JET SHAPES AND OTHER QCD RESULTS AT LEP2

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Recent results from QCD analyses at LEP2 are briefly reviewed. In contrast to LEP1, these analyses are based on very small data sets. They provide, however, new interesting consistency tests of QCD in e^+e^- annihilations at energies never reached before.

1 Introduction

Since the LEP2 program started in the autumn of 1995, the centre-of-mass energy of the collider has been increased to 130, 136, 161, 172 and most recently 183 GeV, providing an interesting opportunity of testing QCD in e^+e^- annihilations in yet unexplored regions. In particular, observables expected to evolve with energy can now be measured, for the first time using the same apparatus and the same analysis techniques, over a wide energy range.

The statistics collected at LEP2 so far [a] is too poor for very detailed studies, but is nevertheless sufficient to provide new interesting results.

In this brief, qualitative and necessarily incomplete review, some recent studies done by the four LEP experiments are presented. Some preliminary results shown at the conference have been finalised or refined in the meantime, and those most updated are presented here.

2 Global Properties of Hadronic Events

In e^+e^- collisions, initial state radiation (I.S.R.) reduces the energy available to the $q\bar{q}$ system. This phenomenon, practically irrelevant when running on the Z^0 resonance, is very important at LEP2. Infact, the cross-section for events in which the radiated initial state photons decrease the available energy such that an on-shell Z^0 boson is produced, is greatly enhanced. The

[a] About 10^3 events/experiment at 183 GeV and roughly 300 events/experiment at lower energies.

events observed at LEP2, then, fall into two main classes: "non-radiative events", characterized by a small amount of initial state radiation, for which the final state system has a centre-of-mass energy close to twice the beam energy; and "radiative events", where a large amount of radiation allowed the resonant production of a Z^0. At LEP2 energies about 2/3 of the hadronic events detected are of this last type, 1/3 are non-radiative and a small fraction of events falls in between. Studies of QCD at the highest available energies require the $q\bar{q}$ events produced in the annihilation process to be non-radiative. Radiative events can be efficiently rejected since they are characterized either by large missing energy and imbalanced momentum (because I.S.R. photons are emitted predominantly close to the beam direction and easily escape detection) or by the presence of energetic and well isolated photons. In general high efficiencies ($\approx 90\%$) and high purities can be obtained.

The background to the genuine annihilation process, in particular from W pairs and other final states involving four fermions, requires appropriate cuts to be reduced to a tolerable level. The residual contamination, evaluated from the analysis of events fully simulated in the detector, never exceeds 10% and is subtracted from the observed distributions.

2.1 Shape Variables

Several event shape variables, such as Thrust (T), Sphericity (S), Oblateness (O), Heavy Jet Mass (M_H), Jet Broadenings (B_T and B_W) etc., have been proposed and their distributions have been measured up to the highest LEP2 energies[b]. According to QCD, event shape distributions evolve with energy in a peculiar way and this can be tested experimentally.

Theoretical predictions are available either in analytical form (discussed in section 3) or in terms of Monte Carlo model predictions. A number of Monte Carlo event generator programs have been developed which provide remarkably accurate, detailed descriptions of complete hadronic events. Among these, QCD Parton Shower (PS) models Pythia[2], Herwig[3], Ariadne[4] and Cojets[5] have been the most successfull. The optimisation ("tuning") of their free parameters, providing the best simultaneous description of a restricted set of sensitive distributions, was done independently by the four LEP experiments using the huge statistics collected at LEP1. Having fixed the free parameters at a given energy, one can test the predictive power of these QCD models by comparing their expectations with measured distributions other than those used for tuning purposes, or with distributions measured at as much as possible different energies.

It was shown that all QCD models could provide a reasonably good overall description of the global hadronic event features observed at the Z^0 peak energy. In addition, PS models were also shown to provide a good global description of lower energy data, in contrast to QCD models based on the Matrix Element (ME) approach which need to be re-tuned at each energy. One goal of QCD studies at LEP2 is to test how well PS models work at much higher energies.

One example is shown in Figure 1 where several event shape distributions measured at 183 GeV (by OPAL[6]) and the energy evolution of some shape mean values (measured by L3) are plotted. The L3 analysis[7] on shape mean values covers an energy range from about 40 GeV to 172 GeV. The points below the Z^0 resonance were obtained from hadronic events collected at the Z^0 peak, involving energetic initial or final state photon radiation. In these events the effective energy available to the hadronic system is given by $\sqrt{s'} = \sqrt{s(1 - 2E_\gamma/\sqrt{s})}$, where E_γ is the energy of the radiated photon. It can be seen that within the present experimental uncertainties all the PS models mentioned above, tuned at 91 GeV, provide a satisfactory overall description of these distributions also at the highest energies and correctly predict the energy evolution of their mean values.

[b]A quite complete list of these observables together with their definitions can be found in reference[1].

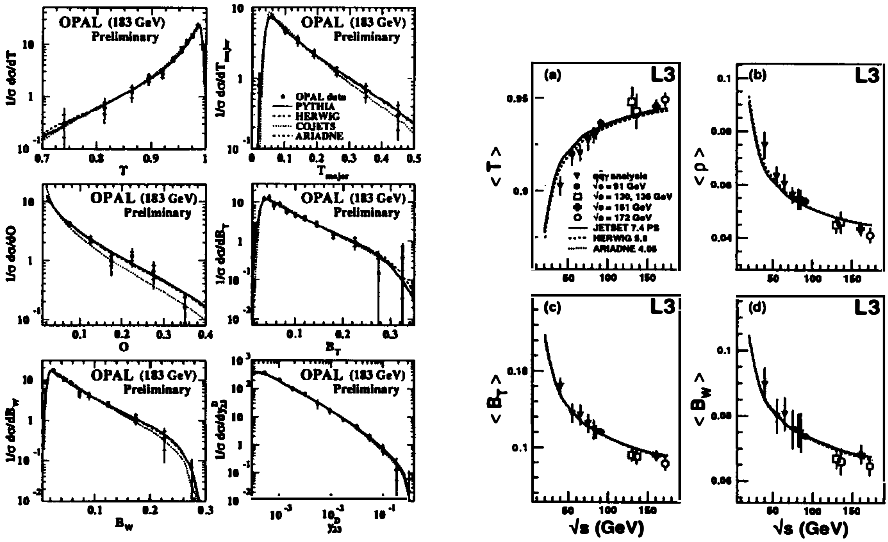

Figure 1: Shape variables measured at 183 GeV and energy evolution of shape mean values.

2.2 Jet Production Rates

The rate of production of events showing a multi-jet structure is another typical observable used to characterise hadronic final states. As an example, the results obtained by OPAL[6] at 183 GeV is shown in Figure 2.

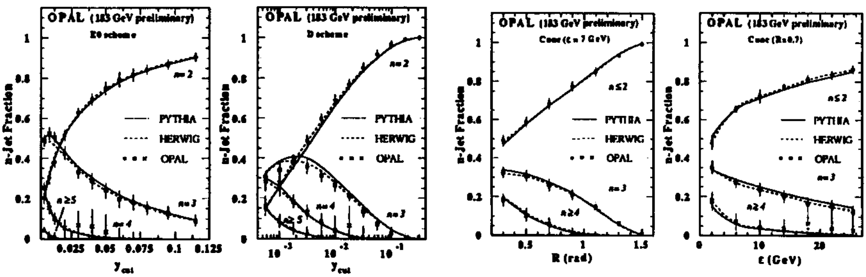

Figure 2: Jet production rates measured at 183 GeV using three different jet finding algorithms.

The well known JADE[8] and Durham[9] jet finding algorithms as well as a Cone jet finding algorithm[10], have been considered in this analysis. The production rates measured with different jet resolution parameters (y_{cut}, R, ε) are shown together with the predictions of Pythia and Herwig. Again, within the present experimental uncertainties, there is no evidence of the existence of unexpected features. The same conclusion was drawn also at lower LEP2 centre-of-mass energies, though with less statistical significance due to the smaller data samples.

2.3 Multiplicities

The charged particle multiplicity is a particularly simple observable which is extremely sensitive to the dynamics of hadron production. A number of predictions for the energy evolution of the multiplicity distribution and its leading moments exist. At LEP2 energies a detailed study of the shape is still limited by the low statistics but the mean value of the distribution can be measured quite precisely.

In Figure 3 an updated compilation of the mean charged multiplicity, $< n_{ch} >$, measured in e^+e^- annihilations at energies $\sqrt{s} > 12$ GeV, is shown. The results at LEP2 have been obtained either by a direct measurement of the event multiplicity or by integration of single particle inclusive distributions, like rapidity or fractional momentum.

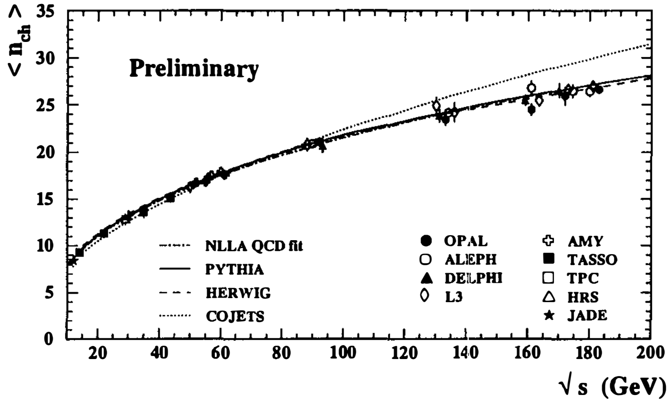

Figure 3: Mean charged particle multiplicity measured in e^+e^- annihilations from 12 to 183 GeV.

The result of a fit to the data using the well known analytic parameterisation based on a Next-to-leading Log (NLLA) QCD calculation [11] as well as the predictions from PS models, are also shown in Figure 3. Both the analytic prediction and the PS models, with the exception of Cojets, continue to work satisfactorily up to the highest energies, describing quite well the experimental results over the full energy range[c].

Before LEP2 started all these models, tuned with data at LEP1, were shown to be able to correctly predict the experimental results up to the Z^0 peak. Now that the energy range explored has been widening by a factor two it is clear that Cojets predicts on average too many particles at high energies. It was also shown by OPAL [12] that the excess of these particles is concentrated at low fractional momenta and at low rapidities. All these observations are consistent with the interpretation that Cojets fails in describing the data over a large energy range because QCD coherence phenomena, in contrast to the other PS models, are not simulated in this model.

2.4 Single Particle Spectra

One of the simplest quantities sensitive to QCD coherence is the single particle inclusive momentum distribution, $x_p = p/p_{beam}$, where p and p_{beam} are the particle and beam momenta, respectively. In order to examine more closely the low momentum region, where one expects

[c]Ariadne prediction is almost indistiguishable from Pythia and is not plotted.

to see effects of soft gluon interference, the variable $\xi = -ln(x_p)$ is studied. The shape of the partonic ξ distribution calculated in the Modified Leading Log Approximation (MLLA) can be approximated by a distorted gaussian [13]. Assuming the validity of the Local Parton Hadron Duality (LPHD) hypothesis this shape can be directly adapted to the measured hadron spectrum [14]. The ξ distributions measured at LEP1 and LEP2, by DELPHI [15], and by other experiments at lower energies, are shown in Figure 4 (left-side) together with fits using the predicted theoretical form. All the measured distributions can be well described by distorted gaussians.

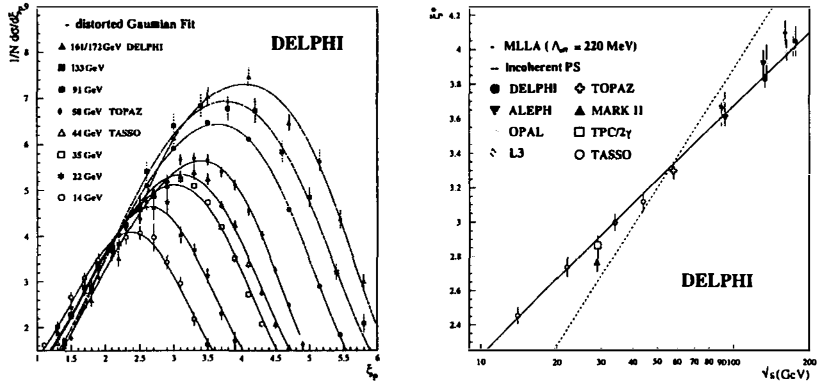

Figure 4: ξ distributions for charged particles and energy evolution of their peak position, ξ^*.

In the same figure (right-side), the position of the maximum of the ξ distribution, ξ^*, is shown as a function of the centre-of-mass energy. One can see that its energy evolution is accurately described by the MLLA expectation [16] (solid line) which takes into account interference, while an approach where coherence is not considered is found to fail (dashed line).

3 Some Recent Results on the Measurement of α_s

For a number of infrared and collinear safe variables, fixed-order perturbative QCD calculations to $O(\alpha_s^2)$ exist [11]. Among them, T, M_H, B_T and B_W, - $\ln(y_3)$ [d] and C parameter, exhibit the property of exponentiation so that leading and next-to-leading logarithms can be resummed to all orders in α_s into analytic functions. Properly "matched" fixed-order and resummed calculations ($O(\alpha_s^2) + NLLA$) provide the most complete theoretical descriptions available for these variables, which can be used to extract α_s by fitting the experimental distributions. Most of the measurements of α_s at LEP2 are based on this method.

As an example, two (out of the five) distributions measured by ALEPH [17] at LEP1 and LEP2 energies as well as their perturbative fit functions (corrected for hadronisation) are shown in Figure 5. The common fit ranges, where three-jet configurations dominate, cover the regions indicated by solid lines. The dashed lines show that the fits extrapolate well also outside the fit range. Within the present uncertainties it can be seen that there is a good overall agreement between the experimental distributions and their energy evolution predicted by QCD. The values

[d] y_3 is the value of cut on scaled invariant mass at which the event changes from being clustered into three jets to being clustered into two jets (Durham scheme).

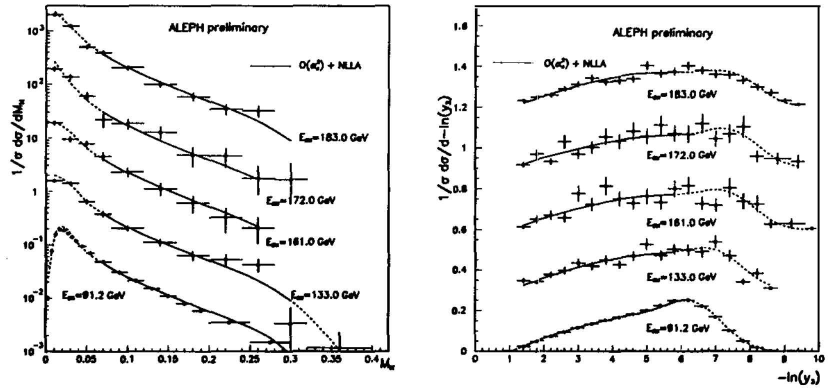

Figure 5: The distributions of M_H and -ln(y_3) measured by ALEPH at LEP1 and LEP2 energies together with the fitted QCD predictions.

of α_s at different energies have been extracted from these fits [17] and it was verified that they are all consistent with the expected running of the strong coupling constant.

In a similar way L3 has extracted α_s from four distributions, 1-T, $\rho = M_H/\sqrt{s}$, B_T and B_W, and determined α_s at each energy as the unweighted average of the four measurements. In addition to data collected at the Z^0 peak and LEP2 energies, L3 used for this analysis also the highly radiative events described in subsection 2.1 and determined α_s at energies below the Z^0 resonance. In Figure 6 the results for α_s obtained by the L3 experiment alone, using exactly the same analysis procedures and variables, are shown in the energy range $40 < \sqrt{s'} < 183$ GeV.

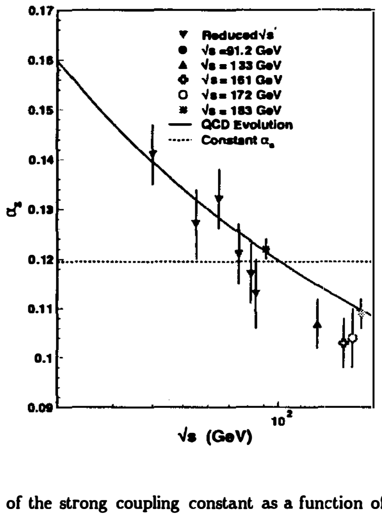

Figure 6: L3 measurements of the strong coupling constant as a function of the centre-of-mass energy.

The data point at 183 GeV is still preliminary [18] while the others have been published [7]. The eleven measurements shown in Figure 6 have been plotted with experimental errors only since the theoretical uncertainties are strongly correlated and are not appropriate to a measurement of the energy dependence of α_s. The solid line shows the result of a fit to the data points using the QCD evolution equation with $\alpha_s(M_Z)$ as a free parameter. A fitted value of $\alpha_s(M_Z) = 0.1215 \pm 0.0016\ 0.0066$, where the first error is experimental and the second error is theoretical, is obtained. The fit gives a $\chi^2 = 16.6$, while a model with constant α_s gives a $\chi^2 = 46.1$, which corresponds to a confidence level of $0.14 \cdot 10^{-5}$.

Acknowledgements

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