence* of the 3-jet production rates (instead from absolute or relative event production *cross sections* as has been done to date [3-5]). For the data shown in Fig. 3 the mean value of r for $y_{cut} > 0.04$ is $r = 0.935 \pm 0.023$. This results, if compared to the second order QCD calculations of KL [16], in $\Lambda_{\overline{MS}} = (450^{+700}_{-370})$ MeV, and corresponds to $\alpha_s = 0.154 \pm 0.038$ at $E_{cm} = 44$ GeV. This is, within the errors, consistent with (205 ± 13) MeV determined from the absolute *normalisation* of R_3 shown in Fig. 2. Note that the determination of $\Lambda_{\overline{MS}}$ from r, although the error is rather large, does not depend on any fragmentation model calculation and even avoids the problem of the 6% normalisation uncertainty between 3-jet and 3-parton rates discussed when presenting Fig. 1.

Prospects on Higher Energies

In view of the forthcoming operation of SLC and LEP at $E_{cm} \approx 93$ GeV and the increasing statistics around 52 to 60 GeV which is currently accumulated at TRISTAN, the method of analysis presented in this article offers many interesting applications. Based on the data of PETRA and PEP and the QCD calculations as shown in Fig. 2, a solid prediction of 3-jet event production rates at the higher energies is provided without relying on fragmentation model calculations. This allows one to perform even more precise tests of QCD and the running coupling strength with only a few thousand hadronic events at the higher energies. As an example, with about 5000 well contained hadronic events at $E_{cm} = 60$ GeV and 93 GeV it should be possible to verify the *logarithmic* decrease of α_s with energy (see Eq. 1). Furthermore, the close agreement between the definitions of jets used in the experimental jet algorithm and the theoretical QCD calculations (cf. Eqs. 3 and 5, 4 and 6) facilitates further analyses of higher order QCD effects in multi-jet events, as for instance the search for effects of the gluon self coupling as proposed in [18] and references quoted therein [19].

The main purpose of the experiments at higher energies is, however, to look out for effects of new and yet unknown physics phenomena, such as the production of new and heavy particles. Since the only parameter used in the jet algorithm is the requirement of minimum invariant pair masses, this algorithm is sensitive to the existence of particles with masses of the order of or greater than the applied jet resolution criterion, provided these particles decay, at least to a certain amount, into hadronic final states (no such particles have been observed at PEP, PETRA and TRISTAN as yet [3;20]). This sensitivity renders precise tests of QCD, if new and heavy objects will be produced at SLC and LEP, rather difficult, but therefore allows to detect first signs of the existence of such objects with masses greater than ≈ 20 GeV. As an example, model calculations show that, at $E_{cm} = 93$ GeV, *top*-quark events with $M_t = 40$ GeV result in 3-jet production rates, defined with the jet algorithm at $y_{cut} = 0.08$, of about 80%. This should be compared with the QCD expectations for light quarks, based on the results shown in Fig. 2, of 17.5%. Similar results are obtained for the production of b'-quark and *Heavy Lepton* events, whereby the population of different jet classes as a function of y_{cut} changes according to the mass of the new objects. This allows one to detect first signs of such objects in a rather early stage of data taking at SLC and LEP: With 1000

(200) measured hadronic events, R_3 will deviate from the QCD expectations shown in Fig. 2 by three (two) standard deviations, if a new *Heavy Lepton* or *top* or *b′ quark* is being produced. Note that the detection of new and heavy objects by analysing jet production rates does not require to identify isolated leptons within the events, thus adding a new and independent way to detect signs of new physics to the "standard" techniques as described e.g. in [**21**].

Summary

The energy dependence of the Strong Coupling Strength, α_s, has been studied by analysing the energy dependence of relative 3-jet event production rates. Experimental 3-jet events are defined by a jet finding algorithm, which is closely related to the definition of resolvable jets used in second order QCD calculations. It has been shown that the observed 3-jet event production rates can be directly compared to the results of perturbative QCD calculations. For fixed values of the dimensionless jet resolution parameter, these calculations predict that the energy dependence of 3-jet event production rates is only determined by the energy dependence of α_s. The experimental 3-jet event production rates decrease significantly with increasing centre of mass energy. The absolute production rates as well as their energy dependence are well described by second order QCD calculations and values for $\Lambda_{\overline{MS}}$, the only free parameter in the theory, of about 200 MeV, depending on the detailed choice of calculations used. Based on the data of JADE and Mark-II, the possibility of an energy independent coupling strength can be excluded with a significance of five standard deviations.

Since the observed energy dependence is rather large compared to the statistical errors of the data, the QCD scale parameter $\Lambda_{\overline{MS}}$ could be determined, for the first time in e^+e^- annihilation, from the *energy dependence* of experimental observables. The ratio of 3-jet event production rates at 44 and 34.6 GeV centre of mass energies results in $\Lambda_{\overline{MS}} = (450^{+700}_{-370})$ MeV, which corresponds to $\alpha_s = 0.154 \pm 0.038$ at 44 GeV centre of mass energy. This result is independent of fragmentation model calculations and free of uncertainties in the absolute normalisation of event production cross sections.

The method of analysis and the data presented in this article provide an accurate prediction of the 3-jet event rates expected for the forthcoming data of SLC and LEP. Since these predictions are based on second order QCD rather than on fragmentation model calculations, they facilitate the performance of more precise tests of higher order QCD and the running coupling strength. Alternatively, the existence of new physics effects like the production of new and yet unknown heavy particles will result in substantial deviations from the standard expectations for 3-jet event production, allowing to detect first signs of such objects in an early stage of data taking.

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For the second order QCD matrix element model (Lund MA), the fragmentation parameters are as described in [7]. In order to maintain a constant phase-space for the fragmentation region at all centre of mass energies, the *invariant mass* of the QCD cutoff parameter, $M^2_{min} = /E^2_{cm} \cdot y_{min}$, is kept constant (at 36 GeV^2) rather than y_{min} itself. The QCD scale parameter is $\Lambda_{\overline{MS}} = 200$ MeV .

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