I review recent QCD results from LEP. The emphasis is on results that represent new studies and on puzzling disagreements of theory and experiment. Further results are nevertheless mentioned by reference. The new studies discussed in more detail are the most precise measurement of unbiased gluon jets to date, strong evidence of color coherence in 3-jet events, and an, albeit unsuccessful, search for penta-quarks. As yet unexplained disagreements are observed in photon-photon collisions for high momentum charged particle and single jet production, and for the total cross section of b-quark production.

The LEP community continues to use the unique data samples collected at center-of-mass energies on and above the Z peak both to improve existing results and to carry out new studies. In the former category a new LEP combined value of the strong coupling constant has been presented: \( \alpha_s(M_Z) = 0.1202 \pm 0.0003 \text{(stat.)} \pm 0.0009 \text{(exp.)} \pm 0.0013 \text{(hadr.)} \pm 0.0047 \text{(theo.)} \). The fragmentation functions have been measured for quark and gluon jets and charged particle spectra have been studied. In photon-photon collisions the exclusive production of particles has been studied for the interaction of two real photons, and the cross section has been measured for the interaction of two virtual photons.

The emphasis of this review, however, will be on new studies, and on persisting discrepancies between data and theory in the QCD domain.

1 New QCD studies from LEP

In theoretical studies gluon jets are often defined to be one hemisphere of a gluon–gluon event. In this case no jet algorithm is needed to define the jet, which is hence referred to as ‘unbiased’. Experimentally jets are mostly defined with the help of jet finding algorithms. Comparisons to theory then become ambiguous, since the properties of the gluon jets thus defined may depend strongly on the algorithm used. These jets are referred to as ‘biased’. OPAL has exploited the
 BOOST algorithm, a new method to construct unbiased gluon jets, to overcome this problem. The method starts from a $Z \rightarrow q\bar{q}g$ event. The partonic final state is decomposed into a $qg$ and a $\bar{q}g$ dipole, which are boosted individually to be back-to-back. The dipoles are then recombined to yield the color structure of a gluon–gluon event. Experimentally three-jet events are selected using a jet-algorithm in the sample of hadronic $Z$-decays collected at LEP1. The gluon jet is identified taking the highest energy jet to be a quark jet, and by requiring a b-quark tag using standard techniques on the second or third highest energy jet. The remaining jet is the gluon jet. The event is now boosted such that the angle $\alpha$ between the gluon jet and either quark jet is the same. The unbiased gluon jet is constructed from all particles inside the cone given by $\alpha/2$ around the direction of the ‘biased’ jet. Monte Carlo studies demonstrate that jets thus defined indeed have the same properties as gluon jets in gluon–gluon events. Figure 1 shows the mean charged particle multiplicity in the unbiased gluon jets as a function of the jet energy. The data are compared to three previous studies of unbiased gluon jets, which use rare three-jet events with the two quark jets almost collinear (OPAL($g_{\text{incl}}$)), a comparison of two-jet and three-jet events (OPAL($q\bar{q}g - q\bar{q}$)), and $\Upsilon \rightarrow \gamma gg$ events in CLEO. The results of the new study are consistent with previous results, but are the most precise to date for gluon jet energies between 5.25 GeV and 20 GeV. Theoretical results fit the data successfully. Many more results have been obtained using these unbiased gluon jets, including the first measurements of the $F_2$ and $F_3$ factorial moments over an energy range, charged multiplicity ratios of quark and gluon jets, and gluon jet fragmentation functions. The fragmentation functions of the unbiased gluon jets have been used for the first time to extract the strong coupling constant $\alpha_s$, yielding a value consistent with the world average.

Interference effects are fundamental to quantum mechanical gauge theories like QCD, but it proves difficult to establish their existence unambiguously in experimental data. For example, incoherent fragmentation models are able to describe the data with similar quality as models including coherence effects, although more parameters are needed in the former case. DELPHI has carried out a study of color coherence using two-jet and three-jet events collected at LEP1. Low energy hadrons produced inside cones perpendicular to the two-jet axis ($d\sigma_2$) or three-jet plane ($d\sigma_3$) cannot be assigned to a specific jet and have to be treated as coherent emissions. The two quantities can be related in leading order QCD by the expression:
dσ_3 = C_Λ/(4C_F) \left[ \hat{q}_g + \hat{\bar{q}}_g - (1/N_c^2) \hat{q}_\bar{q} \right] dσ_2, where the topology dependence is described by the terms inside the square brackets, which use the antennae functions \( \hat{i}_j = 2 \sin^2(\theta_{ij}/2) \). \( \theta_{ij} \) is the opening angle between two jets. The negative term expresses the interference effects. A comparison of the data to theoretical predictions with and without this term shows a strong preference for interference. To quantify this DELPHI fitted the interference term scaled by a factor \( k \) to \( dσ_3/dσ_2 \), assuming \( C_Λ/C_F = 9/4 \). The result is \( k = 1.37 \pm 0.05 \text{(stat.)} \pm 0.33 \text{(sys.)} \) with \( \chi^2/\text{dof} = 1.2 \).

DELPHI has performed a search for a narrow baryonic resonance in the proton–kaon system, motivated by recent reports of such resonances with strangeness \( S = +1 \) with a mass of about 1540 MeV/c^2 by several experiments. Such a resonance would be a candidate for a pentaquark state \( \Theta^+ \). If such a state is produced at LEP1 like an ordinary baryon, its production rate per hadronic event should be similar to that of the \( \Lambda(1520) \), which is 0.0224 ± 0.0027. The left plot of Figure 2 shows the \( pK^- \) invariant mass observed by DELPHI in the data taken at the Z-peak. A resonance consistent with the \( \Lambda(1520) \) is observed, demonstrating the ability of the experiment to reconstruct such states with the available data sets. No resonance structure is observed in the \( pK^0 \) invariant mass spectrum shown on the right hand side of Figure 2.

To extract a limit on the average multiplicity of the \( \Theta^+ \) a mass scan is performed in the region between 1520 MeV/c^2 and 1560 MeV/c^2. The upper limit at 95% C.L. on the average multiplicity of the \( \Theta^+ \) is \( \langle N_{\Theta^+} \rangle < 0.015 \). The \( pK^- \) spectrum was studied in a similar way. Again no resonance structure was observed. A mass scan in the region between 1500 MeV/c^2 and 1750 MeV/c^2 yields an upper limit at 95% C.L. on the average multiplicity of the \( \Theta^{++} \) of \( \langle N_{\Theta^{++}} \rangle < 0.06 \).

2 Puzzling disagreements of theory and experiments

QCD has been very successful in recent years in describing high energy hadronic processes such as jet production in \( e^+e^-\), \( ep \), and \( pp \) reactions. It is all the more important to pinpoint and study areas where discrepancies persist. Such areas exist for example in the hadronic interactions of two photons, as studied at LEP2. L3 has studied the production of charged and neutral pions up to the highest \( e^+e^- \) center-of-mass energies available at LEP2. The left plot in Figure 3 shows the transverse momentum spectrum of charged pions for two values of \( W \), the hadronic invariant mass of the photon-photon system. In each case it is evident that the corresponding
calculation in next-to-leading order (NLO) QCD fails to describe the data for momenta larger than about 4 GeV. At the highest charged particle momenta measured the theory underestimates the data by more than an order of magnitude. A similar measurement by L3 of neutral pion production\(^9\) leads to the same conclusions. Yet the presence of high momentum particles should indicate the presence of a hard scale, and the perturbative calculation should be reliable. The discrepancy can therefore not easily be understood in terms of the NLO calculation on parton level. Furthermore at high momenta the interaction of two photons is expected to be dominated by the so-called direct process, i.e. the exchange of a fermion, such that uncertainties in the knowledge of the photon structure are not expected to be very important. To compare the parton level calculation to the data, it is folded with the appropriate fragmentation function. While it is not expected that fragmentation effects could explain discrepancies of this magnitude, it is interesting to study the same process by different means. L3 has also measured the production of single jets in photon-photon collisions\(^10\). The right plot of Figure 3 shows the transverse momentum spectrum of the jets, again compared to a calculation at NLO QCD. As in case of the particle spectra, the theory underestimates the data significantly at high transverse momenta.

One has to conclude that these discrepancies are very significant, and at present not understood.

Discrepancies between theory and experiment are observed as well for the total hadronic cross section of b-quark production in photon-photon collisions. In this case the relatively large mass of the b-quark should provide the required hard scale for perturbative calculations. Three measurements now exist using LEP2 data\(^11\). The experimental results are consistent with each other and are between 2.5 and 4 standard deviations above the calculation in NLO QCD. While much progress has been made in the description of b cross sections in \(p\bar{p}\) collisions at the Tevatron\(^12\), no solution is in sight yet for photon-photon collisions. It should be noted however, that large extrapolations are necessary to extract the total cross section from the measured distributions. It would be desirable to compare theory and experiment in a restricted phase space directly accessible experimentally.

Figure 3: The transverse momentum spectra of charged pions for two values of the invariant mass \(W\) of the hadronic system (left) and the transverse momentum spectrum of single jets (right) as observed by L3.
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