7 QCD, $\gamma\gamma$, and charm

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This section describes standard model physics, not covered elsewhere in the report, that could potentially be studied with the high luminosity option of LEP (HLEP) operating near the Z^0 resonance. We have tried to be fairly comprehensive and therefore examine a number of quantities that do not obviously benefit from the addition of high luminosity. In this way it is hoped to to give a realistic picture both of the limitations and benefits to be obtained.

7.1 QCD Physics

Standard QCD phenomena are expected to vary smoothly with energy. The Z^0 peak therefore stands out only by virtue of providing a high event rate, not by any unique physics aspects of that particular energy. Although most QCD studies could be done with 10^6 Z^0:s or less, there exists topics where larger event samples are required.

Many QCD studies would profit from using the highest possible energy, and from having data samples at different energies. For these studies, the limit will therefore not be the number of Z^0 events, but the number that can be produced at higher energies. The high-luminosity LEP option is therefore particularly interesting to consider in this connection.

For the study of the foundations of QCD, like the presence and form of three- and four-gluon vertices, one is hampered by the fact that there exists no viable alternative to QCD. It is therefore difficult to quantify what statistics is needed if one wants to 'prove' QCD by excluding 'the alternatives'. In the following we will mention the Abelian toy model as an alternative but, quite apart from internal consistency problems, this model is already excluded by the observed running of α_S with CM energy [1].

As a final, general comment, one must remember that the exploration of QCD is an iterative procedure, to a much larger extent than that of the electroweak theory. We will therefore be in a much better position to assess the usefulness of 10^8 Z^0:s once the first batches of data have been analyzed, and interesting discrepancies between models and data begin to show up.

7.1.1 QCD at the Z^0 Peak — Ordinary Processes

QCD phenomena are, as a rule, not rare ones. The natural expansion parameter in QCD studies is α_S. If jets are required to be well separated, one finds three-jet fractions of order $\alpha_S \approx 0.1$, four-jet fractions of order $\alpha_S^2 \approx 0.01$, etc. If less restrictive jet resolution parameters are used, the multi-jet (i.e. not two-jet) fraction is dominant. In fact, in QCD parton shower based models the data support the use of a cutoff in the 1–2 GeV scale, i.e. with an average parton multiplicity of around 8–10.

The perturbative phase is followed by a nonperturbative one, in which the partons fragment into hadrons, which in their turn may decay further. Since nonperturbative QCD remains unsolved, one here has to rely on (tuned) phenomenological models for fragmentation and decays. For calorimetrically defined quantities, the influence of the

Table 1: Number of events that survive quark jet tagging criteria. For further details, see text.

	3 jets	4 jets
no. of events generated	25000	25000
... with acceptable jets	5382	1040
... with lepton(s) in event	679	124
... with lepton(s) in jets	629	112
1 jet with lepton(s), correct	550	100
1 jet with lepton(s), false	15	3
2 jets with leptons, correct	63	9
2 jets with leptons, false	1	0

nonperturbative aspect should decrease as the CM energy is increased, but fragmentation effects are still non-negligible even at the highest LEP energies.

For the study of global event measures, like thrust or sphericity, every event gives a non-vanishing contribution. The same holds true for simple one particle distributions, like longitudinal and transverse momentum spectra, and also for a number of inclusive correlation measures, like the energy-energy correlation and its asymmetry. The limiting factor is then likely to be, not the statistical errors, but the systematic ones. The experimental systematic errors reflect the loss of particles down the beam pipes or in cracks, track reconstruction efficiencies, energy/momentum reconstruction errors, etc. If one wants to correct for these errors, it is necessary instead to put faith in the Monte Carlo programs used to generate physics events, and in the programs used to simulate the subsequent detector response.

The feeling in the LEP groups seems to be that, for inclusive measures like the ones listed above, already current statistics, i.e. in the order of some 10^4 events, gives statistical errors about as small as the systematic ones. To improve on this, it is necessary to achieve both an improved modelling of perturbative and nonperturbative QCD theory aspects, and a better understanding of the detectors. Ultimately, the break-even point might be at a few 10^5 events.

For the exploration of rare corners of phase space, one may profit from higher statistics. One example is the shape of the fragmenation function close to the kinematic limit, and the relative composition of $\pi/K/p$ among charged particles in this region. Another example is correlations among pairs or triplets of particles, such as $p\overline{p}$, $p\overline{\Lambda}$, $\Lambda\overline{\Lambda}$, $\Lambda\overline{p}K$, $\Xi\overline{\Lambda}K$, or ΞKK, which will provide information on the nature of the fragmentation mechanism. Finally, one might mention the detailed exploration of production properties of rarely produced particles, such as Ω^- and (anti)deuterons.

In many QCD studies, it would be of great interest to have 'tagged' three- or four-jet events, i.e. events in which it is known which are the quark/antiquark jets and which the gluon jet(s). For three-jet events, the main applications are to be found in the study of various coherence phenomena, see e.g. [2,3]. For four-jet events, a detailed study of the three-gluon coupling is on top of the list, using various angular distributions [4]. The most obvious tag method is prompt lepton (μ/e) production in semileptonic decays of charm and bottom hadrons.

In Table 1 is presented results of a Monte Carlo study of event rates, using the

JETSET 7.2 program [5]. Out of the 25000 events generated, the second line shows how many events were found with the right number of jets (using the JETSET cluster algorithm to construct the requested number of jets, but then requiring each jet to have a minimum energy of 10 (8) GeV and all jet-jet opening angles to be above 60° (50°) for three-(four-)jets). The third gives the number of events that contain a lepton above 3 GeV, once e^+e^- and $\mu^+\mu^-$ pairs with an invariant mass below 0.5 GeV have been removed, and the fourth those where these leptons are found only inside 20° cones around the jet axes. These latter events are then divided into four classes, depending on whether one or two jets contain leptons, and on whether these jets then are the two that contain the initial q or $\overline{q}$ (correct) or not (false). Contamination from false assignments appears to be small, contrary to the case for conventional methods based on assuming the lowest-energy jets to be the gluon ones.

If a 50% experimental efficiency for lepton identification is added, the end result is thus a fraction 10^{-3} (10^{-4}) of doubly tagged three-(four-)jet events. Even with normal luminosity one may thus expect roughly 5000 (500) events, which should be enough to reach the limit of systematic errors, although having more tagged four-jet events could prove useful.

One interesting topic might be to tag five-jet events in a corresponding manner. It seems highly doubtful that the presence of the four-gluon coupling could be established at all at LEP, given that its contribution to the total five-jet rate is very small, but at least one might want to establish that five-jet events have the expected angular distributions. Since this would probably mean another order of magnitude reduction of rate compared to the four-jet figure, a high-luminosity LEP option would here be essential.

The non-Abelian nature of QCD might also be tested by a study of the flavour composition of four-jet events, which is dramatically different in an Abelian toy model: the ratio $N(q\overline{q}q'\overline{q}')/N(4\text{ jets})$ is increased by about a factor of 10 compared to standard QCD, from roughly 4% to 40%, using suitable cuts for well separated jets. The main reason is that the group factor T_R is increased from $n_f/2$ in QCD to $3n_f$ in the toy model; in addition the rate of $q\overline{q}gg$ events is reduced by the absence of the three-gluon vertex ($N_C = 0$ rather than 3) and the smaller rate of double gluon bremsstrahlung ($C_F = 1$ rather than 4/3).

One method to study the rate of $q\overline{q}q'\overline{q}'$ is to consider the production of heavy flavours, like $b\overline{b}b\overline{b}$ events, as suggested by Z. Fodor. With four-jet cuts that retain roughly 3% of the total number of hadronic events, the fraction of four-jet events where one jet is a b one is increased from 21.1% in QCD to 31.4% in the non-Abelian model; for events with two b quarks the rate is increased from 0.17% to 2.24% [6]. Note that, to study the latter number, it is important to be able to distinguish b from $\overline{b}$: obviously the rate of $b\overline{b}$ pairs, as opposed to bb ones, is equal to the single b rate (to be precise, a tiny bit larger, by combinatorics in $b\overline{b}b\overline{b}$ events).

The size of the observable $b\overline{b}b\overline{b}$ signal thus depends strongly on the probability to tag b jets, also against the c background (from $c\overline{c}c\overline{c}$ and $b\overline{b}c\overline{c}$ events, and from $b \to c$ decays), and on the probability to distinguish b from $\overline{b}$. As an example, to use the lepton flavour tagging scheme of Table 1, with the additional requirement that two jets contain a same sign lepton pair, does not give a significant separation between QCD and the Abelian model. If one optimistically assumes that vertex tagging techniques could give a 10% b quark tagging efficiency (including the $b/\overline{b}$ separation), then 10^7 hadronic Z^0

events corresponds to 10 doubly tagged bb or $\overline{b}\overline{b}$ events for QCD and 135 in the Abelian model, i.e. just enough to provide a reasonable test. The advantages of having 10^8 Z^0 events are here obvious.

7.1.2 QCD at the Z^0 Peak — Rare Processes

Observation of one or more exclusive Z^0 decays to quarkonia would provide useful information on bound state dynamics. Most calculations to date have been performed within the framework of nonrelativistic potential models. The applicability of such models at the large momentum transfers involved in Z^0 decays has, however, not yet been demonstrated. Moreover, there are final states containing light mesons where the quarkonium picture is not applicable at all. Alternative methods of calculation involve e.g. QCD sum rules or effective Lagrangians. A high-luminosity LEP option should enable at least a couple of these rare decays to be detected, and would therefore shed light on the nature of quark-antiquark bound states.

As an example, we first discuss $Z^0 \to V + \gamma$, where V is J/Ψ or Υ. These processes were first calculated in the nonrelativistic potential model by Guberina *et al.* [7]. They obtained branching ratios of around $5 \cdot 10^{-8}$ and $3 \cdot 10^{-8}$ for the two decays, respectively. Using instead an effective Lagrangian with a pointlike vector VQQ coupling determined by the V leptonic widths, the decays are governed by the anomalous triangle diagram, and we find $1.2 \cdot 10^{-7}$ and $3 \cdot 10^{-8}$, respectively. Taking into account also the higher excitations in the J/Ψ and Υ systems, these numbers should be multiplied by factors of around 1.05 and 1.5, respectively.

If one has to rely on the $V \to \ell^+\ell^-$ decay modes these rates are obviously too small to be detected. It therefore becomes necessary to turn to hadronic decay modes, where the non-resonant background may be nonnegligible: to a first approximation, the signal/background ratio for a given mass of the hadronic system is the same as for the contributions to $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ at the corresponding CM energy (this statement should hold for the hadronic states with $J^{PC} = 1^{--}$, with some modification when other partial waves are included as well). Thus a good mass measurement of the hadronic system is necessary if the peak is to stand out. Note that the recoiling photon energy is so close to the beam energy anyway, at least for the J/Ψ, that a photon energy measurement can not be used to derive the mass of the recoiling hadronic system. In conclusion, a measurement seems less than trivial, even with the maximum luminosity.

We may use the effective Lagrangian approach to calculate also the decays into light mesons, $Z^0 \to \omega + \gamma$, $Z^0 \to \rho + \gamma$. Since the decays go by the axial Z^0 couplings (by C invariance), there is a cancellation of the u and d quark contributions in the ρ case, but a constructive interference in the ω case. We obtain a branching ratio of around $6 \cdot 10^{-8}$ for $Z^0 \to \omega + \gamma$. Since the ω decays almost exclusively into $\pi^+\pi^0\pi^-$, one would get a 45 GeV γ recoiling against a narrowly collimated three-pion system. As in the case of the J/Ψ, to find the signal against the background may be difficult, however.

We note that the corresponding decays $Z^0 \to P + \gamma$ (where P is a pseudoscalar) are likely to be smaller in rate, as indicated by the nonrelativistic calculations [7,8]. Here the effective Lagrangian approach is likely to fail since there is a constant (anomaly) contribution which would make the rates unrealistically high. In reality, the amplitude should be cut off like $(\Lambda_{QCD}/m_Z)^2$, since the compositeness scale of the light mesons is governed by Λ_{QCD}. This indeed renders the rates essentially unobservable, 10^{-10} or smaller. (See, however, Ref. [9].)

Another interesting rare decay is $Z^0 \to ggV$ [10]. This process is related by crossing to $gg \to Vg$ and $gg \to V\gamma$, which are important processes for measuring the gluon structure function at high energy hadron colliders. A measurement of this type of process in the cleaner environment of an e^+e^- collider would give confidence to this gluon calibration scheme. In particular, one could get a handle on the relevant momentum scale in quarkonium production. There are indications [11] that a constant $\alpha_S(m_V^2)$ may fit the measured large p_T J/Ψ production better than the running $\alpha_S(m_V^2 + p_T^2)$ naively expected. In addition, there is a possibility of a 'K factor' around two also in the Z^0 decays. Taking all these factors into account, the branching ratio $Z^0 \to gg + \Upsilon$ (including excited Υ states) may be as large as $1.6 \cdot 10^{-6}$, or as small as $2 \cdot 10^{-7}$. In the former case, there is a fair chance of measurement (using the muon or electron decay channels of the Υ), whereas the latter rate is on the margin. Decays into J/Ψ should be of the same order of magnitude, but here the problem of background from B decays into J/Ψ is probably prohibitive.

Some other Z^0 decays involving quarkonia have recently been discussed in the literature [12]. These are of the type $Z^0 \to Q\overline{Q} + (Q\overline{Q})_{bound}$. The widths were found to be $\Gamma(Z^0 \to c\bar{c} + J/\Psi) = 47$ keV, $\Gamma(Z^0 \to c\bar{c} + \eta_c) = 145$ keV, $\Gamma(Z^0 \to b\bar{b} + \Upsilon) = 6.4$ keV, and $\Gamma(Z^0 \to b\bar{b} + \eta_b) = 6.5$ keV. The final states containing pseudoscalars unfortunately lack a distinctive signature, and J/Ψ production is dominated by B decays, but $Z^0 \to b\bar{b} + \Upsilon$ may possibly be detectable if micro vertex detectors are operational for reconstructing B decays.

The even rarer decay modes $Z^0 \to VV$ and $Z^0 \to PV$ have recently been calculated for the charmonium and bottomonium systems [13]. (The decay $Z^0 \to PP$ is strictly forbidden by Lorentz invariance and Bose symmetry.) As expected, the branching ratios turn out to be very small, around 10^{-12} for charmonium and 10^{-10} for bottomonium. A theoretically interesting feature is the fact that the longitudinal parts of the V polarizations contribute, meaning that the rate does not manifestly go to zero as $m_V \to 0$, as would be expected by analogy with Yang's theorem for $Z^0 \to \gamma\gamma$. This means that the higher order decays $Z^0 \to PV\gamma$ and $Z^0 \to VV\gamma$ (and $Z^0 \to PP\gamma$, which is now allowed) are probably of the same magnitude as the non-radiative decays. Anyway, this type of decays seems to be way beyond observability even at a high-luminosity LEP.

Another type of exclusive decays involving quarkonia in the final state is $Z^0 \to Vl^+l^-$ ($l = e$ or μ) [14]. This has a very clean signature and could in principle interfere with the search for weakly coupled (non-standard) Higgs particles. Of all possible diagrams contributing to order α^2 to this process, only those where the V meson is produced from a virtual photon radiated by the leptons are important. This means that the rate can be calculated essentially without ambiguities since the raditive part is given by QED and the $\gamma^* - V$ transition strengths are measured in the decays $V \to l^+l^-$.

Inserting the experimental values for the $V \to l^+l^-$ decay widths, the following predictions are found [14] for the branching ratios $B_V = \Gamma(Z^0 \to V\mu^+\mu^-)/\Gamma(Z^0 \to \mu^+\mu^-)$: $B_\rho = (2.8 \pm 0.1) \cdot 10^{-4}$, $B_\omega = (2.3 \pm 0.1) \cdot 10^{-5}$, $B_\phi = (3.6 \pm 0.1) \cdot 10^{-5}$, $B_{J/\Psi} = (2.0 \pm 0.2) \cdot 10^{-5}$, $B_\Upsilon = (6.3 \pm 0.2) \cdot 10^{-7}$, where the estimated errors come from the uncertainties in the measured values of the V leptonic decay rate.

The production mechanism of the vector mesons through the γ^* mixing means that

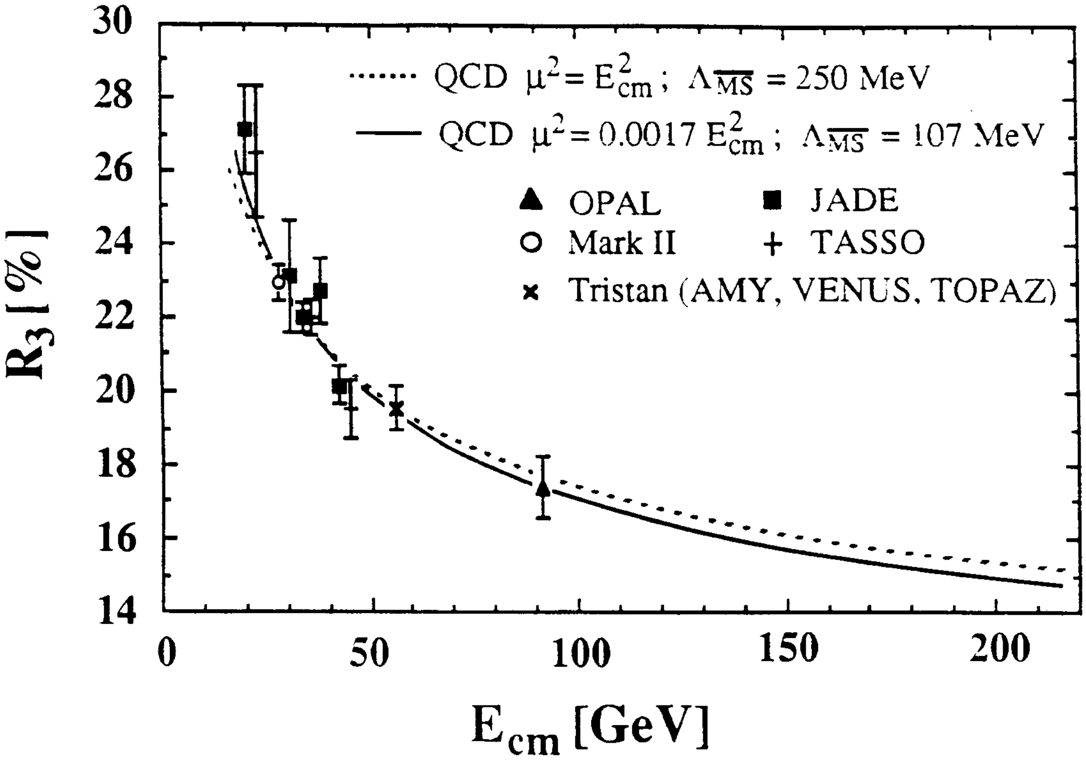


Figure 1: The three-jet fraction as a function of CM energy, with two different scenarios for the energy variation of α_S, and experimental data points. Some of the error bars shown are statistical only, while others include systematic errors as well. For normalization note that the OPAL point is based on 10^4 events [15], and that the inclusion of systematic errors has increased the error bar by roughly a factor 1.7 compared to the purely statistical error.

the differential distribution of the l^+l^- pair will be similar to that of ordinary QED radiation processes. In particular, the differential distribution in invariant mass will tend to peak at the highest values kinematically possible. Since the final state typically is a lepton pair plus a low multiplicity hadronic system, this type of process is a potential background to the Higgs search, as also Higgs radiation tends to give a lepton pair at high invariant mass. To discriminate between the processes one has to use the fact that the hadronic invariant mass here of course fits one of the known vector meson masses, or the fact that this background is non-existent in the $Z^0 \to H\nu\bar{\nu}$ channels.

7.1.3 QCD above the Z^0 peak

As we noted above, there is no *a priori* reason, within the framework of QCD, to prefer the Z^0 energy. Rather, many of the most interesting aspects are related to the energy variation of event properties, i.e. scaling violations. The running of α_S with CM energy has already been demonstrated experimentally up to LEP I energies [15]. It would here be useful to have two further CM energies available, say at 120 and 150 GeV, each with at least 10^4 multihadronic events, to match the error of the OPAL point of Fig. 1. In fact, since a number of detector uncertainties would divide out in a comparison between results at 90, 120 and 150 GeV, an even higher statistical sample would still be of use.

The presence of reasonably high-statistics measurements at a few (evenly spaced)

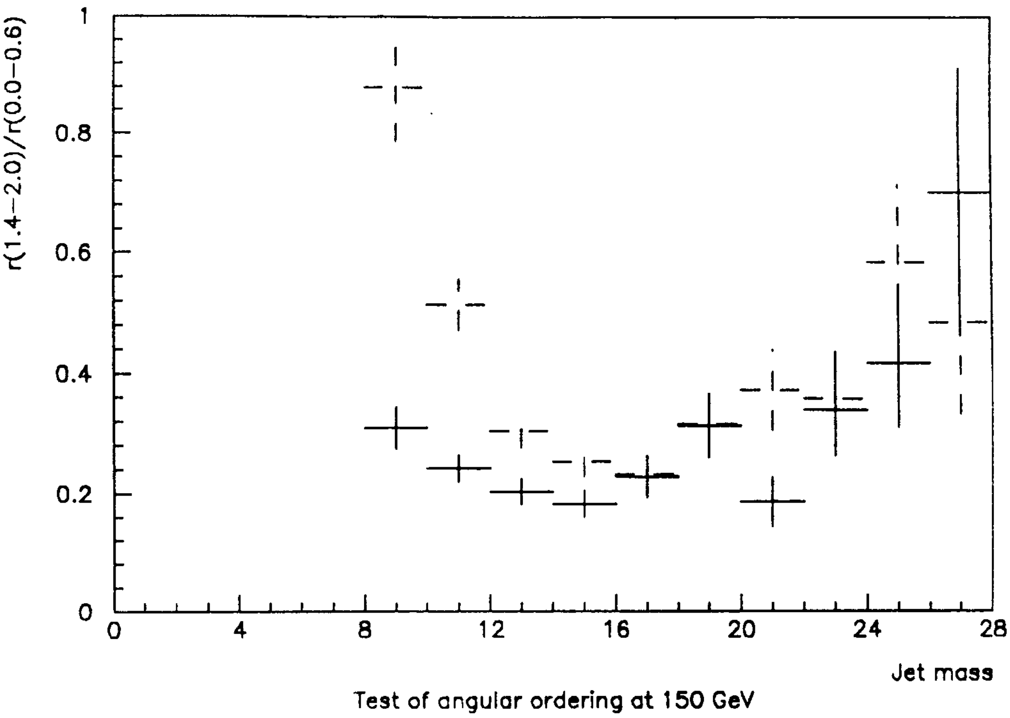


Figure 2: The fraction of R_r of nonordered to ordered branchings as a function of the mass m^* of the branching partons, using the algorithm described in the text. Full crosses give result with angular ordering and dashed without. Results are for 10000 events at 150 GeV (without initial state radiation); vertical bars indicate size of statistical errors.

energy points will also be useful for an extrapolation (directly or via tuning of Monte Carlos) into the region around and above the W^+W^- threshold: one might choose to rely only on the total event rate for a determination of the W^+W^- cross-section as a function of energy, but smaller errors should be achievable if hadronic events could be separated into γ/Z^0 and W^+W^- ones. And, of course, this separation ability becomes crucial for any study that would involve the angular orientation of jets from W^+W^- decays.

The number of jets that may be resolved increases with CM energy. There are therefore a number of multijet studies that require high statistics at the highest possible CM energy (either below the W^+W^- threshold or, if above, with the W^+W^- contribution removed) to be practicable. One example it the study of angular ordering in the shower evolution, as arising from QCD coherence effects [16,3]. While some aspects of QCD coherence may be studies at the Z^0 peak, the direct observation of angular ordering is not feasible, since systematic errors will be too large.

An explicit example of a possible analysis method is given in [17], to which we refer for details. Basically, a clustering algorithm is used to find the number of jets in an event, with the clustering scale set so low that also a possible 'subjet' structure is resolved. Thereafter, the two clusters with smallest invariant mass are successively joined into a new cluster, until only two clusters remain. The ordering in which this clustering procedure happens gives a 'mass-ordered' parton shower event history. It is now possible to study whether successive branchings in this history description also corresponds to angular ordered emissions or not. Specifically, for two consecutive branchings

$1 \rightarrow 2 + 3$, with opening angle θ_1, and $3 \rightarrow 4 + 5$, with opening angle θ_3, the ratio $r = \theta_3/\theta_1$ is studied. In an ideal world, r should always be less than unity in the angular ordering scenario, with no such constraint if coherence effects are not taken into account. Spurious cluster reconstruction and recombination will introduce contaminations. The ratio $R_r = n(1.4 < r < 2)/n(0 < r < 0.6)$ gives a measure of the fraction of nonordered branchings, disregarding the uncertain regions of r close to unity or very large. This ratio is shown plotted in Fig. 2, as a function of $m^* = m_3$, for models with and without angular ordering imposed on branchings. The region of large m^* values provides a control region, while the range $8 < m^* < 16$ GeV gives the best separation between the alternatives. The size of the error bars indicates the need for statistics in the order of 10^4 events at 150 GeV.

7.2 $\gamma\gamma$ Physics

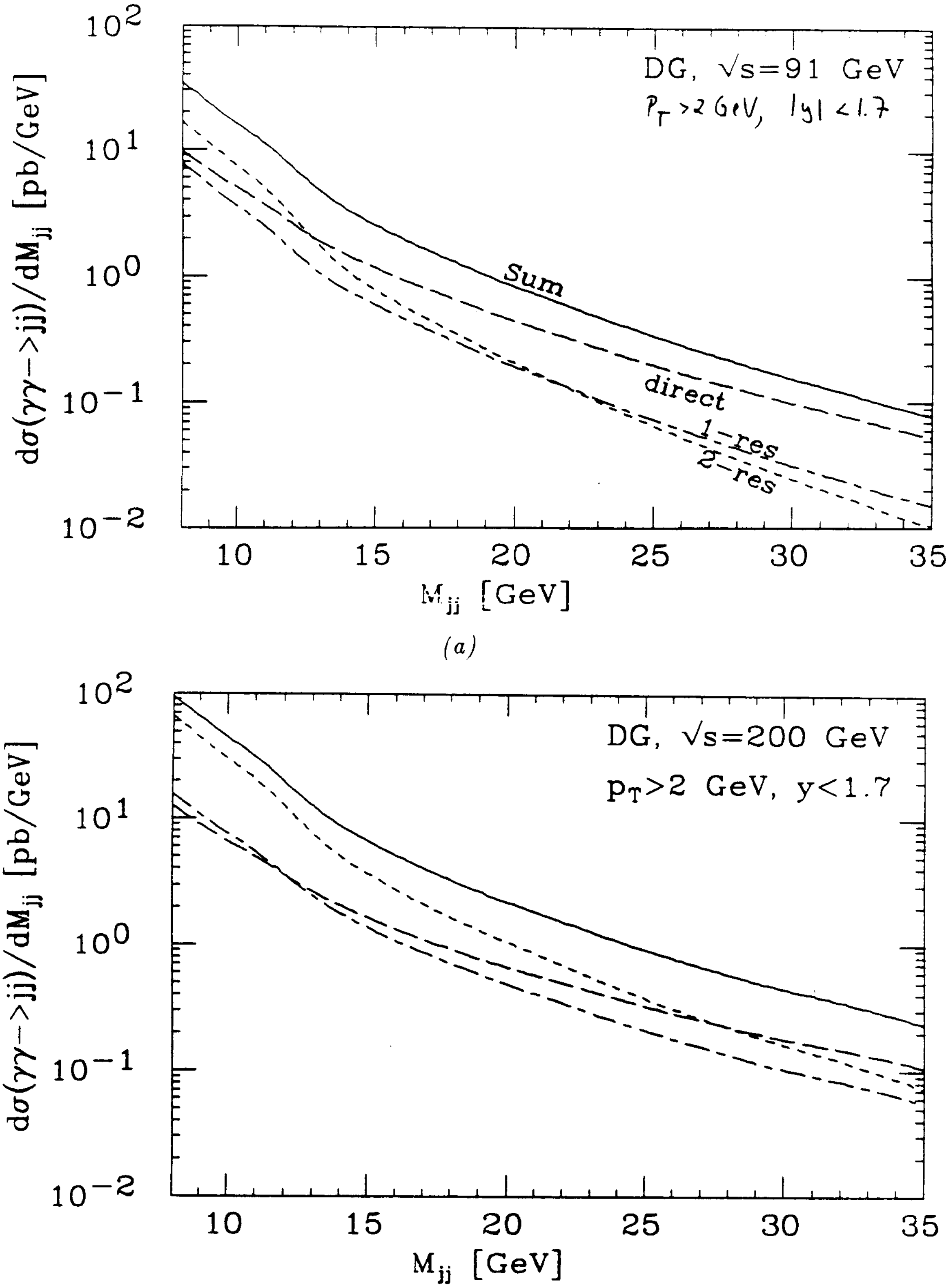
Two-photon physics differs from the physics of e^+e^- annihilation at LEP in two important respects:

- The existence of the Z^0 pole is a handicap rather than an opportunity; it increases potential backgrounds (which are totally negligible away from the peak) without increasing the signal.
- All cross-sections rise with the CM energy with at least some power of a logarithm. This is due to the logarithmic increase of the photon flux with the beam energy. Furthermore, in processes where at least one of the two photons is resolved into quarks and gluons ('resolved processes') the cross-section is proportional to the quark or gluon density inside the electron, which rises even faster with energy.

The question is then whether increasing the luminosity by a factor of ten at the Z^0 peak can compensate for the loss of cross-section (compared to running at the highest possible energy) and the drastic increase of the annihilation background.

Clearly an annihilation event can only be a background if a large part of the energy is lost, mainly due to incomplete detector coverage around the beam pipes. In other words, the background is given by events with at least one energetic jet going in the forward or backward direction. Presumably the outer fringes of this jet will still be detected, which allows for the possibility to discard all events of this type. However, a characteristic feature of all 'resolved' two-photon events is the occurence of forward/backward 'spectator' jets; this large and interesting class of processes could therefore not be studied if a veto against small-angle jets is used. Nevertheless, it seems possible to isolate the 'resolved' production of two high-p_T jets by requiring the p_T of the two jets to balance. More exclusive two-photon processes have usually even less annihilation backgrounds. We will therefore assume in the following that these backgrounds will not be an unsurmountable obstacle for doing $\gamma\gamma$-physics at the Z^0 pole, although they will undoubtedly make life somewhat more difficult.

In order to decide, whether the signal benefits more from an increase of the CM energy to 200 GeV or from an increase of the luminosity by an order of magnitude, we have computed the cross-sections of some relevant two-photon processes, focusing on reactions when both photons are (nearly) on-shell ('no-tag' situation). In Fig. 3 we compare the differential cross-sections for the production of two high-p_T jets as a function of the di-jet invariant mass at the two energies. The cut $p_T > 2$ GeV has



(a)

(b)

Figure 3: Di-jet invariant mass distribution at *(a)* 91 GeV and *(b)* 200 GeV, with cuts as described in the text. Long dashes is the direct (no-resolved) contribution, long-short dashes the once resolved, short dashes the twice resolved, and full the sum.

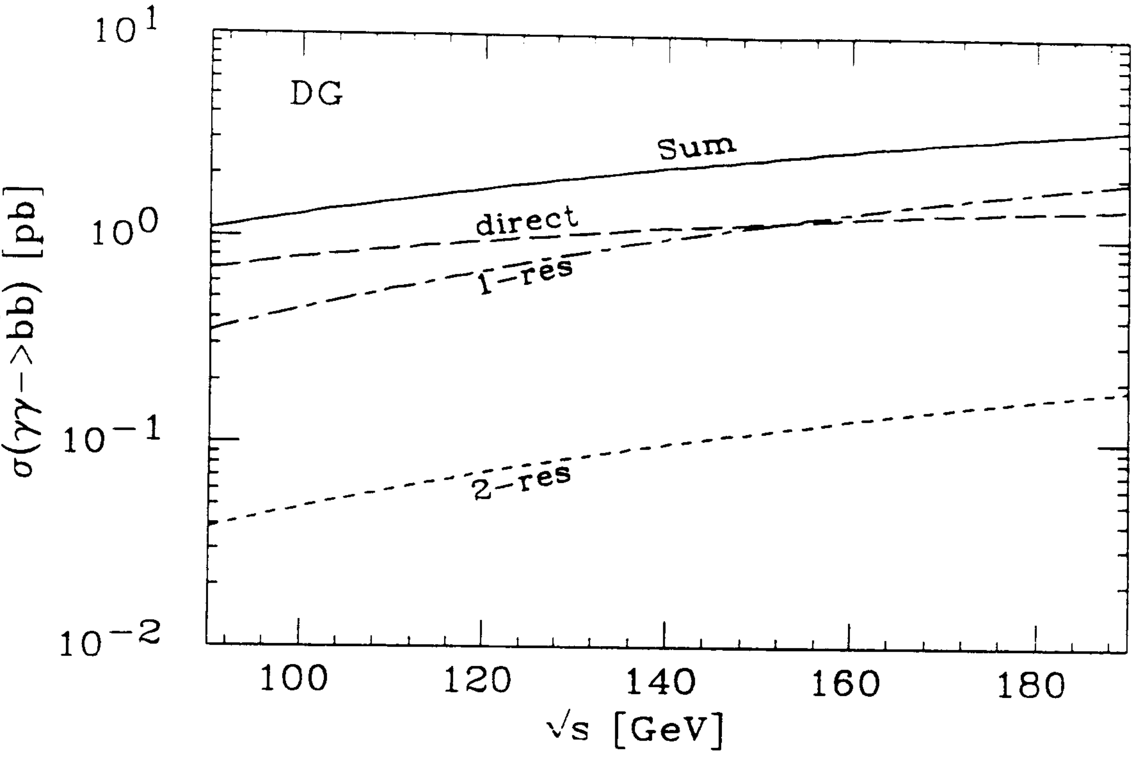


Figure 4: Total cross-section as function of CM energy for the production of $b\bar{b}$ pairs. Curves are labelled as in Fig. 3.

been implemented to assure the applicability (*cum grano salis*) of perturbative QCD, while the rapidity cut $|y| < 1.7$ ensures that both jets can be well reconstructed (in the ALEPH detector). The long-dashed, long-short-dashed, and short-dashed curves represent the contributions where none, one or both photons are resolved into quarks and gluons. The latter two classes of contributions are interesting because they depend on the hadronic structure of the photon, about which very little is known experimentally at present. The direct contribution corresponds to the simpe $\gamma\gamma \to q\bar{q}$ process; while the production is well understood in this case, this process might offer a new opportunity to test fragmentation models in a reaction that is as clean as $e^+e^- \to q\bar{q}$ annihilation.

We see that for all three classes of contributions the 'low'-energy, high-luminosity option allows to probe a larger range of M_{jj} values. Assuming somewhat arbitrarily that with standard luminosity a cross-section of 0.5 pb/GeV is necessarily for a good measurement, we find that the high-luminosity option could investigate the direct process up to $M_{jj} \approx 35$ GeV, whereas the high-energy option would only reach 22 GeV. This difference is smaller for the resolved processes, whose cross-sections grow more rapidly with energy; it should also be noted that annihilation backgrounds close to the Z^0 peak will become more severe at higher M_{jj}.

A similar picture emerges for the two-photon production of $b\bar{b}$ pairs, see Fig. 4. While the low-energy high-luminosity option would produce about 3 times more $b\bar{b}$ pairs in total, the number produced via resolved processes is almost the same for both options. This latter contribution is interesting, because it is proportional to the gluon content G^γ of the photon, about which almost nothing is known experimentally. (The DG parametrization of the quark and gluon content of the photon [18], which was used throughout, assumes G^γ to be rather small; the resolved cross-sections shown in these

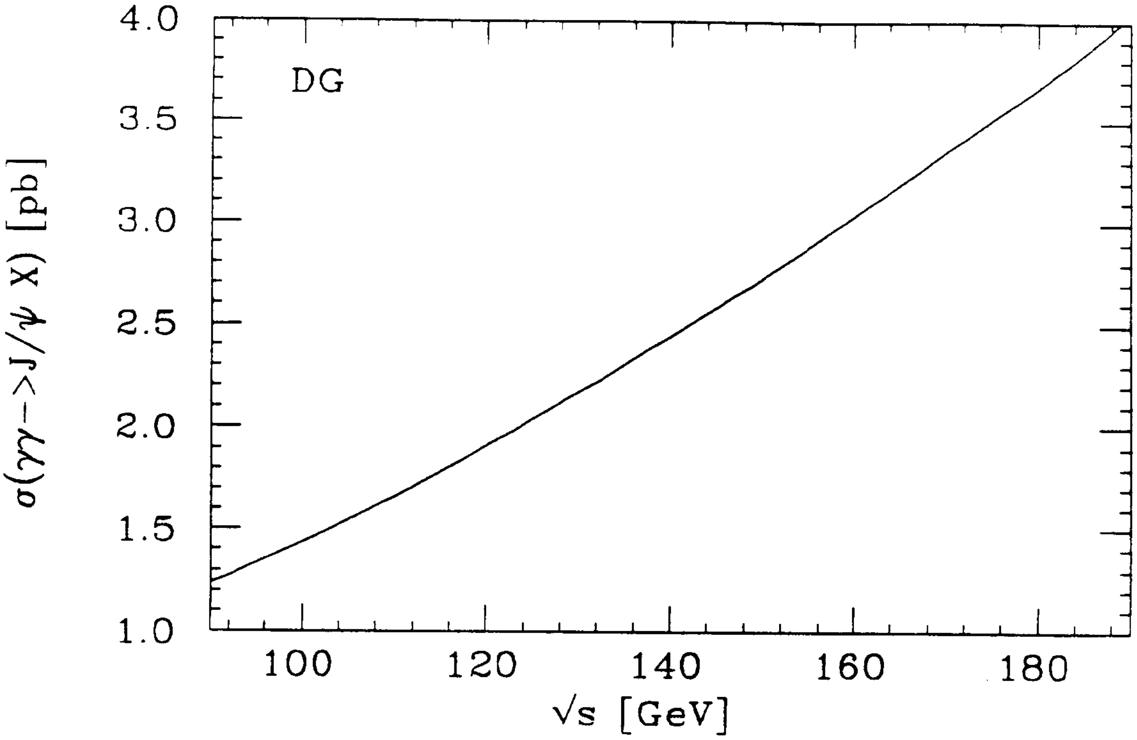


Figure 5: Total cross-section as function of CM energy for the production of J/Ψ.

figures can thus be considered as conservative estimates.)

Another process which directly probes G^γ is the two-photon production of J/Ψ, see Fig. 5, for which no direct process exists in leading order. Here the low-energy high-luminosity option is clearly favoured, giving roughly three times more events before cuts. Note, furthermore, that at higher energies a larger fraction of J/Ψ:s will have such a large rapidity that at least one of the two leptons originating from its decay will be lost. Note that the cross-section of Fig. 5 has not been multiplied with the $\mathrm{BR}(J/\Psi \to e^+e^-, \mu^+\mu^-) \approx 1/7$. The signal rate will thus be marginal at the 'ordinary' LEP I (unless G^γ is much larger than anticipated), but should be easily detectable given 10 times more statistics.

7.3 Charm (and τ) Decays

For the study of τ and charm decays, a dedicated τ-charm factory offers significant advantages. It it doubtful whether LEP could be competitive, except in lifetime measurements and in precision electroweak tests in Z^0 decays. Many of the aspects involved are discussed in the section on comparisons with τ-charm factories. We here only give a few comment on charm decays, which indicate that, although a number of interesting studies could be envisaged, few (if any) have a realistic chance of success at HLEP.

The study of weak charm decays has reached an advanced level, certainly on the experimental side and almost on the theoretical side. Ongoing experiments (at FNAL, CERN, CLEO, ARGUS, Mark III, and the Beijing machine) should, over the next 3–4 years, almost complete the following chapters on standard model physics in charm decays:

- map out D_s decays and determine absolute branching ratios;

- study once- and twice-Cabibbo suppressed D decays in more detail then before; and
- map out the spectroscopy of the weakly decaying charmed baryons, their lifetimes and major decay modes.

As far as standard model physics is concerned, only two items will be left out:

- charm decays with multi-neutrals in the final state; and
- the decays $D^+, D_s \to \mu^+\nu_\mu$ and $D_s \to \tau^+\nu_\tau$.

It seems these processes can be studied in a sensitive way only at e^+e^- threshold machines.

However, there are three topics that are accessible to present machines and deserve further study:

1. rare D decays like doubly Cabibbo suppressed ones and like $D \to \rho\gamma$;
2. $D^0 - \overline{D^0}$ mixing; and
3. CP violation in charm decays.

Typical examples of doubly Cabibbo suppressed D decays are $D^+ \to K^+\pi^+\pi^-$ or $D^0 \to K^+\pi^-$. They are interesting since they can teach us a lot about the mechanisms underlying non-leptonic D decays, and in addition they form an important background to searches for $D^0 - \overline{D}^0$ mixing. Typical branching ratios are $BR(D^0 \to K^+\pi^-) = 0.0002$, $BR(D^0 \to K^+\rho^-) = 0.0001$, $BR(D^+ \to K^+\pi^0) = 0.0002$, and $BR(D^+ \to K^+\pi^+\pi^-) = 0.0002$. To distinguish a doubly Cabibbo suppressed decay from a Cabibbo allowed decay one generally needs flavour tagging. For LEP, the most promising possibility is likely to use D mesons coming from semileptonic decays of B mesons, with the sign of the lepton as tag.

For rare decays, there is a benchmark figure for branching ratios that has to be reached before searches become interesting. Its actual size depends of course on the kind of new physics envisioned. For non-minimal SUSY for example [19], it is $BR(D \to \rho\gamma) \simeq \mathcal{O}(10^{-6})$, where one has used constraints as imposed by the experimental bounds on $D^0 - \overline{D^0}$ mixing. Thus a sample of about 10^7 D mesons is required to make such searches meaningful, i.e. more than any existing experiments are likely to accumulate. Information on the decay vertex is in principle not essential, but in practise quite useful. Unfortunately, searches for signals of this kind may well drown in the general multihadronic background at LEP. Other rare decays, like $D^0 \to \mu^+\mu^-$, are expected to have unobservably small rates, except in very special models.

The present E691 bound on $D\overline{D}$ mixing is $r(D) < 3.3 \cdot 10^{-3}$, which translates into $x = \Delta m/\Gamma$ or $y = \Delta\Gamma/2\Gamma < 0.1$. Standard model predictions are not very refined yet, but they suggest $r(D) < 10^{-3}$, and presumably $r(D) \simeq 10^{-4}$. New physics easily could boost $r(D)$ up to a few times 10^{-3} [20]. Experimental bounds will go down to $r(D) \simeq 10^{-3}$ in the next few years. It is desirable to push sensitivity levels down to $r(D) \simeq 10^{-4}$. A good way to look for $D^0 - \overline{D}^0$ mixing is to study the decay rate evolution in proper time: if it is not purely exponential, then there is mixing. Decay vertex information is clearly essential in such an analysis.

Finally, present experimental bounds on CP violation in D are given by 100% – not too impressive. Standard model predictions are again very rough only: the typical scale is 10^{-4} and maybe could be as 'high' as 10^{-3}. With new physics, like non-minimal SUSY or an extended Higgs sector, it could however reach above the 1% level. The best suited two-body decay modes are D^0 or $\overline{D}^0 \rightarrow K^+K^-$ or $\pi^+\pi^-$ [20]. Flavour tagging is required, i.e. it is necessary to know if the K^+K^- or $\pi^+\pi^-$ comes from a meson that was born as a D or as a $\overline{D}$. A direct CP violation would express itself as a difference between the $D^0 \rightarrow K^+K^-$ and the $\overline{D}^0 \rightarrow K^+K^-$ decay rates that is independent of the proper time of decay. A CP violation involving mixing, on the other hand, would express itself as a difference between the decay rates of the two CP conjugate states. This would give a dependence on proper time behaving like $\exp(-\Gamma t)\sin((\Delta m)t)$. In three- or four-body decay modes like $D^0 \rightarrow K_S\pi^+\pi^-$ or $K_SK^+K^-$, or $D \rightarrow K3\pi$, or the Cabibbo suppressed modes of the analogous type, one can search for CP asymmetries in the Dalitz plot or in kinematically non-trivial triple correlations among momenta in the final state.

In summary, if any variant of new physics exists in D decays, it is not guaranteed that the signal could be dug out at HLEP. However, one should not disregard the possibility to do useful physics with a high statistics sample.

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