Tests of QCD at e^+e^- Colliders

Glen D. Cowan
Physics Department, Royal Holloway and Bedford New College,
University of London, Egham, Surrey, TW20 0EX, England

Results on Quantum Chromodynamics from electron-positron colliders are reviewed, with emphasis on recent publications from the now completed LEP and SLC programmes. The review is restricted to hadronic final states from the decay of a virtual photon or Z boson, and does not consider hadronic events from four-fermion processes. The measured quantities include jet-rates and distributions of event-shape variables. The measurements have been used to test the predictions of QCD and to determine the value of the strong coupling constant α_s.

1 Introduction

Electron-positron collisions have for many years provided key experimental input to the study of Quantum Chromodynamics (QCD). The most significant contributions in the 1970s and early 80s include the establishment of three colours from the total hadronic cross section and the discovery of the gluon. Through the 1990s, the Large Electron-Positron (LEP) Collider and the Stanford Linear Collider (SLC) provided increasingly detailed tests of QCD and have succeeded in determining the strong coupling constant α_s with a precision of several percent.

In this review we will consider only e^+e^- annihilation into hadrons and not hadronic final states resulting from four-fermion production (e.g., W^+W^- and ZZ events). In the annihilation events, a quark-antiquark pair is created from the decay of an intermediate photon or Z. The conversion of the $q\overline{q}$ pair into colour-neutral hadrons leads most frequently to a back-to-back pair of jets. Radiation of high-energy gluons from the $q\overline{q}$ pair results in additional jets. Measurements of the production rates and properties of hadronic jets provide important tests of perturbative QCD and are used to measure α_s.

In Section 2, we describe briefly the data sets on which the measurements are based. Measurements of jet rates and event-shape distributions are shown in Section 3. In Section 4 we show a recent measurement of α_s based on the four-jet rate and a compilation of measurements of QCD colour factors C_A and C_F. Finally in Section 5 we mention briefly an investigation of the flavour independence of α_s and we show a recent example of the many hadronization studies carried out with hadronic Z decays. The review here is, owing to constraints of space, selective and concentrates on recent results. Further QCD results from LEP and SLC are described in other recent reviews [1], [2], [3].

2 Data from e^+e^- colliders

The four LEP experiments—ALEPH, DELPHI, L3 and OPAL—each recorded around 4 million hadronic events during the LEP I programme (1989–1995) at a centre-of-mass energy E_{cm} close to the Z resonance. The SLD experiment at the SLC published QCD results based on approximately 400,000 hadronic Z decays.

In addition, the LEP experiments obtained data at centre-of-mass energies up to around 209 GeV during the LEP II phase of operation (1996–2000). Here initial state photon radiation leads frequently to a hadronic system with an invariant mass significantly less than E_{cm}, often close to the mass of the Z boson. For studies of higher energy QCD effects, however, only those events with a hadronic mass close to E_{cm} were of interest, and cuts were applied to remove the radiative events. Further cuts were used to suppress W^+W^- and ZZ events, and background corrections were applied to account for those events of this type not removed. After cuts, each of the LEP experiments recorded around $10,000$ hadronic events at energies between 183 and 209 GeV, with smaller data samples at energies between 130 and 172 GeV [1].

3 Measurements of jet rates and event shapes

Emission of a gluon at a large angle from the initially created $q\bar{q}$ pair has a probability proportional to α_s and leads to a three-jet event. For purposes of measuring jet production rates, a jet is defined by means of a specific procedure, e.g., the Durham clustering algorithm [4]. Here the number of jets in an event depends on a resolution parameter y_{cut}, which is related to the minimum transverse momentum of a jet relative to the directions of the others.

Figure 1(a) shows n-jet rates with $n = 2,3,4,5$ as a function of y_{cut} measured by the L3 experiment at $E_{cm} = 206$ GeV [6] together with the predictions of several hadron production models. The models contain a 'parton level' which describes a system of quarks and gluons using perturbative QCD, followed by a non-perturbative model of hadronization. At the parton level, the models shown here all use the $\mathcal{O}(\alpha_s)$ matrix element, which provides at most a single high-energy gluon. Multigluon emission is included by using the leading-log approximation. This leads to a parton-shower picture where the quarks and gluons undergo successive branchings of the type $q \to qg$, $g \to gg$ and $g \to q\bar{q}$. As the $\mathcal{O}(\alpha_s)$ matrix element provides only a leading order description of the three-jet rate, it is not surprising to see significant discrepancies between the data and model predictions.

In addition to jet rates, one can define variables whose value reflects the level of departure of an event's shape from the two-jet configuration. An example is the variable y_3, defined as the value of y_{cut} used in a jet clustering algorithm for which an event is on the border between being classified as having two or three jets. Other examples include thrust T, heavy jet mass M_h, and jet broadening variables B_W and B_T. Full definitions can be found in, e.g., [7].

Figure 1(b) shows the distribution of thrust measured by DELPHI at $E_{cm} = 206$ GeV [8]. The contribution from W^+W^- and ZZ events is also shown as the curve peaking at high values of $1-T$. This background has been subtracted, and the corrected data are shown together with model predictions for annihilation events only. Distributions such as these constitute an important probe for new physics, since a new event type resulting in a multijet structure would manifest itself as an excess at high $1-T$. Overall good agreement with the models is found.

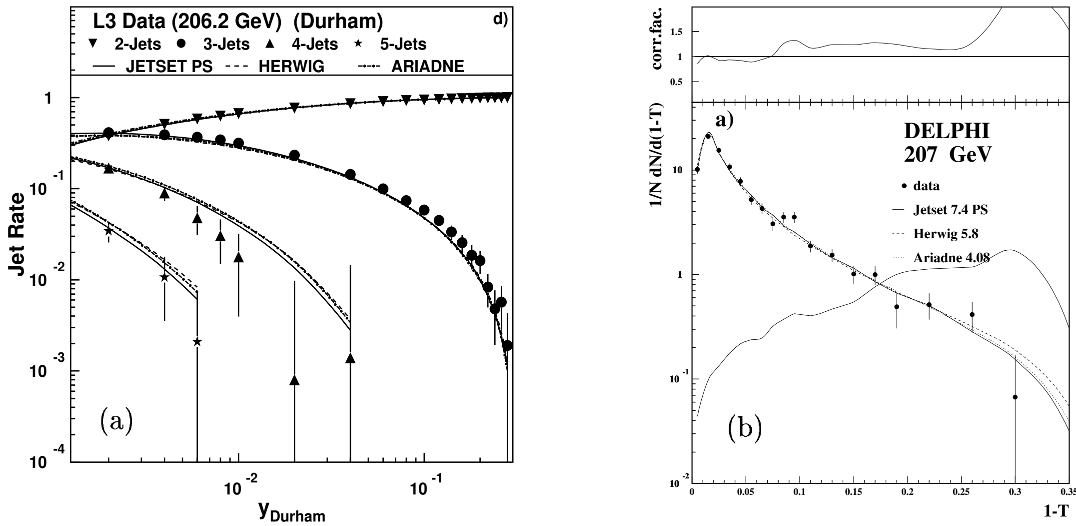

Figure 1: (a) Jet rates as a function of the resolution parameter $y_{\rm cut}$ measured by the L3 experiment at $E_{\rm cm} = 206$ GeV (points) and the predictions of several Monte Carlo models (curves). (b) The thrust distribution measured by the DELPHI experiment at $E_{\rm cm} = 207$ GeV (points) with model predictions (curves).

Distributions of infrared- and collinear-safe event-shape variables can be predicted by QCD to $\mathcal{O}(\alpha_{\rm s}^2)$. For certain appropriately defined variables the leading- and next-to-leading logarithmic contributions (LLA, NLLA) can be included as well, which leads to a greatly improved prediction close to the two-jet region.

The strong coupling constant $\alpha_{\rm s}$ can be determined by fitting the QCD prediction to the measured event-shape distributions. Effects of hadronization are taken into account by means of Monte Carlo models or by power law corrections. Distributions of the variable y_3 measured by the ALEPH experiment at a number of centre-of-mass energies are shown in Fig. 2(a) [5] together with the fitted QCD predictions.

Through coordinating efforts in the LEP QCD Working Group, the four LEP collaborations have analysed event-shape distributions in a manner which allows the results to be combined in a meaningful way. Combined measurements of $\alpha_{\rm s}(E_{\rm cm})$ are shown as a function of the centre-of-mass energy in Fig. 2(b) [9] together with the QCD prediction. The outer error bars reflect the total uncertainty, which is dominated by the missing higher-order terms in the perturbative part of the QCD prediction. These errors are highly correlated between different energies, and therefore it is mainly the inner error bars that are relevant for a test of the predicted running. The most accurate determination of $\alpha_{\rm s}$ from event-shapes at LEP comes from the LEP II data alone. By combining results from all four experiments on several observables one finds a preliminary value of [9]

$$\begin{aligned}\alpha_{\rm s}(M_{\rm Z}) = 0.1202 \quad &\pm \quad 0.0006\ (\text{stat.}) \pm 0.0010\ (\text{sys.}) \\ &\pm \quad 0.0010\ (\text{hadronization}) \pm 0.0046\ (\text{pert. theo.})\ ,\end{aligned}$$

where the total error is dominated by the uncertainty in the perturbative part of the QCD prediction [10].

All of the amplitudes needed to predict event-shape distributions to $\mathcal{O}(\alpha_{\rm s}^3)$ have been calculated, but a number of computational challenges remain to be overcome before the ingredients can be assembled [11]. Once these predictions become available, a reanalysis of the LEP and SLC data will lead to a significantly more accurate determination of $\alpha_{\rm s}$.

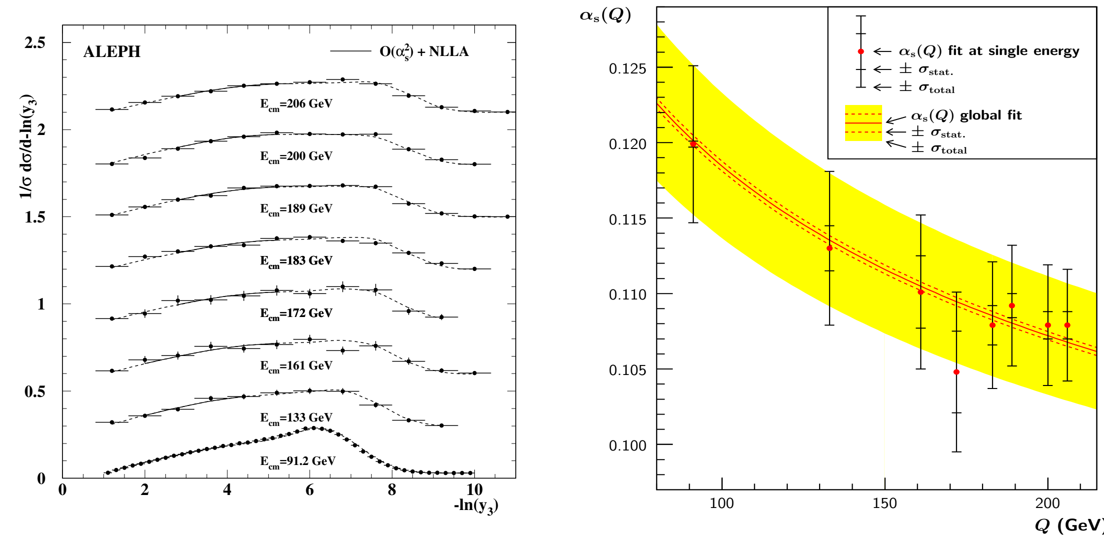

Figure 2: (Left) The distribution of $-\ln y_3$ measured by the ALEPH experiment at different centre-of-mass energies (points) and the fitted QCD predictions (curves). (Right) Values of $\alpha_s(E_{\text{cm}})$ from averages of several event-shape variables measured by the LEP experiments.

4 Measurements of four-jet observables

Emission of two high-energy gluons from the initial $q\overline{q}$ pair leads to a four-jet final state. The next-to-leading order prediction, i.e., to $\mathcal{O}(\alpha_s^3)$ for the four-jet rate using the Durham algorithm has recently been computed [12], [13] and this has been matched to the NLLA resummed prediction. Using this, measurements of α_s from the four-jet rate have been carried out recently by the ALEPH [14] and DELPHI [15] experiments. Figure 3(a) shows the four-jet rate measured by ALEPH together with the fitted QCD prediction, from which the value

$$\alpha_s(M_Z) = 0.1170 \pm 0.0022$$

is obtained. The uncertainty is dominated by a variation in the renormalization scale μ, which reflects the error due to missing higher order terms. In this analysis it was not possible to include an uncertainty due to the matching of the NLLA and NLO parts of the QCD prediction, which could account—at least partially—for the surprisingly small total error.

QCD predicts for the so-called colour factors (related to the SU(3) gauge structure of the theory) values of $C_A = 3$ and $C_F = 4/3$. The probabilities for the branchings $g \to gg$ and $q \to qg$ are proportional to C_A and C_F, respectively. A recent compilation of values of C_A and C_F from four-jet properties, events shapes and particle multiplicities is shown in Fig. 3(b) [2]. Excellent agreement with the QCD predictions is found. Combining all the observables considered gives

$$\begin{aligned} C_A &= 2.89 \pm 0.03 \text{ (stat.)} \pm 0.21 \text{ (sys.)} , \\ C_F &= 1.30 \pm 0.01 \text{ (stat.)} \pm 0.09 \text{ (sys.)} . \end{aligned}$$

5 Brief look at other recent results

Finally we will mention two more recent results from LEP and SLC: studies of the flavour independence of α_s, and production rates of identified hadrons.

QCD predicts that the quark-gluon coupling strength is independent of the quark's flavour. This can be tested by measuring α_s using event samples enriched in primary $q\overline{q}$ pairs of a given

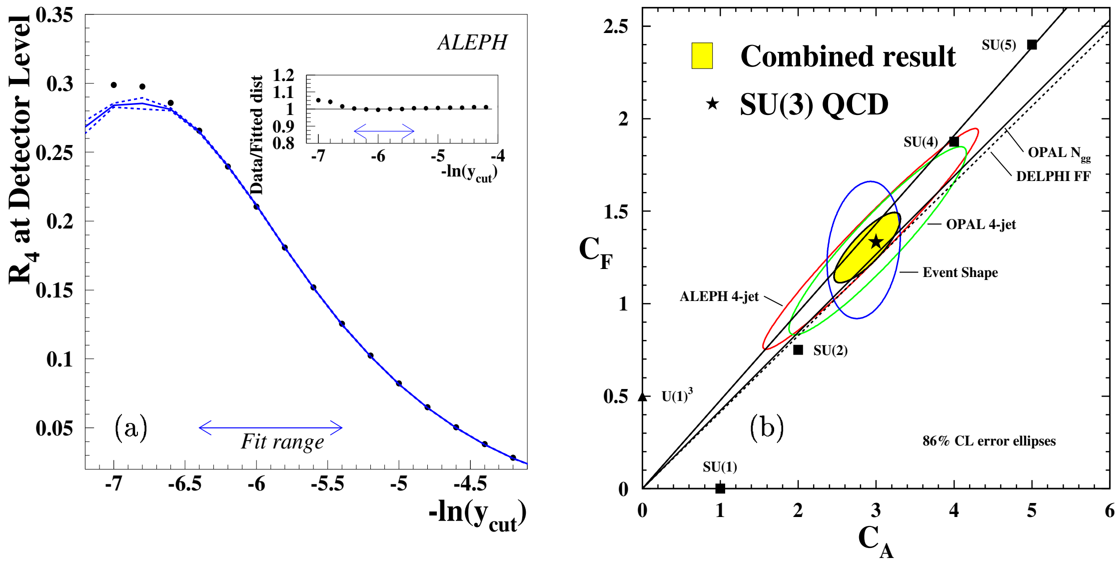

Figure 3: (a) The differential four-jet rate measured by the ALEPH experiment (points) and the fitted QCD prediction (curve). (b) A compilation of fitted values of the QCD colour factors C_A and C_F.

flavour. Accurate studies of this type of been published recently by the OPAL experiment [16], where they compare α_s from $b\bar{b}$, $c\bar{c}$ and a mixture of light-quark (uds) events. Ratios of the α_s values are shown in Fig. 4(a). OPAL finds

$$\begin{aligned} \alpha_s^c/\alpha_s^{uds} &= 0.997 \pm 0.038 \text{ (stat.)} \pm 0.030 \text{ (sys.)} \pm 0.012 \text{ (theo.)} , \\ \alpha_s^b/\alpha_s^{uds} &= 0.993 \pm 0.008 \text{ (stat.)} \pm 0.006 \text{ (sys.)} \pm 0.011 \text{ (theo.)} \end{aligned}$$

The values are in good agreement with unity and the result for $\alpha_s^b/\alpha_s^{uds}$ is at an accuracy approaching the percent level.

Although the studies presented in this review have been related mainly to perturbative QCD, the LEP and SLC programmes provided many detailed measurements on hadronization. Most importantly, there have been many investigations of the production rates of identified hadrons. These measurements are valuable to model builders who are attempting to achieve a better understanding of non-perturbative QCD. In addition, the models are an important tool in studies of electroweak physics and searches for any new phenomena involving hadronic final states.

As a recent example we show here measurements of production rates of charged pions, kaons and protons in hadronic Z decays carried out by the SLD experiment [17]. Hadron identification was made possible by SLD's Cherenkov Ring Imaging Detector (CRID). The fractions of these hadron types are shown in Fig. 4(b) as a function of the momentum along with the predictions of several Monte Carlo models. Although the models reproduce the data reasonably well, there are clearly significant discrepancies which are not easily removed by a simple tuning of the available parameters. In addition to the measurements shown here, SLD has measured the hadron fractions in jets initiated by identified quark types. This provides important input for tagging b-jets from, e.g., Higgs boson decays to $b\bar{b}$.

6 Conclusions

The LEP and SLC programmes have produced several hundred publications on QCD. These include determinations of α_s to the level of several percent. A reanalysis of the data should reduce

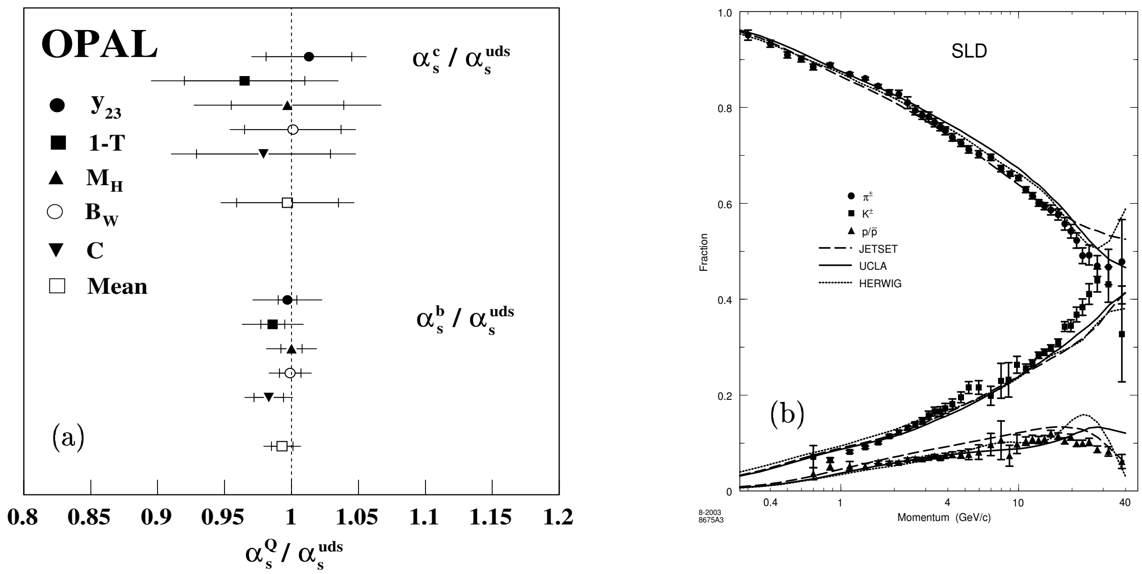

Figure 4: (a) Ratios of α_s values determined from event samples with different flavours of primary quarks. (b) Fractions of charged pions, kaons and protons found as a function of momentum from hadronic Z decays as measured by the SLD experiment (points) and the predictions of several Monte Carlo models (curves).

this uncertainty when the $\mathcal{O}(\alpha s)$ predictions for event-shape distributions become available. The flavour independence of α_s has been tested to the percent level and the colour factors C_A and C_F agree with the QCD predictions with a precision of around 7%. The benefits of these studies will no doubt be clear at future colliders such as the LHC, where a detailed understanding of QCD and hadronic jets will be needed in order to uncover convincing evidence of physics beyond the Standard Model.

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