PROCEEDINGS

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Jets and Multiplicities in e^+e^-

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ABSTRACT: Recent results on jet and inclusive charged particle production in hadronic e^+e^- interactions are reviewed.

1. Introduction

The production of jets and hadrons in e^+e^- interactions provides a suitable laboratory to study quantum chromodynamics. Both the coupling strength and the group structure of the theory can be determined. We discuss a number of recent measurements concerning jet and hadron production. These include a determination of the strong coupling constant, α_s, from 4-jet rates[1], two studies of 4-jet angular correlations[2, 3], in which α_s and the colour factors, C_A and C_F, are determined, a study of charged particle multiplicity in 3-jet events[4] and two helicity analyses of charged hadron production[5, 6].

2. Determination of α_s from 4-jet rates

In a recent study[1] DELPHI has measured n-jet rates, R_n, as a function of the jet resolution parameter y_{cut}, at centre-of-mass energies in the range 89-207 GeV, using various jet algorithms. The 4-jet rate, R_4, is compared to NLO QCD predictions[7] to determine α_s. As there are expected to be considerable higher order contributions, still missing in these predictions, in particular due to large logarithmic terms, DELPHI uses the method of scale optimisation when determining α_s. This implies that both α_s and the renormalisation scale parameter $x_\mu = \frac{\mu_R^2}{Q^2}$ are varied when fitting the NLO predictions to the data. It is argued that the obtained optimal scale, x_μ^{opt}, accounts for missing higher order contributions.

Fig. 1 shows the result for R_4 based on the Durham[8] jet algorithm, at $\sqrt{s} = 91$ GeV, compared to fitted theory predictions. The fitted value for the strong coupling constant is: $\alpha_s(M_Z) = 0.1178 \pm 0.0012(\text{exp.}) \pm 0.0023(\text{had.}) \pm 0.0014(\text{scale})$ and the corresponding optimal scale: $x_\mu^{\text{opt}} = 0.015$. The low value obtained for the scale suggests that missing higher orders are indeed important. The scale uncertainty on α_s is determined by varying

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x_μ between $\frac{1}{2}x_\mu^{\mathrm{opt}}$ and $2x_\mu^{\mathrm{opt}}$, yielding a smaller uncertainty than obtained with the conventional variation of x_μ between $\frac{1}{4}$ and 4. The obtained α_s value is in good agreement with a similar ALEPH[9] result, obtained using resummed NLO predictions.

Using R_4 measurements from different centre-of-mass energies, DELPHI has also studied the scale dependence of α_s, finding good agreement with the running behaviour predicted in QCD.

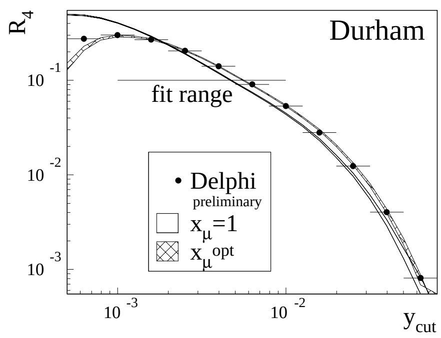

Figure 1: Durham R_4 distribution at $\sqrt{s} = 91$ GeV compared to fitted NLO predictions with a fixed or a fitted scale.

3. Determination of α_s, C_A and C_F from 4-jet angular correlations

OPAL[2] and ALEPH[3] have recently presented studies of angular correlations in 4-jet events at $\sqrt{s} = 91$ GeV. A combined fit of theory predictions to these correlations and to jet rates is used to determine α_s, C_A and C_F. The theory predictions[7, 10] compared to are to NLO accuracy for the angular correlations and to resummed NLO accuracy for the jet rates.

In both the OPAL and the ALEPH studies the theory predictions have been fitted simultaneously to 4 angular variables, to R_4 and, in the OPAL study, also to the differential 2-jet rate, D_2. The 4-jet angles measured are the Bengtsson-Zerwas[11] angle, χ_{BZ}, the modified Nachtmann-Reiter[12] angle, Θ_{NR}, the Körner-Schierholtz-Willrodt[13] angle, Φ_{KSW}, and the angle between the two lowest energy jets, α_{34}. Fig. 2 shows these angles as measured by OPAL, compared to the fitted NLO predictions.

The fit results obtained by OPAL are: $\alpha_s(M_Z) = 0.120 \pm 0.011 \pm 0.020$, $C_A = 3.02 \pm 0.25 \pm 0.49$, $C_F = 1.34 \pm 0.13 \pm 0.22$, and by ALEPH: $\alpha_s(M_Z) = 0.119 \pm 0.006 \pm 0.022$, $C_A = 2.93 \pm 0.14 \pm 0.49$, $C_F = 1.35 \pm 0.07 \pm 0.22$, where the uncertainties are the statistical and systematic uncertainties, respectively. In Fig. 3 68% confidence level contours in the

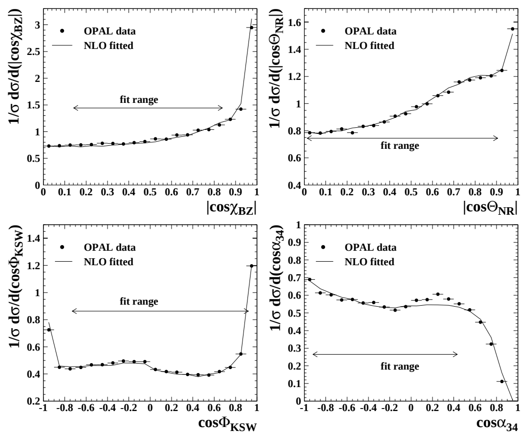

Figure 2: 4-jet angles measured by OPAL at $\sqrt{s} = 91$ GeV, compared to fitted NLO predictions.

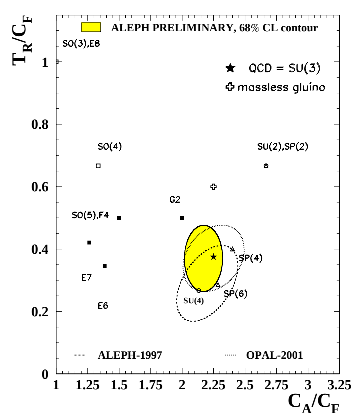

Figure 3: 68% confidence level contours in $\left(\frac{T_R}{C_F}, \frac{C_A}{C_F}\right)$, compared to the expectated values in various Lie group structures.

$\left(\frac{T_R}{C_F}, \frac{C_A}{C_F}\right)$ plane are shown from the results presented here and from an earlier ALEPH study. The results are compared to the expected values for different group structures. All results agree well with the SU(3) group structure while several alternatives are disfavoured.

4. Charged particle multiplicity in 3-jet events

Multiplicity differences in the fragmentation of quark and gluon jets are of great interest as they provide a direct measure of the colour factor ratio $\frac{C_A}{C_F}$. Most measurements of the multiplicity in gluon jets, however, rely on a jet algorithm to separate the gluon fragmentation products from those of the quarks in 3-jet events, rendering the obtained results biased. Unbiased gluon jet multiplicity has so far only been measured in Υ-decays[14, 15] and in e^+e^- 3-jet events, where the gluon is associated with the highest energy jet and it's fragmentation products can therefore be separated in one hemisphere of the event[16].

Recently a formalism[17] has been proposed (in MLLA[18]) to express the multiplicity in 3-jet events as a function of the unbiased gluon jet multiplicity and a biased quark jet multiplicity, where the latter is defined as the multiplicity in hadronic e^+e^- events with no gluon radiation harder than the scale associated with the gluon jet in the 3-jet event.

$$N_{q\bar{q}g} = N_{q\bar{q}}(L_{q\bar{q}}, \kappa_{\perp Lu}) + \frac{1}{2}N_{gg}(\kappa_{\perp Le}) \tag{4.1a}$$

$$N_{q\bar{q}g} = N_{q\bar{q}}(L, \kappa_{\perp Lu}) + \frac{1}{2}N_{gg}(\kappa_{\perp Lu}) \tag{4.1b}$$

where $L = \ln\frac{s}{\Lambda^2}$, $L_{q\bar{q}} = \ln\frac{s_{q\bar{q}}}{\Lambda^2}$, $\kappa_{\perp Lu} = \ln\frac{s_{qg}s_{\bar{q}g}}{s\Lambda^2}$, $\kappa_{\perp Le} = \ln\frac{s_{qg}s_{\bar{q}g}}{s_{q\bar{q}}\Lambda^2}$ and $s_{ij} = (p_i + p_j)^2$. The two alternative formulations reflect an ambiguity in defining the transverse momentum of the emitted gluon with respect to the $q\bar{q}$ system. In the same formalism both the biased quark jet multiplicity and the energy dependence of the gluon jet multiplicity can be derived from the inclusive multiplicity in hadronic e^+e^- events.

In a recent analysis[4] the DELPHI collaboration has measured the charged particle multiplicity in 3-jet events, in which the two lowest energy jets have identical angles with respect to the highest energy jet. In these so-called "Y" events all scales in equations 4.1a and 4.1b are determined by the angle between the two lowest energy jets, θ_1. The charged multiplicity in 3-jet events as a function of θ_1 is shown in Fig. 4. The data are compared to predictions based on the above formalism, where the normalisation of the gluon jet multiplicity has been fixed to the direct measurement of [14] and an additional offset is fitted to the data to account for the bias in the multiplicity due to c and b quarks which are not considered in the formalism.

The formalism (equation 4.1a) has also been used to obtain a measurement of $\frac{C_A}{C_F}$ which determines the

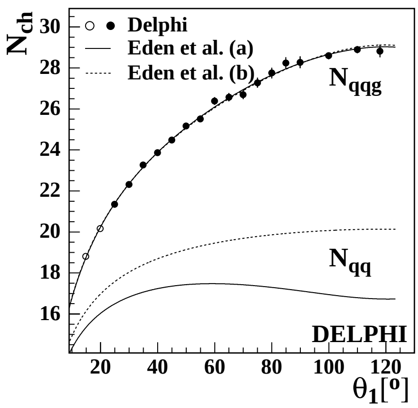

Figure 4: Charged particle multiplicity in 3-jet events in bins of θ_1, compared to predictions based on equations 4.1a and 4.1b.

ratio of the energy slopes of the multiplicity in gluon and quark jets. DELPHI obtains: $\frac{C_A}{C_F} = 2.221 \pm 0.032(\text{stat.}) \pm 0.047(\text{exp.}) \pm 0.058(\text{had.}) \pm 0.075(\text{theo.})$. In agreement with the QCD expectation of 2.25. Recently DELPHI has extended this study to include also asymmetric 3-jet events, obtaining similar results.

5. Helicity analysis of inclusive charged hadron production

The inclusive hadron production cross section in e^+e^- annihilation can be expressed as a function of x_p, the scaled momentum of the hadrons and θ, the angle of the hadrons with respect to the electron beam:

$$\frac{\mathrm{d}^2\sigma^h}{\mathrm{d}x_p \mathrm{d}\cos\theta} = \frac{3}{8}(1+\cos^2\theta)\frac{\mathrm{d}\sigma_T^h}{\mathrm{d}x_p} + \frac{3}{4}\sin^2\theta\frac{\mathrm{d}\sigma_L^h}{\mathrm{d}x_p}. \tag{5.1}$$

A transverse and a longitudinal component are distinguished, which can be separated by measuring the $\cos\theta$ distribution. This separation is of interest because the relative size of the longitudinal component, which is associated with gluon radiation, provides a measure of the strong coupling constant. A prediction up to NLO in α_s for the longitudinal fraction has been given in [19]:

$$\frac{\sigma_L}{\sigma_{tot}} = \frac{\alpha_s}{\pi} + \frac{\alpha_s^2}{\pi^2}\left(13.583 - 1.028N_f + (0.167N_f - 2.750)\ln\frac{Q^2}{\mu^2}\right). \tag{5.2}$$

In a recent DELPHI study[6] of hadronic e^+e^- interactions at $\sqrt{s} =$ 91 GeV, transverse and longitudinal charged particle fragmentation functions have been determined from the $\cos\theta$ distribution measured in bins of x_p. To study possible hadronisation effects on the hadron angles, which are not accounted for in equation 5.2, alternative ways of measuring these angles were tested, either using the angles of the hadrons themselves or using the angles of the jets to which the hadrons are assigned. In the latter case jets were defined using different values of the non-scaled distance measure y_{cut}. The obtained transverse and longitudinal fragmentation functions are shown in Fig.5. Taking the measurements with $y_{\text{cut}} = 1.290$ GeV as the nominal results, DELPHI obtains the longitudinal fraction: $\frac{\sigma_L}{\sigma_{\text{tot}}}(M_Z) = 0.0445 \pm 0.0006(\text{stat.}) \pm 0.0060(\text{syst.})$. Using equation 5.2 the corresponding value for α_s is found to be: $\alpha_s(M_Z) = 0.1083 \pm 0.0012(\text{stat.}) \pm 0.0119(\text{syst.})$.

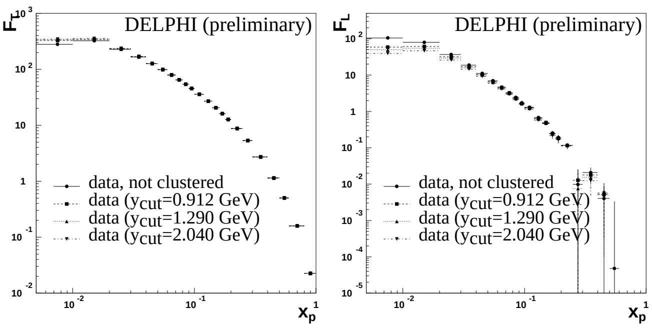

Figure 5: Transverse and longitudinal fragmentation functions at $\sqrt{s} = 91$ GeV using angles of individual hadrons or those of jets.

In a similar analysis of data from the JADE experiment[5] the $\cos\theta$ distribution was measured for e^+e^- interactions at a mean centre-of-mass energy of 36.6 GeV. The longitudinal fraction was determined to be: $\frac{\sigma_L}{\sigma_{\text{tot}}}(36.6\ GeV) = 0.067 \pm 0.011(\text{stat.}) \pm 0.007(\text{syst.})$

and the corresponding value of the strong coupling constant: $\alpha_s(36.6\text{ GeV}) = 0.150 \pm 0.020(\text{stat.}) \pm 0.013(\text{syst.}) \pm 0.008(\text{scale})$. Evolved up to M_Z this corresponds to $\alpha_s(M_Z) = 0.127^{+0.017}_{-0.018}$, in agreement with the DELPHI result and with the world average value of $\alpha_s(M_Z)$ $(0.1184 \pm 0.0031$[20]).

6. Summary

Various new results on jet and inclusive hadron production in e^+e^- annihilation have been presented. The measurements have been compared to higher order QCD predictions to test this theory and to extract it's coupling constant and it's colour factors. The obtained results for α_s agree with results obtained in other measurements and the obtained values for the colour factors agree with the values expected in QCD.

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