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QCD STUDIES WITH RESURRECTED JADE DATA

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We report on recent studies of QCD performed using reanalysed e^+e^- annihilation data recorded at centre of mass energies $14 \leq \sqrt{s} \leq 44$ GeV by the JADE experiment operated 1979 to 1986 at the PETRA e^+e^- collider at DESY, Hamburg, Germany. The data for some event shape observables are compared to modern Monte Carlo event generators using parameter values obtained from LEP 1 data. The distribution of $\xi = \ln(1/x)$ with $x = 2p/\sqrt{s}$ and p the momentum of a charged hadron is measured and compared to QCD predictions. Fits of $\mathcal{O}(\alpha_s^2)$+NLLA (resummed) QCD predictions combined with power corrections to event shape data including for the first time the $\sqrt{s} = 14$ and 22 GeV data samples are discussed.

1 Introduction

QCD as the theory to describe many features of hadron production in e^+e^- annihilation such as the total cross section, jet formation, multiplicity or momentum spectra has been established mainly with data from the experiments at the PETRA e^+e^- collider, see e.g. [1, 2, 3, 4, 5]. However, the analyses of that time were limited by the theoretical understanding of QCD as well as the models needed to correct for hadronisation effects.

In particular during the LEP era from 1989 to 2000 enormous progress in improving QCD calculations by adding higher order radiative corrections and creating generic numerical integration programs [6, 7] or resummed logarithmic contributions (e.g. [8]) was made. Also, detailed predictions directly relating perturbative QCD (pQCD) predictions with hadron distributions for e.g. multiplicity or momentum spectra became available, see e.g. [9, 10].

The modelling of hadronisation effects had benefited from the use of Monte Carlo event generators such as PYTHIA/JETSET [11], HERWIG [12] or ARIADNE [13] containing consistent descriptions of parton and hadron production tuned to precise data from the LEP experiments, see e.g. [14,15]. In another approach analytical models of hadronisation applicable to some event shape or jet production observables had been developed allowing comparisons of theory with data without Monte Carlo hadronisation models, see e.g. [16].

PQCD effects grow with decreasing energy scale Q like $1/\ln Q$ and in particular non-perturbative effects in many event shape or jet production observables grow with $1/Q$. Therefore the data from the JADE experiment can still be used for important and unique tests of modern QCD predictions. From another point of view one can argue that only now our understanding of QCD and hadronisation processes is sufficiently advanced to allow consistent interpretation of the PETRA data.

The JADE experiment is described in [1]. The data used in the studies presented here correspond to samples of about 1500 events at $\sqrt{s} = 14, 22$ and 38 GeV, about 4000 events at 44 GeV and about 35000 events at $\sqrt{s} = 35$ GeV. The JADE software consisting of a detailed detector simulation program and the reconstruction programs has been installed on an IBM RS6000 AIX system using the IBM Fortran compiler [17]. It is possible to generate final states from e^+e^- annihilation using modern generator programs like PYTHIA/JETSET, HERWIG or ARIADNE, to pass these through the JADE detector simulation and to finally reconstruct the output of the detector simulation in the same way as the data.

2 Data vs modern MCs

Before the modern Monte Carlo generators can be used with confidence in the data analysis they must be compared with data to establish their performance. The data for the event shape observable thrust T and the distributions of y_{23}[a] shown in figure 1 are corrected for acceptance, detector resolution and initial state radiation (ISR). In addition the contribution from $e^+e^- \to b\overline{b}$ events has been subtracted using simulated events from PYTHIA. The $e^+e^- \to b\overline{b}$ events, approximately 9% of the JADE samples, are considered as background since the high masses of the b-hadrons are known to distort e.g. event shape distributions, in particular at lower $\sqrt{s}$ [18, 19, 17]. The data are compared with predictions based on u, d, s and c quarks from the generator programs PYTHIA 5.7, ARIADNE 4.08, HERWIG 5.9 and COJETS 6.23 as well as JETSET 6.3 as used in earlier JADE analyses. The parameter sets for all programs except JETSET are taken from the OPAL collaboration, i.e. they are derived from LEP 1 data at $\sqrt{s} \simeq M_{Z^0}$, while the JETSET parameters are taken from JADE, see [17] for details.

We find that the PYTHIA and ARIADNE generators generally describe the JADE data well. HERWIG is seen to produce somewhat too many 3-jet like events and correspondingly too few 2-jet like events at lower values of $\sqrt{s}$ while COJETS does not give a reasonable description of the data. The COJETS model implements a leading-log parton shower without taking colour coherence into account combined with independent fragmentation [20]. The JETSET 6.3 predictions also describe the data fairly well. In conclusion we find that modern Monte Carlo Generators using parameter sets derived from LEP 1 data can be used for QCD analyses with JADE data.

3 Scaled Momentum Distribution

The shape of the distribution of $\xi = \ln(1/x)$ with x being the momentum of charged particles normalised to the beam energy is predicted in pQCD to be approximately a skewed Gaussian, see

[a] The value of the jet resolution parameter where the event changes from a 2-jet to a 3-jet configuration with the Durham jet algorithm.

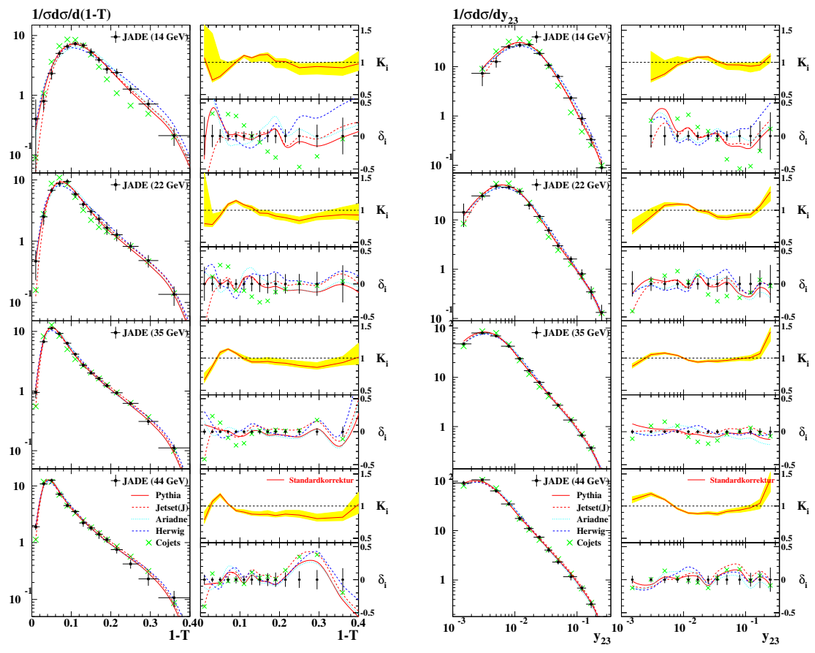

Figure 1: Comparison of JADE data for 1-T (left) and y_{23} (right) corrected for experimental and ISR effects and $b\bar{b}$-background with Monte Carlo predictions [17].

e.g. [9,10]. The position of the peak ξ^0 is predicted as a function of $\sqrt{s}$. The pQCD predictions in the modified leading log approximation (MLLA) including subleading effects [21,10,22] may be directly compared with the hadron-level data up to a normalisation factor, a property known as local parton hadron duality (LPHD).

The ξ distributions have been measured using JADE data at 22, 35 and 44 GeV [22]. In this analysis no correction for the presence of $e^+e^- \to b\bar{b}$ events has been made consistent with analyses by other experiments. Figure 2 (left) shows the result for $\sqrt{s} = 35$ GeV. Superimposed is a fit of the pQCD prediction to determine the position of the peak ξ^0. The figures for the other $\sqrt{s}$ points at 22 and 44 GeV look similar but have larger statistical errors due to the smaller data samples.

The fit is seen to describe the data well around the peak region; the prediction is not expected to be in good agreement with the data outside of the fit region. The results for the peak positions and effective QCD scales are given in table 1.

Table 1: Results for peak position ξ^0 and $\Lambda_{\rm eff}$ from pQCD fits to JADE data with total uncertainties [22].

$\sqrt{s}$ [GeV]	ξ^0	$\Lambda_{\rm eff}$[MeV]
22	2.74 ± 0.09	136 ± 28
35	3.06 ± 0.05	142 ± 25
44	3.19 ± 0.06	110 ± 38

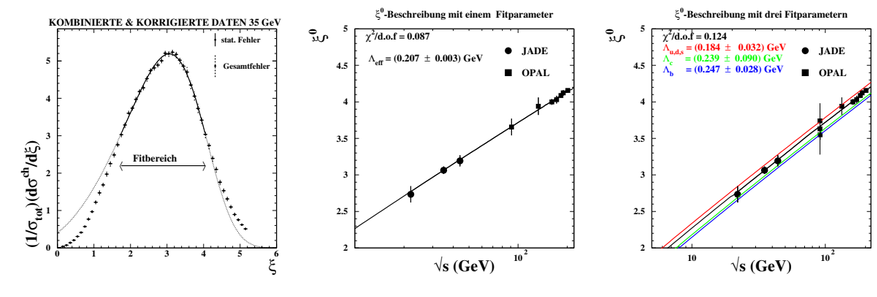

Figure 2: The figure on the left shows the distribution of ξ measured at $\sqrt{s} = 35$ GeV corrected for experimental effects. The figure in the middle shows the JADE results for ξ^0 together with results derived from OPAL data and compared with a pQCD fit for the $\sqrt{s}$ dependence of ξ^0. The figure on the right shows the same results for ξ^0 except at $\sqrt{s} \simeq M_{Z^0}$ where results from flavour separated data from OPAL are given; the fits are explained in the text [22].

The dependence on $\sqrt{s}$ of ξ^0 is shown in figure 2 (middle). The three JADE data points are compared with results derived using the same fits from OPAL data and fitted with the pQCD prediction. The fit describes the data reasonably well, however, the result for $\Lambda_{\rm eff}$ differs from the results shown in table 1 by two to three standard deviations.

In order to study effects of heavy flavours in the data samples a fit with an effective QCD coupling $\Lambda_{\rm eff}$ for each flavour (uds, c or b) is made. The three $\Lambda_{\rm eff}$ are related by $\xi_{\rm c,b} = \xi_{\rm uds} + 0.5\ln(\Lambda_{\rm c,b}/\Lambda_{\rm uds})$ and flavour separated data from OPAL are used at $\sqrt{s} \simeq M_{Z^0}$. At the other $\sqrt{s}$ the known flavour fractions in $e^+e^- \to q\overline{q}$ are employed. The results $\Lambda_{\rm uds} = 184 \pm 33$ MeV, $\Lambda_{\rm c} = 239 \pm 90$ MeV and $\Lambda_{\rm b} = 247 \pm 28$ MeV indicate the presence of quark mass effects of about 20 to 30%; the fits are shown in 2 (right).

4 Extended Power Correction Fits

In this section we return to the study of event shape and jet production observables, describing results of [17]. We concentrate on fits of pQCD predictions in $\mathcal{O}(\alpha_s^2)$ matched with resummed NLLA calculations as described e.g. in [19,16,23]. In these fits the hadronisation corrections are implemented using the analytic DMW model [24]. The strong coupling $\alpha_{\rm S}$ is assumed to remain finite at very low scales below and above the Landau pole such that it can be integrated: $\alpha_0(\mu_{\rm I}) = 1/\mu_{\rm I}\int_0^{\mu_{\rm I}} \alpha_{\rm S}(k)dk$ with $\mu_{\rm I} = 2$ GeV. The value of α_0 cannot be predicted and is a free parameter of the model. The main prediction of the model for differential event shape distributions of some selected observables is that a shifted pQCD prediction describes the corresponding hadron-level data: $\mathrm{d}\sigma/\mathrm{d}y = (\mathrm{d}\sigma/\mathrm{d}y)_{PT}(y - D_y P)$, where D_y is an observable specific factor or function and P is an universal factor: $P \sim \mu_{\rm I}/Q(\alpha_0 - \alpha_{\rm S})$. Thus P contains all non-perturbative dependence on the scale $Q = \sqrt{s}$ and the parameter α_0.

We want to discuss fits of such predictions to the observables B_W and y_{23} which have special properties with standard fits. With B_W global fits to data from $\sqrt{s} = 189$ to 14 GeV are found to describe the data less well compared to other observables, in particular at low $\sqrt{s}$ [17,19]. Attempts were made to add extra terms to the power correction part of the prediction and a term of the form $A_{11}\ln(Q)/Q$ was found to provide the best improvement, albeit with a negative coefficient $A_{11} = -0.60 \pm 0.06$(fit). The χ^2/d.o.f. value of the fit improved from 134/154 for the standard fit to 77/153. The results are shown in figure 3 (left), displaying for clarity only data at $\sqrt{s} \leq M_{Z^0}$. The dotted lines are the standard pQCD combined with power correction fits which are seen to deviate from the data in particular at $\sqrt{s} = 14$ and 22 GeV. The fit of the

same prediction with a $A_{11}\ln(Q)/Q$ term added shown by the solid lines improves the agreement significantly. There is thus evidence for the presence of additional terms in the B_W prediction probably behaving like $\ln(Q)/Q$.

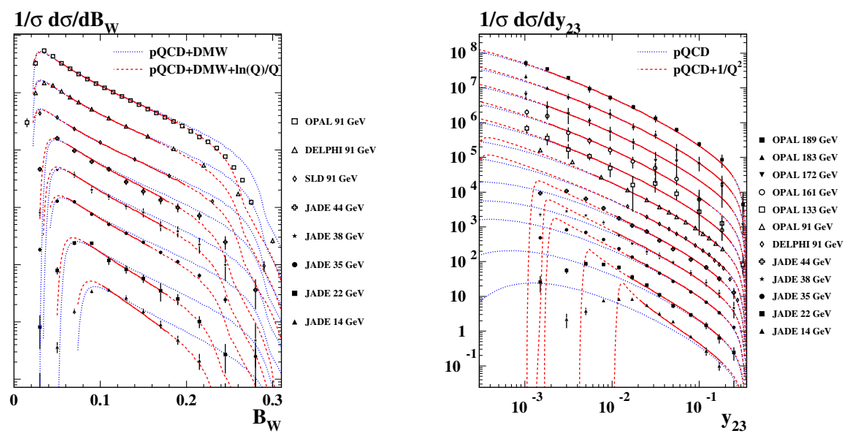

Figure 3: The figures show data at $\sqrt{s} = 91$ to 14 GeV for B_W (left) and y_{23} (right), including data from JADE. The data are compared with pQCD combined with standard power corrections and modified power corrections as indicated on the figures [17]. The solid lines indicate the fit ranges for all fit variations.

The DMW prediction for $\langle y_{23}\rangle$, the mean value of the distribution, is that its power correction is proportional to $\ln(Q)/Q^2$ [24]. Previous analysis of mean values have supported a strongly suppressed power correction [19]. Here the new data for y_{23} from JADE are used to study the y_{23} distribution [25, 17]. Figure 3 (right) shows fits of pure pQCD to the data as dotted lines[b]. The fits are seen to describe the data well at large $\sqrt{s}$ but deviations become visible within the fit ranges at low $\sqrt{s} = 14$ and 22 GeV. The fit of pQCD with a A_{20}/Q^2 term added is shown by the solid and dashed lines. These fits are indistinguishable from the pure pQCD fits at large $\sqrt{s}$ but have improved agreement at low $\sqrt{s}$. The χ^2/d.o.f. values changed from 151/107 for the pure pQCD fit to 71/106 for the fit with the additional A_{20}/Q^2 term. The parameter is found to be $A_{20} = 2.25 \pm 0.18(\text{fit})$ GeV^2. The new data at 14 and 22 GeV play an important rôle in discriminating between the two possible predictions. We thus find evidence for a power correction probably behaving like $1/Q^2$ at low $\sqrt{s}$ for y_{23} distributions.

5 Summary

The continuing analysis of the e^+e^- annihilation data of the JADE experiment provides unique opportunities for tests of QCD. Modern Monte Carlo generators with parameter sets derived from LEP 1 data are found to describe event shape and jet production observable distributions reasonably well, with PYTHIA and ARIADNE showing a somewhat better agreement at low $\sqrt{s}$ compared to HERWIG. New measurements of the charged particle momentum fractions $\xi = \ln(1/x)$ have been presented and compared with MLLA pQCD predictions including subleading effects. Studies of extended DMW power correction fits using the new JADE data at $\sqrt{s} = 14$ and 22 GeV have provided evidence for additional power correction like terms in the DMW power correction for the observables B_W and y_{23}.

[b] We don't yet use the improved numerically resummed prediction [26]

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