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Heavy quark production at e^+e^- colliders in three- and four-jet events ☆

Alessandro Ballestrero [a], Ezio Maina [b,a] and Stefano Moretti [a]

[a] INFN, Sezione di Torino, I-10125 Turin, Italy
[b] Dipartimento di Fisica Teorica, Università di Torino, I-10125 Turin, Italy

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The contribution of massive quarks to three- and four-jet distributions in e^+e^- collisions is studied at LEP I energies using exact helicity amplitudes Total cross sections as a function of y_{cut}, in both the JADE and the k_T algorithms, are presented and compared with massless results Some distributions for variables of interest for QCD studies at LEP are examined

Hadronic decays of the Z^0 produced in e^+e^- annihilations provide an ideal environment for precise tests of QCD [1] All LEP experiments have performed a large number of measurements In particular

- α_s has been measured from jet rates [2] and from global event shape variables [2,3] Flavor independence of the coupling has been verified [4]
- Three- [5] and four-jet [6] distributions have been studied and compared with QCD predictions Additional evidence for the presence of the three-gluon vertex has been found The color factors, which determine the gauge group which is responsible for strong interactions, have been measured [7]
- The differences between gluon and quark jets have been investigated [8]

In some cases the possibility of tagging quarks jets using the semileptonic decays of b and c quarks has been used All QCD results mentioned are based on a careful comparison of experimental data with Monte Carlo simulations To our knowledge, all available programs are based on massless matrix elements and kinematics Mass effects are known to give corrections at the percent level to quantities like $\Gamma(Z\to b\bar{b})$ in the Born approximation, and one expects their relevance to increase with the number of final partons A close examination of the differences between the results obtained with massive and massless matrix elements would determine the range of applicability of the latter and would give better control on this source of systematic errors

The partial width of the Z^0 in $b\bar{b}$, though very difficult to measure with great accuracy, is potentially very interesting because of the presence of one-loop vertex corrections, sensitive to the top mass, which do not contribute for other fermion species Clearly an understanding of mass effects in multijet events is highly desirable

QCD production of heavy quarks is also relevant for Higgs searches at LEP since the Higgs decay to $b\bar{b}$ is by far the dominant one for light Higgs masses, and probably the only channel with rates large enough for detection at e^+e^- colliders [9]

In the coming years, improvements in statistics, in secondary vertex reconstruction with silicon vertex detectors and in particle identification will allow much more detailed studies of heavy quark production at LEP

In this paper we present cross sections for three- and four-jet events at LEP energies which include all quark mass effects in leading order Among previous calculations [10–15], the only one which does not neglect quark masses is that of ref [15], where, however, the Z^0 contribution is not included The matrix element for all processes has been computed at the

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amplitude level following both the method of ref [16] and that of ref [17] as a check of the correctness of our results In our experience it is easier to produce fast routines with the formalism of ref [17] but it is clearly much simpler to give compact, easy to implement formulae using the formalism of ref [16] The higher speed of the routines based on ref [17] is certainly related to the smaller number of subroutine calls we are using in this case and may not reflect an intrinsic superiority of the method More details on our calculation and the explicit expressions of the amplitudes for production of heavy quarks and/or leptons in events with three or four final partons at LEP energies will appear in a separate paper [18] Three-parton quantities are computed at $O(\alpha_s)$ and four-parton quantities at $O(\alpha_s^2)$ Virtual corrections to $e^+e^-\to q\bar{q}g$ would be needed for a treatment of three parton quantities to $O(\alpha_s^2)$

The amplitudes have been checked for gauge invariance and in the appropriate limit reproduce the formulae in refs [14,15] We have used $\alpha_s=0\ 115$, $\sqrt{s}=M_Z=91\ 1$ GeV, $\Gamma_Z=2\ 5$ GeV, $\sin^2(\theta_w)=0\ 23$, $m_c=1\ 7$ GeV and $m_b=5\ 0$ GeV

The experimental definition of a jet is based on a clustering procedure The most widely used scheme is the JADE algorithm The two (pseudo)particles i and j for which the quantity

$$y^J_{ij}=2\frac{E_iE_j}{E^2_{vis}}(1-\cos\theta_{ij}) \tag{1}$$

is minimum are combined into a single pseudoparticle k of momentum $p_k=p_i+p_j$ The process is iterated until all pseudoparticle pairs satisfy $y_{ij}\geqslant y_{cut}$ The objects generated by this procedure are called jets The JADE algorithm has been recently criticized [19] and a new clustering variable

$$y^T_{ij}=2\frac{\min(E_i^2,E_j^2)}{E^2_{vis}}(1-\cos\theta_{ij}) \tag{2}$$

has been proposed The corresponding algorithm is known as the k_T-clustering In what follows we neglect all hadronization effects, and apply cuts at the partonic level

In fig 1 we present the cross sections for $e^+e^-\to q\bar{q}g$, $q=c$, b as a function of y_{cut} for both definitions of y The range in the two cases has been chosen in such a way that the $q\bar{q}g$ cross sections for the smallest y_{cut} values are of similar magnitude As obvious from their definition (1), (2), a cut in y^T is much stronger than a corresponding cut in y^J and the effect becomes more prominent for smaller y_{cut} This can be clearly seen in the different slopes of the two groups of curves In fig 2 the ratios of the cross section for massive

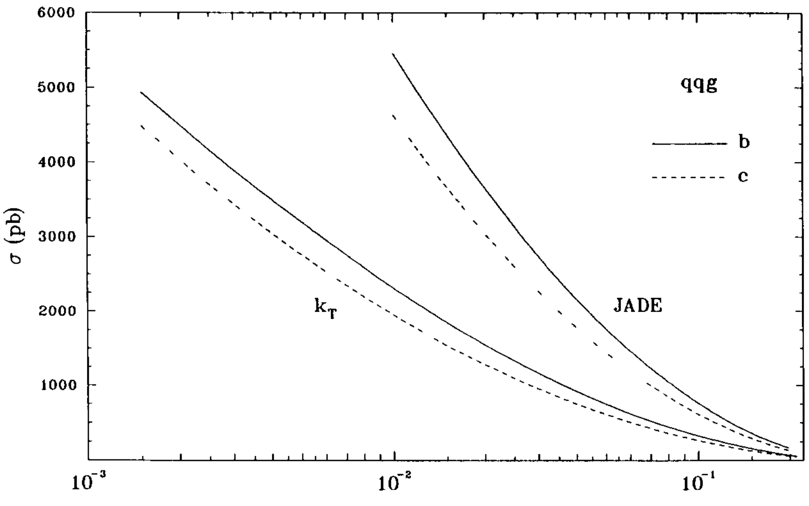

Fig 1 Cross sections for $e^+e^-\to q\bar{q}g$, $q=c$ (dashed) and b (continuous) as a function of y_{cut} for y^J (upper curves) and y^T (lower curves)

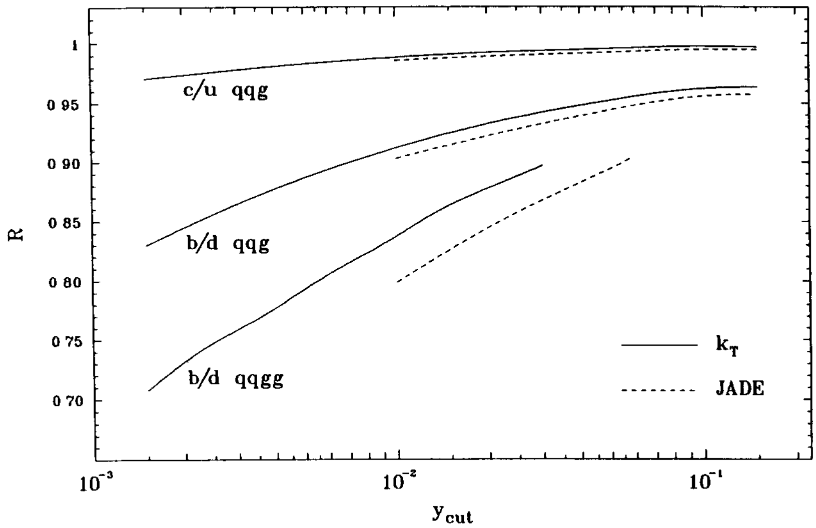

Fig 2 $R_3^{cu}=\sigma(c\bar{c}g)/\sigma(u\bar{u}g)$, $R_3^{bd}=\sigma(b\bar{b}g)/\sigma(d\bar{d}g)$ and $R_4^{bd}=\sigma(b\bar{b}gg)/\sigma(d\bar{d}gg)$ as a function of y_{cut} for y^J (dashed) and y^T (continuous)

quarks to the cross section for massless quarks with identical charge and I_3, $R_3^{cu}=\sigma(c\bar{c}g)/\sigma(u\bar{u}g)$ and $R_3^{bd}=\sigma(b\bar{b}g)/\sigma(d\bar{d}g)$, are shown as a function of y_{cut} For small y_{cut} the cross section for b quarks is almost 20% smaller than for d's As expected the ratios become closer to one for larger y_{cut}, but for y_{cut} as large as 0 2, still $R_3^{bd}\leqslant 0$ 96 In the same figure, for comparison, we also report $R_4^{bd}=\sigma(b\bar{b}gg)/\sigma(d\bar{d}gg)$

In fig 3 we give the cross sections for $e^+e^-\to q\bar{q}gg$, q=d, c, b The $q\bar{q}gg$ final state is the dominant contribution to the four-jet cross section The cross section for two u quarks and two gluons is within 5% of the result for charmed quarks It is interesting that the charm and the bottom cross sections are approximately equal in this case

In fig 4 the cross sections for $e^+e^-\to q\bar{q}q\bar{q}$, q=d,

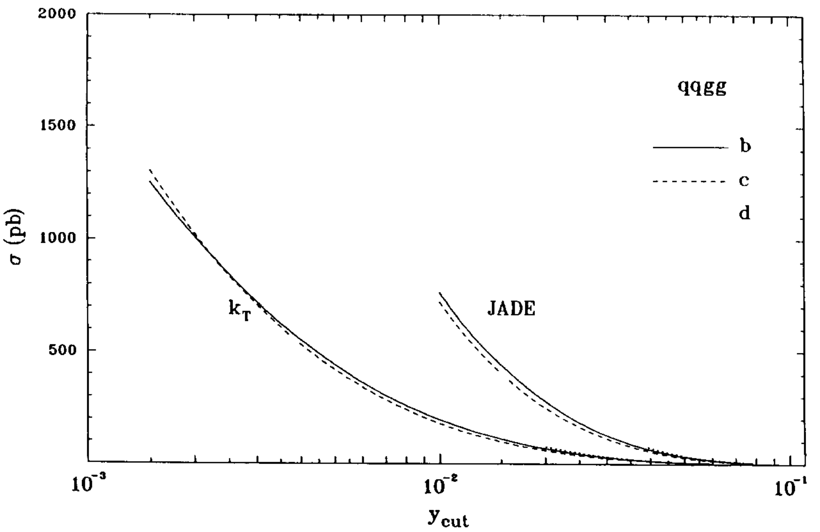

Fig 3 Cross sections for $e^+e^-\to q\bar{q}gg$, q=d (dotted), c (dashed) and b (continuous) as a function of y_{cut} for both definitions of y

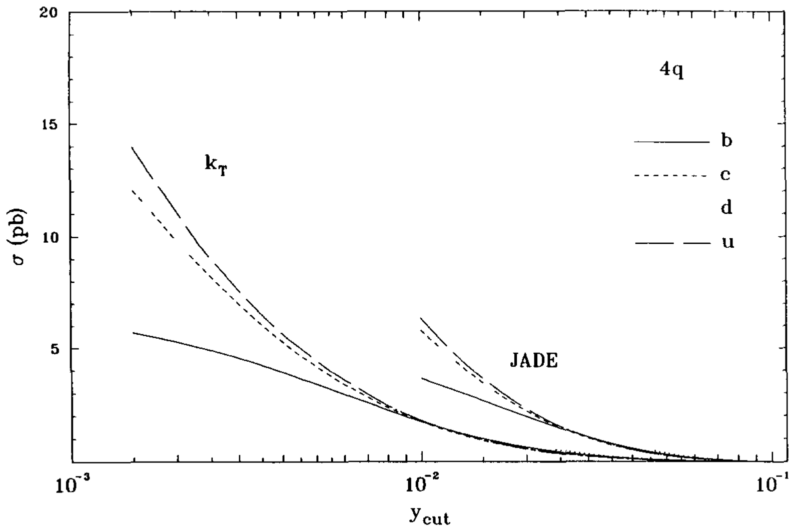

Fig 4 Cross sections for $e^+e^- \to q\bar{q}q$, q=d (dotted), u (dash-dotted), c (dashed) and b (continuous) as a function of y_{cut} for both definitions of y

u, c, b is shown as a function of y_{cut} Though very small compared with the $q\bar{q}gg$ case this case could be quite interesting if heavy quarks can be tagged with high efficiency For 10^6 Z^0, corresponding to an integrated luminosity of about 30 pb^{-1}, one expects approximately 100 events with 4b quarks From figs 1, 3 and 4 it can be seen that, while for the three-parton case the cross sections for $y^J_{cut}=0\ 01$ are approximately matched by the cross sections for $y^T_{cut}=0\ 0015$, in the four-parton case this happens for $y^T_{cut}=0\ 003$

The distributions in $\sqrt{y^T s}$ for all jet pairs in $e^+e^- \to q\bar{q}g$, q=d, b is shown in fig 5 Jets are ordered according to their energies, i e , $E_i \geqslant E_{i+1}$ Since the third jet is in most cases the gluon jet, fig 5 shows that the gluon jet is on average slightly harder for light quarks

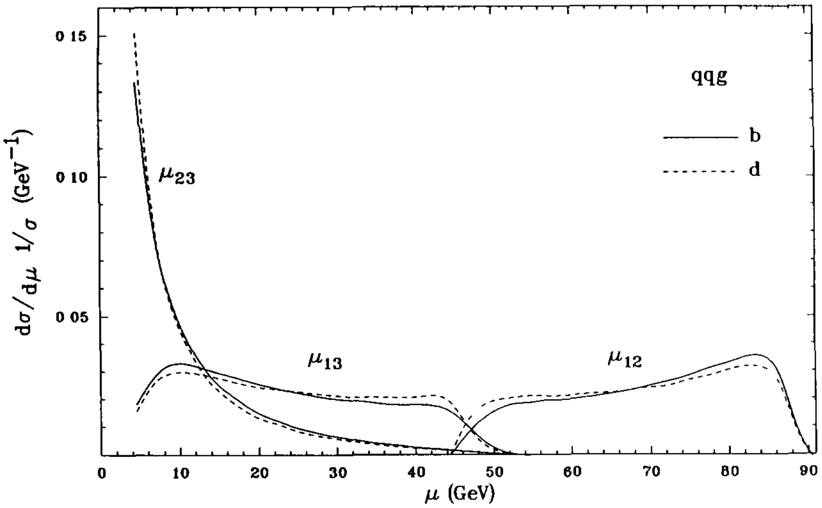

Fig 5 Distribution for $\mu_{ij}=\sqrt{s y^T_{ij}}$ in $e^+e^- \to q\bar{q}g$ for q=d (dashed) and b (continuous) Jets are ordered according to their energies $y_{cut}=0\ 0015$ in the k_T algorithm

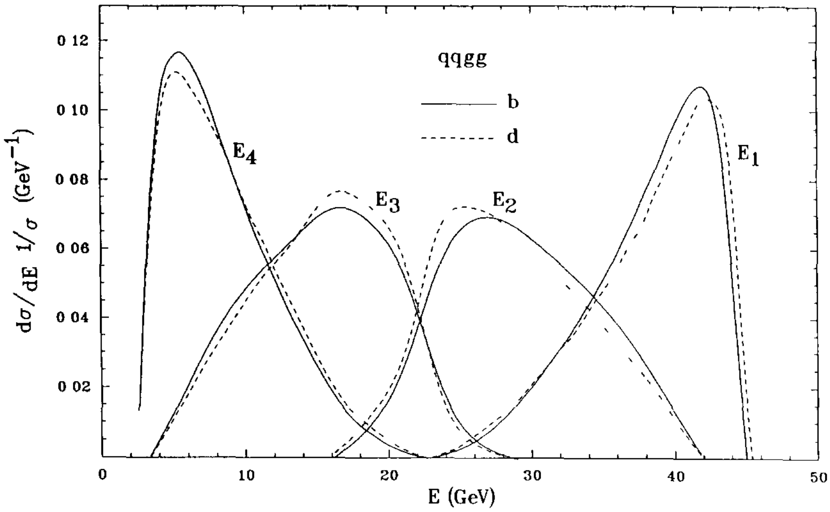

Fig 6 Energy distribution of all four jets in $e^+e^- \to q\bar{q}gg$ for q=d (dashed) and b (continuous) Jets are ordered according to their energies $y_{cut}=0\ 0015$ in the k_T algorithm

then for heavy quarks This is also confirmed by the distribution in $x_2=2E_2/E_{CM}$, which we do not show

In fig 6 we present the energy distributions of all four, energy ordered, jets in $e^+e^- \to q\bar{q}gg$, q=d, b Beside the distribution shown we have examined other variables like the modified Nachtmann–Reiter angle [20,21] and the Bengtsson–Zerwas angle [22] The results for massive b and c quarks differ very little from the corresponding massless distributions Masses seem to primarily affect total cross sections Their effect depends on the number of jets, on the clustering algorithm and on y_{cut} Therefore jet rates are sensitive to quark masses A precise determination of mass effects would require the calculation of two- and three-jet rates to $O(\alpha_s^2)$ From our preliminary analysis it appears that distributions of event shape variables at the parton level are only slightly modified by the inclusion of masses On one hand, this means that all previous analyses based on these variables maintain their validity On the other hand, this shows that event shape variables, as studied in this paper, are unable to discriminate massive quark events from massless quark events

Conclusions We have computed the exact matrix elements for $e^+e^- \to q\bar{q}g$, $e^+e^- \to q\bar{q}gg$ and $e^+e^- \to q\bar{q}q\bar{q}$ with massive quarks Total cross sections have been presented as a function of the cut which defines the jet reconstruction algorithm For b quarks and a not too large y_{cut} the mass effects on total cross sections are large Some distributions for variables of interest for QCD studies at LEP have been examined They show that analyses based on event shape variables are not affected by mass effects but also that they do not provide efficient means for enriching the heavy quark sample

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