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ON THE MODEL DEPENDENCE OF THE DETERMINATION OF THE STRONG COUPLING CONSTANT IN SECOND ORDER QCD FROM e^+e^--ANNIHILATION INTO HADRONS

CELLO Collaboration

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Hadronic events obtained with the CELLO detector at PETRA are compared with second order QCD predictions using different models for the fragmentation of quarks and gluons into hadrons. We find that the model dependence in the determination of the strong coupling constant persists when going from first to second order QCD calculations.

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1. Introduction. The observation of 3-jet events in e^+e^--annihilation at high energies is attributed to the QCD process $e^+e^- \to q\bar{q}g$ [1]. In this process, a virtual photon creates a quark–antiquark pair ($q\bar{q}$) which radiates a gluon g. The rate of gluon radiation is determined by the strong coupling constant α_s which is the only free parameter in QCD once the energy scale and the quark masses have been specified. Quarks and gluons are only observed indirectly as jets of hadrons, but perturbative QCD does not predict how partons turn into hadrons. Therefore, one has to rely on phenomenological models to relate the cross section for a given number of partons to the corresponding 2-, 3-, and 4-jet cross sections.

The CELLO collaboration has found previously a strong influence of these phenomenological fragmentation models on the determination of α_s using first order QCD formulae for parton production [2]. For the rather large values of α_s found in first order, the second order contributions to jet cross sections are expected to be non-negligible. Recently, it has been claimed [3] that they reduce the fragmentation model dependence in the determination of α_s.

To investigate this quantitatively, we have used the LUND Monte Carlo program [4] [‡1] [6], which includes the generation of $q\bar{q}$, $q\bar{q}g$, $q\bar{q}gg$, and $q\bar{q}q\bar{q}$ states, as well as the second order virtual corrections to the $q\bar{q}g$ states. The program incorporates several fragmentation models, so one can study their influence on the determination of α_s with identical initial parton states and identical generation and decay of the primary hadrons.

We have studied the model dependence in the determination of α_s from the asymmetry of the energy weighted angular correlations [7,8] and the cluster thrust [9,10]. In addition, we have studied the influence of different energy momentum conservation schemes.

2. Description of the models. Higher order QCD corrections to the process $e^-e^+ \to q\bar{q}$ have been calculated up to second order [5,11,12], which corresponds to the production of two, three and four partons in the final state.

The emission of soft and/or collinear massless gluons leads to divergent terms in the 3- and 4-jet cross section. The virtual corrections to the 2- and 3-jet cross sections have similar divergent terms with an opposite sign, so the addition of these terms leads to a finite total cross section. In the Monte Carlo program, the divergences are eliminated by introducing a resolution parameter y: Two partons are called irresolvable if the invariant mass suqared $(p_i + p_j)^2 < y \cdot E_{\mathrm{cm}}^2$. Here p_i and p_j are the 4-momenta of the partons. Irresolvable partons are combined to one. If a soft gluon is equally close to more than one parton, its energy is given randomly to one of them [5]. The 2- or 3-jet cross section is defined as the cross section for producing two or three parton clusters each having an invariant mass squared below $y \cdot E_{\mathrm{cm}}^2$. In choosing a value of y, two considerations are important. A small value of y leads to a large positive 4-jet cross section, which is cancelled by a large negative virtual correction to the 3-jet cross section. If $y \lesssim 0.2\ \alpha_s/\pi$, these virtual corrections lead to an unphysical negative 3-jet cross section in some regions of phase space. In addition, a low y value implies the generation of many soft gluons for which the fragmentation models are not expected to be adequate. On the other hand, in the limit of large y only 2-jet events are generated and the sensitivity to the α_s value disappears. We generally have used $y = 0.03$ which corresponds to a minimum invariant mass of 5.9 GeV between any pair of partons for $E_{\mathrm{cm}} = 34$ GeV. As will be discussed later, the value of α_s depends little on the specific choice of y.

To study the influence of fragmentation models, the partons are fragmented either independently (IF model) à la Field–Feynman [13], or by connecting them through colour strings (SF model) [4,6]. For $q\bar{q}$ events, there is no practical difference between the schemes. However, the string kinematics in a $q\bar{q}g$ event shifts the particles from the original parton directions towards the regions between quarks and gluon, thus making a 3-jet event look more 2-jet-like [2]. Therefore, in the SF model the α_s value will be higher than in the IF model, if the same data are fitted.

The gluon in the IF model was fragmented as a quark. In the SF model the gluon was treated à la LUND [4,6]. For most of the fragmentation parameters we used the standard values [4,6].

The parameters a and b in the longitudinal fragmentation function $f(z) = \exp(-bm_\perp^2/z)(1-z)^a/z$

[‡1] We used version JETSET 5.1 which includes the complete second order corrections using the formula of ref. [5].

were taken to be 2.2 and 1.2 for SF and 2.6 and 1.0 for IF, respectively. Here $m_\perp$ is the transverse mass of the particle, and z is the fraction of remaining energy momentum which the particle takes. With these values, the z-distribution peaks at 0.6 for charmed and 0.9 for bottom mesons in both models [14]. The transverse momentum spread in the "slim" jet is well described by a gaussian with a standard deviation of 0.25 and 0.3 GeV/c for SF and IF, respectively. As will be shown later, the value of α_s does not depend strongly on this parameter.

In the SF model, energy and momentum (E.P.) are both conserved during each breakup of the string. However, in the IF model, energy and momentum cannot be conserved simultaneously, since during fragmentation the jets acquire an average mass much larger than the parton mass. Therefore, one has to impose E.P. conservation for the complete event after fragmentation. Usually, this has been considered an unessential complication. However, by studying various E.P.-conservation schemes, we found that they can influence the kinematic structure of 3-jet events considerably [‡2]. This is due to the fact that the missing momentum of the quark jet tends to be compensated by the missing momentum of the opposite antiquark jet, but for a gluon jet there usually exists no compensating jet on the opposite side [15]. The missing momentum is on the average of the order of ~1 GeV/c. Several E.P.-conservation schemes exist. For example, one can first redistribute the momentum imbalance between the particles and rescale the energies afterwards [16,17], or one can adjust the longitudinal energies in the jets such that energy and momentum are conserved simultaneously [18]. The first scheme, called IF1 hereafter, changes systematically the *directions* of the jets, whereas the second scheme changes systematically the *energies* of the jets. This last scheme has been our standard scheme and will be referred to as IF. The case, in which no E.P.-conservation algorithm is applied, will be referred to as IF0.

We have implemented a version for both schemes in the independent fragmentation part of the LUND program following the algorithms of the programs described in refs. [17,18] for IF1 and IF, respectively.

3. Determination of the strong coupling constant. The data used for this analysis were taken at an average center of mass energy of 34 GeV. The analysis was done using charged particles above 120 MeV/c and neutral showering particles above 200 MeV/c. The basic cuts for the multihadron selection are the visible energy $E_{\mathrm{vis}} > 0.4\,E_{\mathrm{cm}}$ and the charged particle multiplicity larger than four. All candidates were scanned visually, leaving 2600 events with a negligible amount of background. As mentioned before, we have used two methods to determine α_s, namely the asymmetry in the energy weighted angular correlations $F(\chi)$ and the cluster thrust.

$F(\chi)$ is obtained by plotting the angles χ between all pairs of hadrons and weighting each entry with the product of the fractional energies of the hadrons involved. By normalizing the fractional energies to the total visible energy, one is insensitive to few missing particles, as was checked by performing the analysis with all particles and with charged particles only. We have also checked that the asymmetry is insensitive to variations in fragmention parameters, as expected [7], and to the resolution parameter y. We varied y between 0.017, corresponding to the lower limit mentioned in section 2, and 0.05. The four jet cross section varies by an order of magnitude in this range of y.

At least squares fit of the asymmetry $A(\chi) = F(\pi - \chi) - F(\chi)$ for $|\cos\chi| < 0.7$ from Monte Carlo events to the corrected data yields $\alpha_s = 0.12 \pm 0.02$ and 0.19 ± 0.02 for IF and SF, respectively. The errors are statistical only. The data were corrected for

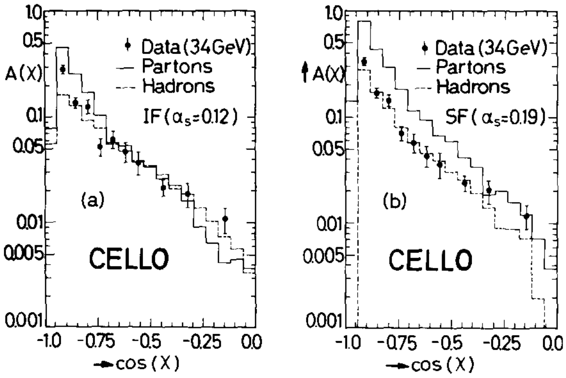

Fig. 1. (a) Corrected asymmetry data compared with the asymmetry of the partons and the generated final state hadrons in the independent fragmentation model (IF). (b) As (a), but now for the string model.

[‡2] The importance of E.P.-conservation became clear in discussions with the MARK-J collaboration.

radiative corrections and detector biases using a full simulation of the detector for each model separately. Within errors the corrected data for the different models agree. The large difference in α_s between the models is not due to a statistical fluctuation or a bad tuning of the fragmentation parameters. This was verified by a careful adjustment of the parameters in the different models and subsequently considering the hadrons generated with the SF model as data from which the α_s in the IF model is determined. This yielded similar differences in α_s. The difference in α_s comes from the fact that the partons in the SF model have a much higher asymmetry than the final state hadrons, as shown in fig. 1b. For IF the parton asymmetry is close to the asymmetry of the final state hadrons, as shown in fig. 1a. The α_s value for IF does not change, if no E.P.-conservation algorithm is applied (IF0). However, if one imposes E.P.-conservation by redistributing the momentum imbalance over all hadrons (IF1), α_s increases by 25%. The two fragmentation models used by the MARK-J collaboration [3] were similar to IF1 and SF, which also in our study give the smallest difference in α_s. However, since we have no reason to prefer IF1 to IF, we have to conclude that the determination of α_s also in second order QCD is still model dependent. The fact that the MARK-J collaboration finds α_s values about 30% lower than ours for a similar fragmentation model has not yet been understood. Part of the difference may come from the fact that they used the virtual corrections to the 3-jet cross section from ref. [11], while we used the ones from ref. [5]. These calculations agree only in the limit of a small resolution parameter [19]. Additional differences may come from the data and different gluon fragmentation functions. Systematic errors in α_s coming from different treatment of the gluon fragmentation are 10 to 20% [2].

Another determination of α_s has been made from events with three clusters and having a cluster thrust T_c smaller than 0.85. The three cluster events were selected with a cluster algorithm similar to the one in our previous publication [10]. The cluster thrust is determined from the four vectors of the three clusters. Fig. 2 shows the fraction of three cluster events as function of α_s for the various models. As can be seen, also the cluster thrust depends on the E.P.-conservation scheme. The error bars on some of the points indicate the systematic errors coming from a variation in σ_q between 0.18 and 0.45 GeV/c, and variations in y between 0.017 and 0.05. The differ-

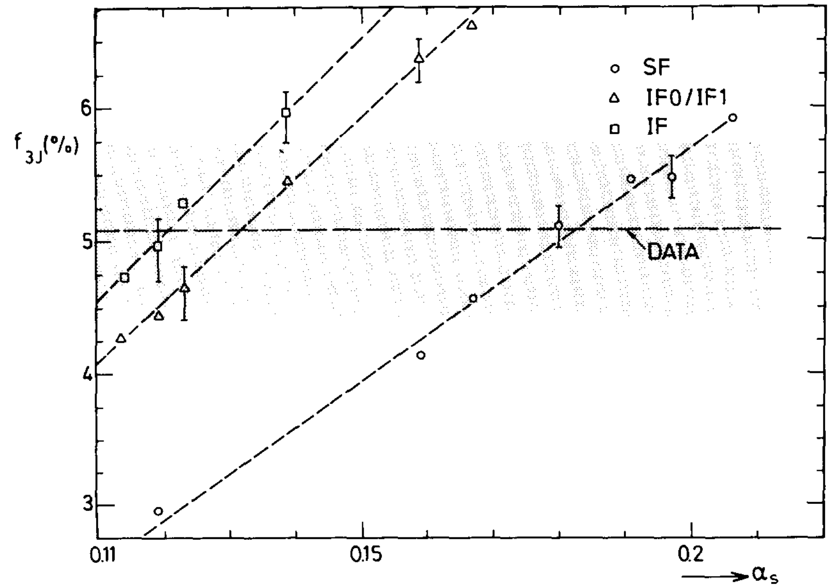

Fig. 2. The fraction of three cluster events with a cluster thrust below 0.85 versus α_s for different models. The error bars indicate an upper limit for the systematic errors coming from variations in y and σ_q (see text). The shaded area is allowed by our data.

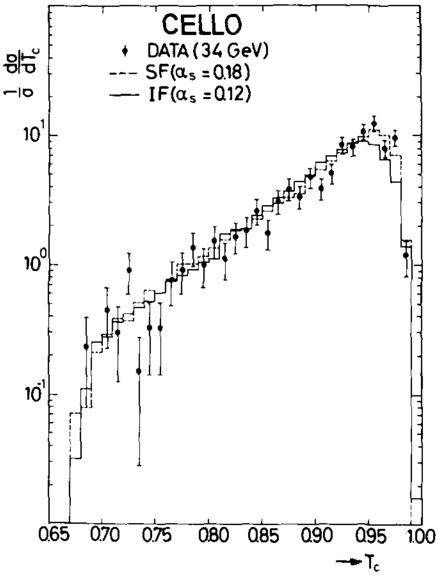

Fig. 3. The corrected cluster thrust of three cluster events compared with different models. The corrections to the data for initial state radiation and detector biases were found to be independent of the fragmentation model within errors.

ence between the models is much larger than the systematic errors coming from uncertainties in these parameters (see fig. 2). This difference is also a factor two larger than the systematic uncertainty in α_s coming from different fragmentation models as published by the JADE-collaboration [20]. The fraction of events with $T_c < 0.85$ is 0.051 ± 0.007 giving α_s = 0.18 ± 0.02 for SF and 0.12 ± 0.02 for IF. The errors are statistical only. Fig. 3 shows the corrected thrust distribution of three cluster events observed in the data and predicted by the IF and SF models using the different values of α_s.

The data discussed so far do not allow to discriminate between the models. Therefore, one cannot determine α_s precisely, unless one finds reasons to reject some of the models. The JADE collaboration has tried to do so by studying the particle distributions in 3-jet events [21]. They find a clear preference for string fragmentation over independent fragmentation. However, the difference between the models is mainly connected with soft particles. Therefore, it remains to be seen if this difference is fundamental or if the parameters in the IF models can be tuned to agree with the data.

Table 1
Summary of α_s values for the string fragmentation model (SF) and independent fragmentation models with different energy momentum conservation schemes (IF0, IF, and IF1). The statistical and systematic errors are both ~10%. The ratio of α_s values between the models is much less dependent on the choice of fragmentation parameters, since their effect on α_s is strongly correlated.

method	SF	IF0	IF	IF1	SF/IF
asymmetry	0.19	0.12	0.12	0.15	1.58
cluster thrust	0.18	0.13	0.12	0.13	1.50

4. Conclusion. We have determined the value of the strong coupling constant α_s up to second order in QCD from the asymmetry in the energy weighted angular correlation and from the fraction of 3-cluster events. The results have been summarized in table 1 for the various models. The α_s values found in second order are about 20% lower than the values found in first order [2]. For the string fragmentation model, the values are 40–50% higher than the values for independent fragmentation. This strong model dependence is similar to the model dependence we observed in first order [2].

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