QCD PHYSICS AT LEP 2

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Abstract

I will discuss, in a concise way, the main objectives of QCD studies at LEP 2.

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1. Introduction

I was nominated by the Program Committee of this wonderful conference to play the role of a scapegoat by covering the prospects for QCD studies at LEP 2. Focusing on this subject one immediately becomes an easy target for sceptics. The scepticism is rooted in the unfriendly statistics of hadronic events which limits the potential of high accuracy measurements at LEP 2. Recall that with total integrated luminosity of 500 pb$^{-1}$ per experiment[1,2] the rates of annihilation events will be reduced considerably, typically by 3 orders of magnitude, as compared to the $Z^0$ peak. There is also a somewhat psychological problem. Contrary to the exciting prospects for Higgs searches or studies of New Physics, the QCD program deals with the standard, so-called “down-to-earth” physics. Moreover, up to now the perturbative QCD scenario has worked too well, see e.g. Refs. [3-5]. In some sense QCD is a victim of its own successes.

I cannot resist mentioning that although LEP 2 will start operating in about two years, its physics program until now has not been of primary interest and the efforts of the theoretical community have been concentrated mainly on the far more distant NLC, see e.g. [6,7].

Now let us move on to the sunny side. After all, at LEP 2 we enter an unexplored energy region and there are definite advantages here over the existing $e^+e^-$ colliders even for the standard QCD studies.

1. One would expect a higher credibility for the perturbative predictions since the sub-asymptotic corrections become less important. At the same time, since multiplication in the QCD cascades grows quite rapidly with increasing energy ($\sim e^{\sqrt{E_{\text{tot}}}}$), the nontrivial perturbative predictions[8,9] should become more spectacular.

2. Collimation of a jet around the parent parton momentum grows as energy increases. Moreover, the collimation of an energy flow grows much more rapidly compared to a multiplicity flow. This is of special interest when studying the dynamics of interjet particle production, see [9] for details.

3. LEP 2 can provide a remarkable laboratory for testing QCD in photon-photon reactions. Both effective energy and luminosity of $\gamma\gamma$ collisions are here higher than at LEP1. At the same time the background due to annihilation events is incomparably smaller.

4. Some interesting vistas on QCD studies arise in hadronic $W^+W^-$ and $Z^0\gamma$ events.
5. LEP 2 results will provide a testing ground for the experiments at the future NLC facilities.

6. Recall also the important subsidiary role of the QCD processes. They are always going to give a background to whatever other physics one is interested in. Therefore their detailed knowledge is quite mandatory.

There are some auxiliary virtues of LEP 2 for QCD tests.

1. The operation is expected to start from the $Z^0$ resonance. This will provide especially good calibration for many technical and physical purposes.

2. The $b$-tagging efficiency is expected to be stretched to the limit. This is driven, first of all, by its crucial role in Higgs identification at LEP 2.

Finally, recall that the $W^+W^-$, $Z^0\gamma$ processes, which are interesting in their own right, will complicate a comparison of event characteristics with QCD. However, it seems that the appropriate experimental cuts will not introduce major additional distortions of the QCD expectations, see e.g. [6,7].

2. Standard QCD Tests

Hadronic final states of high energy $e^+e^-$ annihilation have traditionally been a fruitful testing ground for QCD. We discuss here the standard QCD tests from studies of the hadronic jet profiles. We concentrate on the aspects of the so-called semisoft and hard QCD physics.

2.1. QCD studies in the semisoft region

During the past years LEP, SLC and TRISTAN have provided an exceedingly rich source of information on QCD jets, see [3-5]. Moreover, the first experimental tests of the QCD cascading picture and, in particular, of the spectacular colour coherence effects have been successfully performed at the Tevatron\textsuperscript{10} and at HERA\textsuperscript{11}. The data demonstrate fairly good agreement with the results of the analytic perturbative approach (MLLA + LPHD)\textsuperscript{8} which has been developed in the last decade by the international CIS collaboration\textsuperscript{2}.

\textsuperscript{2}CIS $\equiv$ Columbia University/Cambridge-Italy-St. Petersburg (the names can be found in [8]). The name of this collaboration has been changed following the renaming campaign in the FSU.
The well-developed Monte-Carlo programs based on a QCD parton shower mechanism (the so-called WIG’ged MC’s\(^3\)) describe the existing data very successfully and provide very useful tools for experimentalists. Despite the fact that all these models are of a probabilistic and iterative nature, up to now their predictions for the gross jet characteristics have been in peaceful coexistence with the analytic results. Unfortunately, LEP 2 does not appear to be the best place to observe the breakdown of this coexistence (for discussion of the subtle QCD collective phenomena see refs. [8,9]).

Much of the semisoft physics is concerned with distributions and correlations of particles in jets in circumstances where colour coherence is important. The coherent effects give rise to the so-called hump-backed shape of particle spectra. This striking perturbative prediction is very well confirmed experimentally (see e.g. [12]). The analytic results for particle spectra can be expressed in terms of confluent hypergeometric functions\(^8\). The simplified version, in the case when the cutoff parameter in cascades \(Q_0 = \Lambda\) (the so-called limiting spectrum), is quite convenient for numerical calculations. In the context of the LPHD picture the limiting formulae are applied for the description of \(\pi\)’s and for all charged particle spectra\(^{13}\). To approximate the distributions of identified massive hadrons the partonic formulae truncated at the different \(Q_0\) values can be used. One can encode the MLLA effects in terms of a few analytically calculated shape parameters by means of the distorted Gaussian \((\ell = \ell n(1/x_p), \delta = (\ell - < \ell >/\sigma)\)\(^{13,14}\):

\[
\bar{D}(\ell, Y, \lambda) = \frac{N(Y, \lambda)}{\sigma \sqrt{2\pi}} \exp \left[ \frac{1}{8} k - \frac{1}{2} s \delta - \frac{1}{4} (2 + k) \delta^2 + \frac{1}{6} s \delta^3 + \frac{1}{24} k \delta^4 \right].
\]

Here \(Y = \ell n(E/Q_0), \lambda = \ell n(Q_0/\Lambda), 2E = W\), the total c.m.s. energy.

An important measure is the position of the maximum of the spectrum, \(\ell_{\text{max}}\). For the limiting case, the energy dependence is

\[
\ell_{\text{max}} = Y \left[ \frac{1}{2} + \sqrt{\frac{C}{Y} - \frac{C}{Y} + ...} \right]
\]

with \(C = 0.2915(0.3513)\) for \(n_f = 3(5)\). This is in surprisingly good agreement with the observed energy evolution of the peak position, see Fig. 1. It is predicted that for the truncated distributions the energy dependence of \(\ell_{\text{max}}\) is practically universal and the difference in \(Q_0\) values leads only to approximately constant shift of the peak\(^{13}\). Measurements at LEP 2 could

\(^3\)WIG = With Interfering Gluons (HERWIG, JETSET, ARIADNE).
provide a new insight in studies of the perturbative universality for different particle species. An intriguing puzzle, intimately related to the various aspects of the LPHD concept, is the unravelling of the connection between $Q_0$ and the particle masses and their quantum numbers.

The energy evolution of particle distributions in the energy region from PETRA/PEP to NLC is illustrated in Fig. 2. It clearly demonstrates the rise of $\ell_{max}$ with increasing $W$ and a fast growth of the hump height reflecting the rise of jet multiplicity. The exploration of LEP 2 energy domain would provide the possibility of further tests of the underlying cascading dynamics of multiple hadroproduction in jets.

We turn now to studies of the properties of heavy flavour jets. The analytic perturbative formulae\cite{15} allow one to predict the inclusive distribution of a heavy quark $Q$. They account for all significant logarithmically enhanced contributions in high orders including the two-loop anomalous dimension and the proper coefficient function with exponentiated Sudakov-type logs, as well as the controllable dependence on the heavy quark mass $M_Q$. These results are expected to describe the energy distributions averaged over heavy-flavour hadron states. Such a situation naturally appears, e.g., when studying inclusive hard leptons from heavy quark initiated events. Confronting the perturbative results with the data allows one to determine the scale parameter
Λ and to quantify the low-momentum behaviour of the effective coupling. The first comparison of perturbative predictions with the experimentally measured mean scaled energies $<x>_{c,b}$ at different $W^{[16]}$ looks rather encouraging. Further studies in the wide energy region could be quite instructive. At LEP 2 one can expect about a hundred identified $b \rightarrow$ lepton events and a precision in measurements of $<x_{b\rightarrow\text{lepton}}>_{17}$ at the 1% level.

The mean multiplicity in $e^+e^- \rightarrow Q\bar{Q}$ can be expressed in terms of the multiplicity in light quark production as$^{[15,18]}$

$$\Delta N^{QQ}(W) = N^{q\bar{q}}(W) - N^{q\bar{q}}(\sqrt{e}M_Q) + O(\alpha_s(M_Q^2)N(M_Q))$$

with $\Delta N$ the accompanying hadron multiplicity. An immediate consequence is that the difference $\delta_Q$ between particle yields from $q$ and $Q$-jets remains $W$ independent. This QCD result contradicts the naive expectation

$$\Delta N^{QQ}(W) = N^{q\bar{q}}(W(1 - <x>_{Q}))$$

according to which $\delta_Q$ would be a decreasing function of $W$. The existing data on $b$-quarks are consistent with the MLLA and the hypothesis (4) appears to be disfavoured$^{[19]}$. Further detailed
measurements, especially with $c$-quark events, could provide stringent tests of MLLA-LPHD predictions. The study of $b$-quark events at the energies of LEP 2 looks rather promising. In this region the naive formula (4) predicts a negative value of $\delta_b$ (about $-(3/4)$) in marked contrast with the LEP 1 result ($\langle \delta_b \rangle_{\text{exp}} \sim 3$).

Finally, let us mention that LEP 2 could be a useful laboratory for further studies of colour-related interjet phenomena, such as the celebrated string/drag effect in 3-jet events.

2.2. Hard QCD physics

Studies of hard QCD usually concern measurements of the jet production rates, hadronic event shapes, energy correlations etc., see [3,4]. We shall illustrate here the potential of LEP 2 to examine the running of the strong coupling constant basing on the 3-jet event production rate $R_3$. The foreseen luminosity of 500 pb$^{-1}$ would provide measurement of the ratio $\frac{\alpha_s(\text{LEP2})}{\alpha_s(\text{LEP1})}$ with a statistical error of about 2%[3].

A summary of measurements of $R_3$ is presented in Fig. 3 borrowed from [4]. As one can easily see, the high-order terms affect the energy dependence of $R_3$ only slightly. The existing data provide quite convincing evidence for the logarithmic decrease of $\alpha_s$. The significance
will be much increased with the measurements at LEP 2. Here the possibility to use the same detector (in order to eliminate experimental point-to-point uncertainties) in a wide energy range is especially beneficial. I would like to stress that I do not belong to the “light gluino club”. The gluino curve in Fig. 3 aims only to demonstrate the potential of LEP 2 and NLC for this type of study (see Ref. [4] for details and references). It is important to achieve the precision necessary to distinguish between the standard QCD and the scenarios like light gluino hypothesis.

3. Hadronic $W^+W^-$ Events and Colour Rearrangement Effects

QCD interference effects between $W^+$ and $W^-$ undermine the traditional meaning of a $W$ mass in the process $e^+e^- \rightarrow W^+W^- \rightarrow q_1\bar{q}_2q_3\bar{q}_4$. Specifically, it is not even in principle possible to subdivide the final state into two groups of particles, one of which is produced by the $q_1\bar{q}_2$ system of the $W^+$ decay and the other by the $q_3\bar{q}_4$ system of the $W^-$ decay: some particles originate from the joint action of the two systems. Since a determination of the $W$ mass is one of the main objectives of LEP 2, it is important to understand how large the ambiguities can be. A statistical error of 55 MeV per experiment is expected\textsuperscript{[1,2]}, so the precision of the theoretical predictions should match or exceed this accuracy. A complete description of interference effects is not possible since non-perturbative QCD is not well understood. The concept of colour reconnection/rearrangement is therefore useful to quantify effects. In a reconnection two original colour singlets (such as $q_1\bar{q}_2$ and $q_3\bar{q}_4$) are transmuted into two new ones (such as $q_1\bar{q}_4$ and $q_3\bar{q}_2$). Subsequently each singlet system is assumed to hadronize independently according to the standard algorithms. Depending on whether a reconnection has occurred or not, the hadronic final state is then going to be somewhat different. The reconnection effects were first studied in Ref. [20] but these results were mainly qualitative and were not targeted on what might actually be expected at LEP 2. The picture in [20] represents an example of the so-called instantaneous reconnection scenario, where the alternative colour singlets are immediately formed and allowed to radiate perturbative gluons. For a detailed understanding of QCD interference effects in $W^+W^-$ events one needs to examine the space-time picture of the process. A systematic analysis of QCD rearrangement phenomena in $W^+W^-$ events has been performed in Ref. [21] (see also [22]). It was shown that interference is negligibly small for energetic perturbative gluon emission. Firstly, the $W^+$ and $W^-$ decay at separate times
after production, which leads to large relative phases for radiation off the two constituents of a rearranged system, and a corresponding dampening of the QCD cascades\cite{23}. Secondly, within the perturbative scenario the colour transmutation appears only in order $\alpha_s^2$ and is colour-suppressed. It was concluded that only a few low-energy particles could be affected. In order to understand the reconnection effects occurring at the non-perturbative hadronization stage, the standard Lund fragmentation model\cite{24} has been considerably extended and several alternative models for the space-time structure of the fragmentation process have been developed. Comparing different models with the no-reconnection scenario, it turns out that reconnection effects are very small. The change in the averaged charged multiplicity is at the level of a percent or less, and similar statements hold for rapidity distributions, thrust distributions and so on. The total contribution to the systematic error on the $W$ mass reconstruction may be as large as 40 MeV. This is good news. Otherwise, LEP 2 would not have significant advantages in the measurements of $M_W$ over hadronic machines where the accuracy is steadily improving\cite{25}.

Let us emphasize that in view of the aimed-for precision, 40 MeV is non-negligible. However, remember that as a fraction of the $W$ mass itself it is a half a per mille error. Reconnection effects are therefore smaller in the $W$ mass than in many other observables, such as the charged multiplicity etc.

Clearly, colour rearrangement effects are interesting in their own right, for instance, as a new probe of the non-perturbative QCD dynamics\cite{20–22}. However, the standard measures considered in \cite{21} seem to be below the experimental precision one may expect at LEP 2. A more optimistic conclusion has been reached in Ref. \cite{22}, where some specific ways to disentangle colour reconnection phenomena were proposed. But personally I still believe that one will need good luck in order to establish the nature and size of the QCD rearrangement effects in real-life experiments.

4. Gamma-gamma Topics

One of the most promising areas for QCD tests at LEP 2 will be the study of photon-photon collisions in the processes $e^+e^-\rightarrow e^+e^-+\text{hadrons}$. Two-photon physics is a remarkably rich subject, having elements in common with both $e^+e^-$ and hadron-hadron collisions. Photons can interact in different ways: as vector mesons, as partons, or through their quark-gluon content.
There has been a lot of recent activity in this field covering various aspects of $\gamma\gamma$ physics\(^4\). I have not much to add to the existing comprehensive studies and I will only enumerate here a few topics where some significant progress is expected from the measurements at LEP 2.

1. Studies of the photon structure function $F_2^\gamma(x, Q^2)$

   This classic probing of QCD in $\gamma\gamma$ collisions can be extended at LEP 2 to the higher regime of $Q^2$ up to $\sim 10^3$ GeV\(^2\) (for some details see Ref. [30]). Further definite tests of the QCD prediction that $F_2^\gamma$ rises linearly with $\log Q^2$ can be made here. At the same time, one can go down significantly further in $x$ ($x_{\text{min}} \geq 0.0015$ for $Q^2 = 15$ GeV\(^2\)). One of the challenging tasks here is to find a rapid rise of $F_2^\gamma$ at low $x$ analogous to that reported by experiments at HERA. The measurements would provide important information on the low-$x$ dynamics which is now a field of strong theoretical interest.

2. One of the interesting $\gamma\gamma$ topics at LEP 2 is the exploration of heavy quark production in the newly accessible region. This process has been analysed in detail in Ref. [31]. The interest in this subject has been boosted by the new measurements from TRISTAN, indicating a possible excess of open charm production over the QCD calculations, see Ref. [27].

3. The production of jets (and multi/mini jets)

   Here the combination of different processes (VDM-like, direct, resolved) provides one with the extra degrees of freedom in testing QCD theory. This subject by itself is a vast phenomenological field and it needs special detailed reviewing. It is worth mentioning that especially in the case of the so-called minijet production, the uncertainties in calculations are still quite large\(^3\).

4. Traditional studies of $\gamma\gamma$ cross-sections and global event properties, and their comparison with $pp$ and $\gamma p$ events. More activity (transverse energy flow, multiplicity, jet rate ...) is predicted in $\gamma\gamma$ events than in $\gamma p$ and $pp$ ones, see Ref. [28]. Fig. 4 illustrates the $\frac{dE_T}{dy}$ flow for $\gamma\gamma$ c.m. energy of 25 GeV. Further interesting issues can be addressed when

\(^4\)Recent reviews of theoretical and experimental results are given in Refs. [26-29] and in the proceedings of the International Workshops on photon-photon collisions.
either photon or both of them are virtual. This would open a quite new window on the structure of the photon.

5. Summary

This talk represents a (rather biased) attempt to highlight the potential of LEP 2 for QCD studies. The main conclusion can be stated as follows. With a lot of work and some luck, LEP 2 will still have much to teach us about QCD physics.

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**Figure Captions**

Fig. 1 Energy evolution of the peak position compared to a prediction of Eq. (2).

Fig. 2 $\ln \frac{1}{x_p}$ distribution of charged particles at $W = 30,90,200$ and $500$ GeV computed with the JETSET program (recall that the spectra are practically blind/democratic towards the WIG’ged MC’s). The figure is borrowed from the presentation of G. Cowan in [6].

Fig. 3 Energy dependence of $R_3$ (JADE algorithm, $y_{cut} = 0.08$) compared with analytic QCD calculations and with the hypothesis of the existence of a light gluino.[4]

Fig. 4 Transverse energy flow at $E_{cm} = 25$ GeV as a function of rapidity for different beams.[28] 
$\gamma\gamma$: full histogram; $\gamma p$: dashed one; and $pp$: dash-dotted one.
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