

# QCD IN $e^+e^-$ COLLISIONS AT 2 TEV

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## Abstract

We discuss some topics in QCD studies at 2 TeV. Particular emphasis is given to the separation of pure QCD events from the  $WW$  and the  $t\bar{t}$  backgrounds.

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# 1 Introduction

QCD studies in  $e^+e^-$  colliders at 2 TeV will be similar in many respects to QCD studies at lower energy (for a review of studies in  $e^+e^-$  collisions at 500 GeV, see *e.g.* ref. [1]). One will attempt to measure the strong coupling constant, scaling violation in fragmentation functions, detailed studies of multi-jet distributions, and the like. In this short study we concentrate of features which are novel to collisions at this high energy. The general theoretical and experimental framework for QCD studies in  $e^+e^-$  collisions can be found in previous reviews [1].

The main problem at this energy, is how to disentangle the  $t\bar{t}$  and  $W^+W^-$  backgrounds from the pure QCD di-jet or multi-jet events. The  $W^+W^-$  cross section is particularly high and when the  $W$ 's decay into hadrons one will be unable to distinguish the final state from that of two ordinary high energy jets. A typical 1 TeV QCD jet will in fact have an invariant mass of the order of  $\alpha_S$  times 1 TeV, which is roughly 90 GeV, of the same order of the  $W$  mass. In fig. 1 we show the

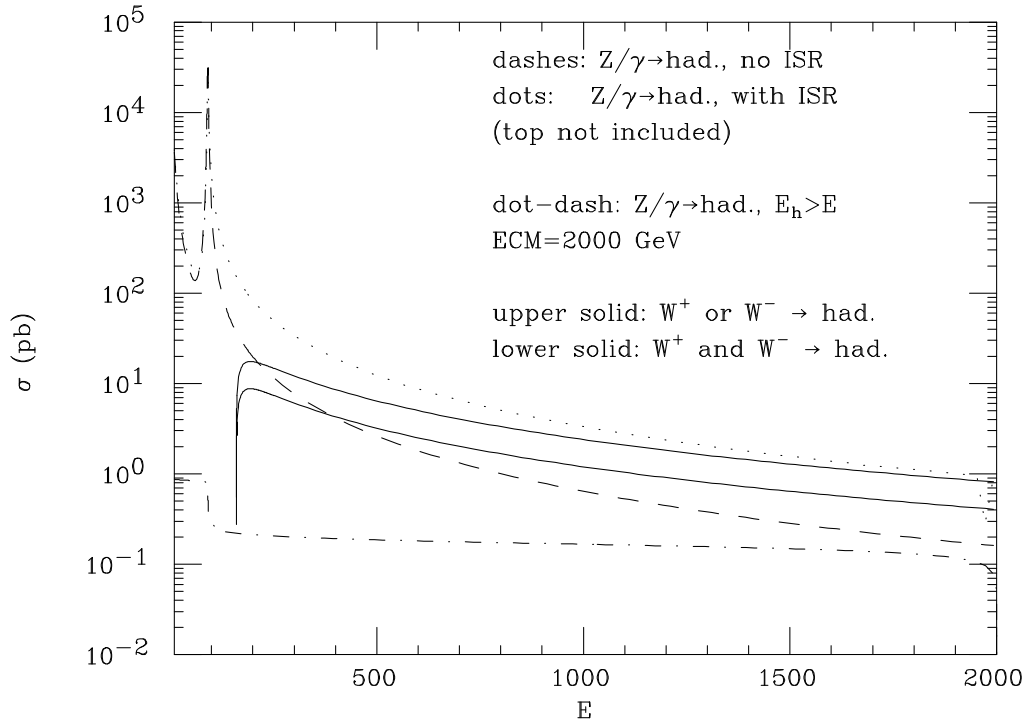


Figure 1: Cross sections for  $e^+e^-$  into light hadrons and into  $WW$  pairs, as a function of  $\sqrt{s}$ . The solid lines represent the  $WW$  cross section (upper curve: at least one  $W$  hadronic decay; lower curve: both  $W$  hadronic decays). The light hadrons cross section is given by the dotted line (no initial state radiation), and by the dashed line (ISR included). The dash-dotted line is the integral of the light hadron cross section at  $\sqrt{s} = 2$  TeV, integrated above a given value of the energy of the final hadronic state, in presence of ISR.

cross section for  $e^+e^-$  into light hadrons (from now on, by “hadronic events” we will mean  $e^+e^-$  into light hadrons, *i.e.* top contribution excluded), and the  $WW$  cross

section. Initial state radiation causes a loss of cross section around a factor of two, depending on the cuts one imposes. In the figure the ISR effect is only shown for hadronic events, but we should expect something similar for the  $W$ . It is therefore reasonable to assume that the Born cross sections give a good indication of the relative magnitudes of the  $WW$  and hadronic cross sections. We should therefore compare 0.16 pb for the hadronic cross section to 0.4 pb for the  $WW$  fully hadronic events. Fortunately, the  $WW$  events are concentrated in the forward region, because of their  $t$ -channel nature. This is shown in fig. 2, where the cross section is shown

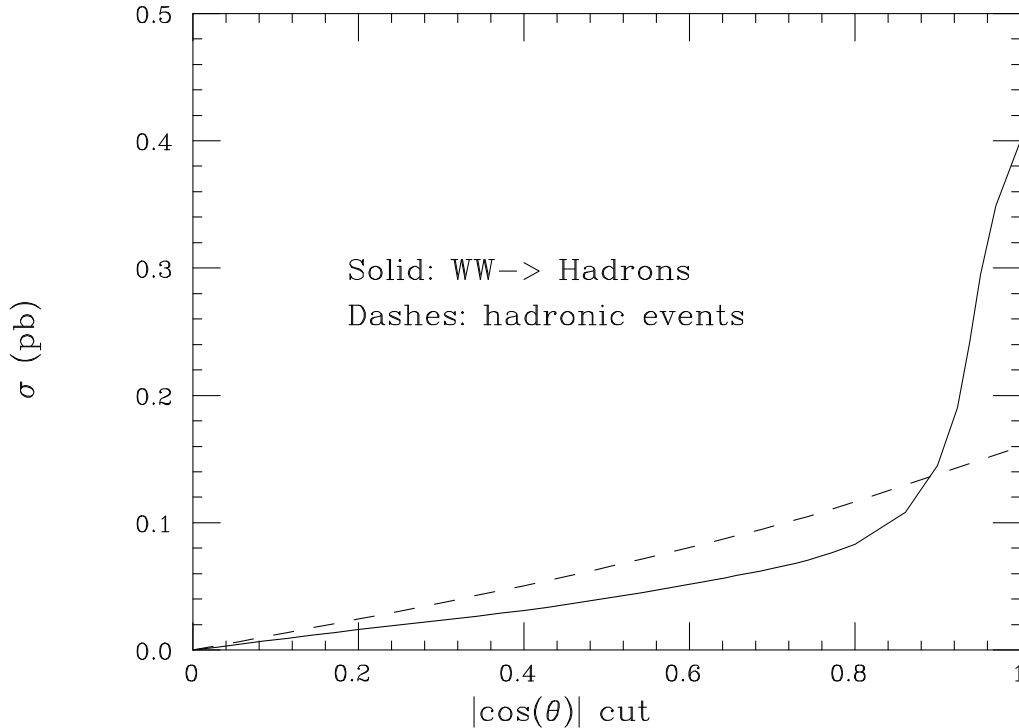


Figure 2: Cross section at 2 TeV as a function of the cut on the direction of the thrust axis.

as a function of an angular cut on the thrust axis. We see that requiring  $\cos\theta < 0.8$  leaves us with a 60% of the hadronic events and 40% of  $WW$  events. Further work is needed to clean the sample in a better way. For example, one expects in general that  $WW$  events will always have high thrust. Conversely, one can assume that the  $WW$  events are well understood ( $W$  decays will be similar to  $Z$  decays, a fact that can be verified at LEP2), and subtract them from the measured distributions.

The separation of  $t\bar{t}$  events will also require some work. The relative fraction of each flavour is given in fig. 3. At 2 TeV the top quark production represents 22% of the total.

In the following sections we will study some simple variables which allow to separate the various contributions, and will discuss to which extent a separation is indeed necessary. A complete study of the potential for QCD studies at 2 TeV would require some detailed knowledge of the detector specifications. In what follows, we

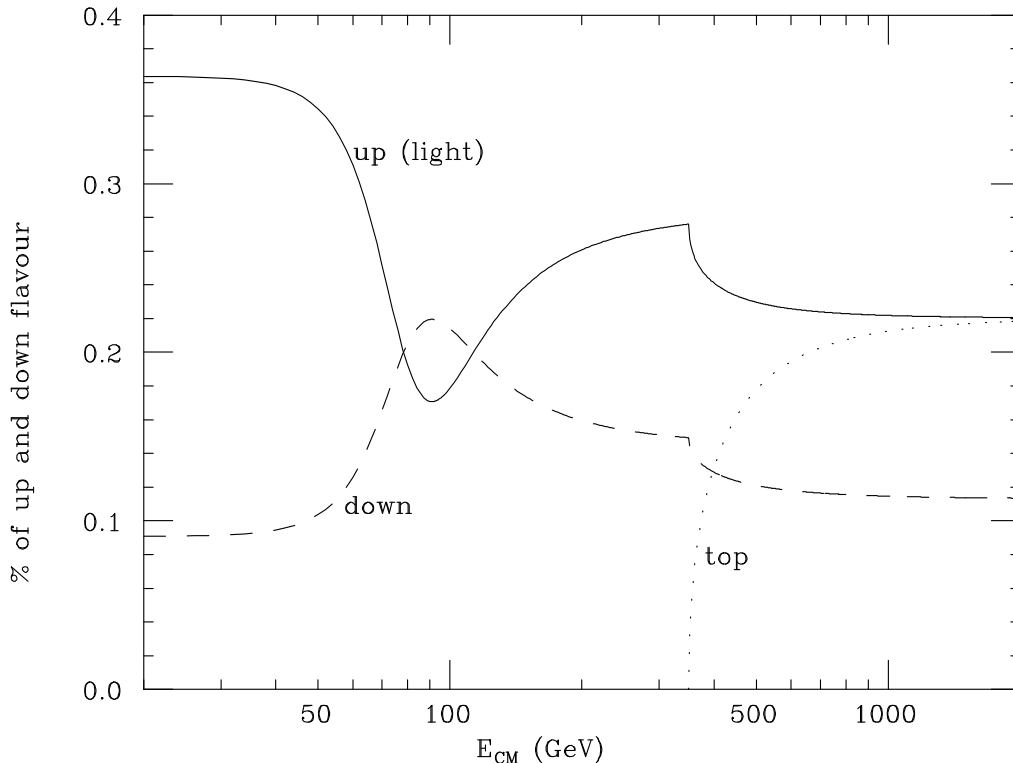


Figure 3: *Flavour composition for  $Z/\gamma \rightarrow q\bar{q}$  as a function of  $\sqrt{s}$ .*

will therefore briefly comment on which detector parameters have an impact on this physics.

## 2 Conventions

We will define jets using the Durham algorithm [2], in the E recombination scheme. Unless otherwise stated, the MC studies are done using HERWIG [3] version 5.8, and use partons as opposed to hadrons. Namely, jets are reconstructed out of the partons after the full shower evolution and gluon splitting, and before being clustered and hadronized.

No QED ISR nor beamstrahlung have been included, as our assigned goal was to study QCD at *exactly* (or very close to) 2 TeV.

A word of caution must be added, however, before we present the results of our case study: here, we are extrapolating our current knowledge to c.m. energies which are about *twenty times larger* than those energies which are presently available. This is equivalent to a hypothetical attempt to predict the physics at LEP-I based on the knowledge of the early data from SPEAR ( $\sqrt{s} \sim 5$  GeV).

### 3 Separation of QCD and $WW$ events

It is hard to separate the two samples without significantly biasing the properties of the jets. The typical property of a  $WW$  event is that no hard emission at large angle is possible. In fact the  $W$ 's will decay in flight into  $q\bar{q}'$  pairs, and the mass of the hadronic system resulting will never exceed  $M_W$ . Since the  $W$ 's are boosted to 1 TeV, the two or more jets from their decay will coalesce into a single thin jet, with angular aperture of the order of  $M_W/1 \text{ TeV} \sim 5^\circ$ . Particles emitted outside this cone cannot be too energetic, or else they would form together with the leading jet an object of invariant mass higher than  $M_W$ . We tried to use this property to separate  $WW$  events from QCD events. In fig. 4 we plot the multiplicity distribution of

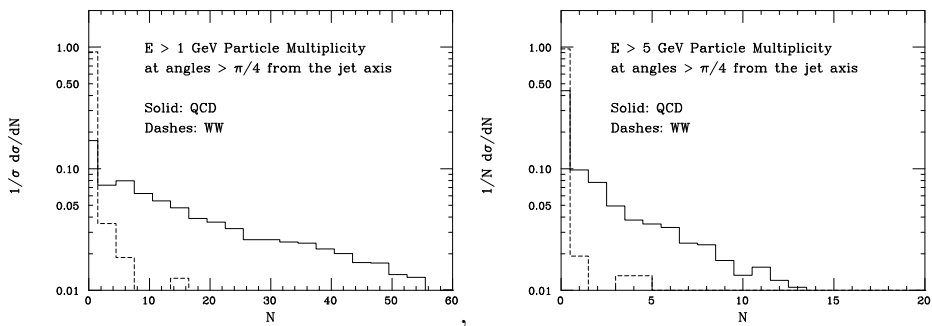


Figure 4: *Multiplicity distribution for particles above 1 GeV (left) and 5 GeV (right) found in the region outside cones of radius  $45^\circ$  centered around the axis of the two leading jets. QCD events (solid) vs.  $WW$  events (dashed).*

particles above 1 and 5 GeV found in the region outside cones of radius  $45^\circ$  centered around the axis of the two leading jets. The continuous lines are for QCD events, the dashed lines for  $WW$  events. From the figures we learn the following:

- The area outside the jet cores is indeed much quieter in  $WW$  events.
- Only a fraction of the order of 10% of the  $WW$  events would survive the request that particles above 1 GeV be present outside the  $45^\circ$  cones. More than 80% of the QCD sample would survive this cut.
- If we require the 5 GeV cut, only a fraction of the order of  $10^{-2}$  of the  $WW$  events would survive. Approximately 50% of the QCD sample would be left.
- It is not clear how this request would bias the jets, and whether the extraction of  $\alpha_S$  from the properties of jets selected in this way would have a significant systematic uncertainty. This issue can however be studied using shower Montecarlo programs.

## 4 Jet Production Rates and $t\bar{t}$ Events

For the studies presented in this section we generated hadronic final states at  $\sqrt{s} = 2$  TeV using PYTHIA version 5.7 [4] with QCD- and hadronisation parameters as optimised to describe the data from LEP1. As before, effects due to initial state radiation, beamstrahlung and detector acceptance are not taken into account. The Durham ( $k_{\perp}$ ) jet algorithm [2] is used to study jet multiplic-

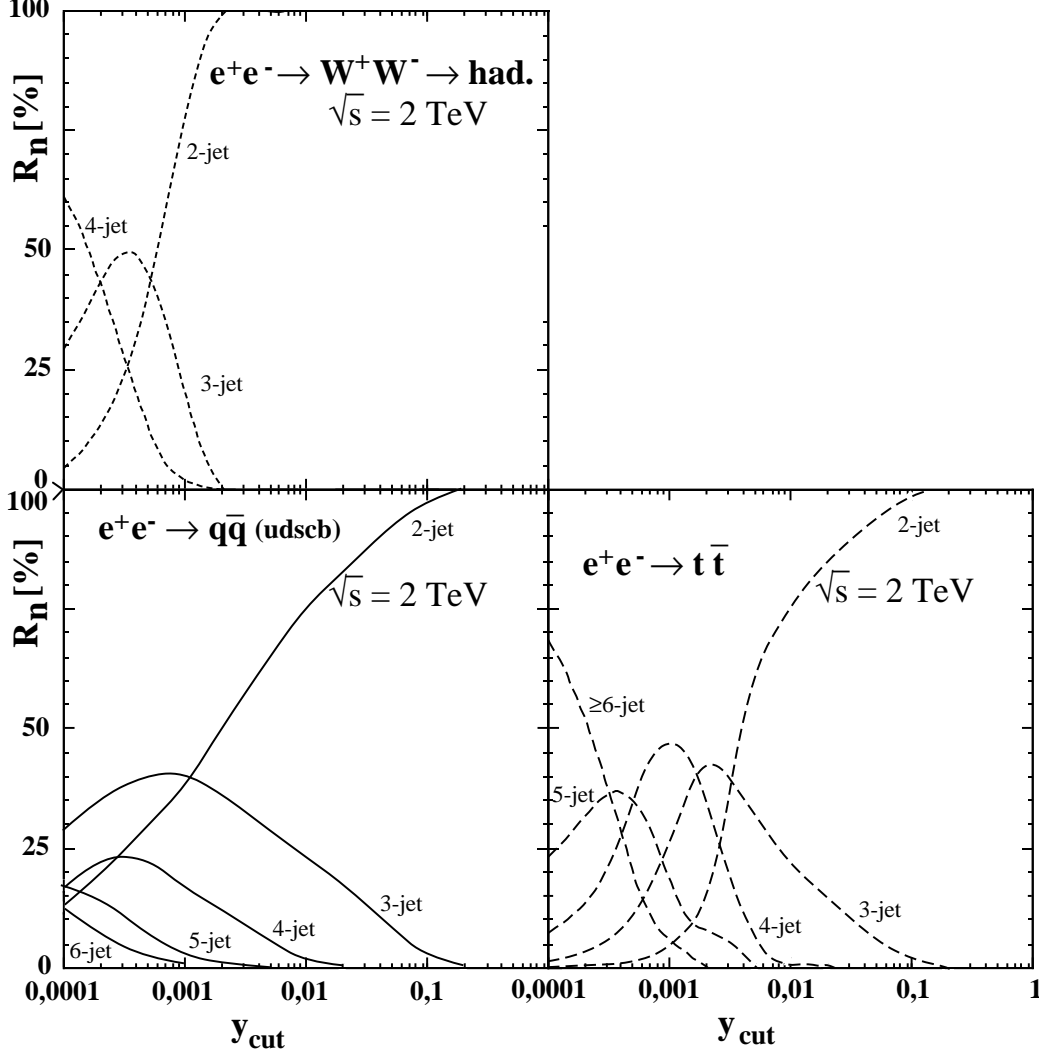


Figure 5: Integral relative production rates of  $n$ -jet events ( $n = 2, 3, 4, 5, \geq 6$ ), as a function of the jet resolution parameter  $y_{cut}$ .

ities for different event classes, namely for hadronically decaying W-pair events ( $e^+e^- \rightarrow W^+W^- \rightarrow \text{hadrons}$ ), for hadronic events from primary ‘light’ quark pairs ( $e^+e^- \rightarrow q\bar{q}$ ; where  $q$  may be a  $u, d, s, c$  or  $b$ -quark) and for top quark events ( $e^+e^- \rightarrow t\bar{t}$ ). The results are shown in Fig. 5, where the integral, relative production rates of  $n$ -jet events ( $n = 2, 3, 4, 5, \geq 6$ ) are plotted as a function of the jet resolution parameter  $y_{cut}$ . The following observations can be made:

- for  $y_{cut} > 0.002$ , all  $W^+W^-$  events are classified as 2-jet ( $\sqrt{0.002} \times 2000 \text{ GeV} = 98.4 \text{ GeV} > M_W$ ).
- $t\bar{t}$ -events have a markedly enhanced and clear 6-jet signal around  $y_{cut} \sim 0.0001$ . This allows to select top-quark events and study e.g. the decay  $t \rightarrow 3$  jets in detail. Of course, the reconstruction of jets at such small values of  $y_{cut}$  might require particular granularity in the calorimeter. The accuracy with which the top mass will be measured from the reconstruction of these high energy jets could significantly depend on this parameter.
- for  $y_{cut} > 0.01$ , the 3-jet production rates of  $t\bar{t}$  and  $q\bar{q}$  events are almost identical - which is intuitively clear since  $\sqrt{0.01} \times 2000 \text{ GeV} \geq M_t$ .

From these observations and other studies we conclude:

- At c.m. energies of 2000 GeV, the separation of  $t\bar{t}$  events from light-quark QCD events for a typical QCD analysis, like e.g. the determination of  $\alpha_S$  from 3-jet rates, seems not to be necessary: these event classes show similar QCD properties in regions where the jet resolution is coarser than the mass of the top quark. The situation is similar as for b-quark events at e.g. TRISTAN energies ( $\sqrt{s} \leq 60 \text{ GeV}$ ), where the mass of the heaviest quark also was about 10% of the c.m. energy.
- In fact we tried to separate  $t\bar{t}$  events from light quark QCD events using kinematic variables, similarly to the separation of  $W^+W^-$  events described in the previous section. While the algorithms which we devised are good in extracting a sample of top events with good purity, they are not very good at providing a pure sample of light quark QCD events which is not too biased. The same is true when selecting  $t\bar{t}$  events by requiring 6 jets at  $y_{cut} = 0.0001$ ; see Fig. 5.
- Determination of  $\alpha_S$  from 3-jet event rates will be possible by analysing *relative* production rates or by analysing *absolute* cross sections of 3-jet events. In the first case, one has to correct the measurement according to the large production of  $W^+W^-$  events, which all end up as 2-jets for decent values of  $y_{cut}$  and therefore spoil the relative number of 3-jets by the overall normalisation. The absolute normalization of the  $WW$  rate is well known within the SM, this being a purely EW process. If we allow for possible new phenomena, we could still determine the  $WW$  rate from the data, by counting the number of events where one of the  $W$ 's decays leptonically. The statistical error of this measurement is comparable to the statistical error on the QCD 2-jet production rate. The use of the *absolute* 3-jet event production rate is not influenced by the production of  $W^+W^-$  pairs, provided one works with  $y_{cut} > 0.002$ . This method however relies on a good knowledge of luminosities, acceptances and theoretical expectations. The uncertainty on these last ones is in principle correlated to that at LEP1 and LEP2, and should not constitute a major source of systematics for comparisons between results at LEP1/LEP2 and NLC.

- With 5000 selected hadronic ( $q\bar{q}$  and  $t\bar{t}$ ) events (i.e. after about 2-3 years of data taking with luminosities around  $10^{33} s^{-1} cm^{-2}$ ), we expect about 750 3-jet events at  $y_{cut} = 0.02$ , leading to a statistical precision in  $\alpha_S$  of about 3%. Including the systematic sources mentioned in the previous point, we would estimate the final uncertainty on  $\alpha_S$  not to exceed 5%. Starting with  $\alpha_S(M_Z) = 0.123 \pm 0.002$  we evaluate an expected  $\alpha_S(2 \text{ TeV}) = 0.085 \pm 0.004$ . The evidence for running would therefore be a clear  $7 \sigma$  effect. On the contrary, with the value preferred by DIS ( $\alpha_S(M_Z) = 0.111$ ) as a boundary condition one should expect  $\alpha_S(2 \text{ TeV}) = 0.078 \pm 0.004$ . The difference between the two values at 2 TeV is less than  $2 \sigma$ . As expected, operations at 2 TeV will not enable any improvement in the measurement of  $\Lambda_{QCD}$ .

## 5 Fragmentation Functions

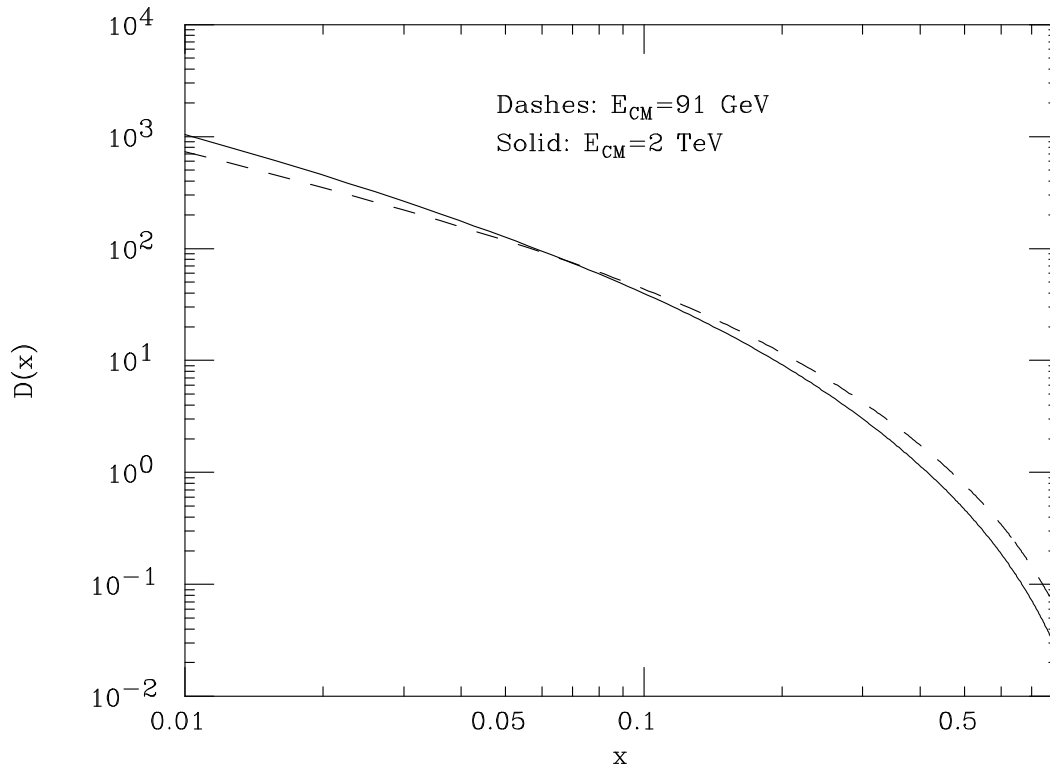


Figure 6: *Inclusive charged particle fragmentation function at  $\sqrt{s} = M(Z)$  (dashed) and 2 TeV (solid).*

The study of the evolution of fragmentation functions provides another interesting test of perturbative QCD. In fig. 6 we show the expected evolution of the inclusive fragmentation functions from  $\sqrt{s} = M_Z$  to 2 TeV. Although the differences are quite noticeable (the fragmentation function is softer by almost a factor of 2 at  $z > 0.5$  because of the larger amount of radiation given off), it is not clear to which extent such effects can be measured. The highest energy jets will be extremely



collimated, and fundamental parameters such as track reconstruction efficiency, fake track rates and momentum resolution will depend very strongly on the detector parameters: magnetic field, tracking resolution etc. It is therefore impossible at this stage to formulate a potential for a physics measurement based on fragmentation functions.

In fig. 7 we plot the  $b$  fragmentation function, separated between non- $t\bar{t}$  events and  $t\bar{t}$  events. We point out the following features:

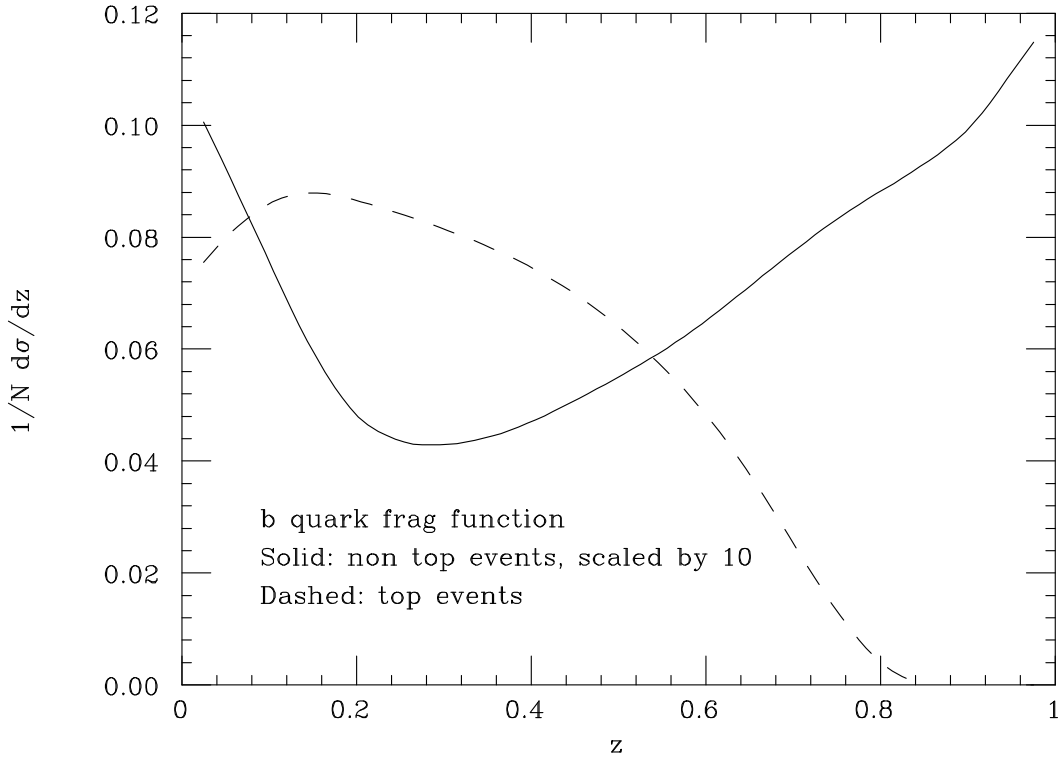


Figure 7: *Inclusive  $b$  quark fragmentation function at 2 TeV. Non- $t\bar{t}$  events (solid) and  $t\bar{t}$  events scaled by 10 (dashed).*

- The high tail at small- $z$  in non- $t\bar{t}$  events comes from the splitting of gluons emitted during the evolution of light  $q\bar{q}$  events.
- A large fraction of inclusive  $b$ 's therefore comes from non- $b$  events. Measurements of the direct  $Zb\bar{b}$  vertex at 2 TeV will therefore be severely biased by our capability to predict the precise contamination due to events initiated by light quarks. The requirement of double tagging on opposite jets would significantly reduce the non- $Zb\bar{b}$  signal, but at the expense of a loss in statistics.
- In addition, the only region of  $z$  in which a pure sample of non- $t\bar{t}$  events can be selected is for  $z > 0.8$ . Below this value, the two fragmentation functions do not differ enough to allow an event-by-event separation of the two components.
- The average momentum of a  $b$  is of the order of  $z = 1/2$ , i.e. 500 GeV, both in  $t\bar{t}$  and in non- $t\bar{t}$  events. This is more than ten times the momentum

of  $b$ 's produced at LEP1, and corresponds to decay lengths of the order of 4 cm. The secondary-vertex tagging detectors should therefore be optimized accordingly. In particular, the radius should be such as to guarantee that the acceptance for the decay taking place *before* the tracking device be large enough. Furthermore, in comparison with LEP1  $b$ 's at 2 TeV will be softer relative to the remaining tracks of the jet, and surrounded by larger hadronic activity.

Altogether, it is therefore very difficult to estimate the impact of the detector design on the physics potential. Simple extrapolations from LEP1 values could be seriously misleading, and realistic designs and tracking reconstruction algorithms will have to be used before numbers such as  $b$ -tagging efficiency can be estimated.

## References

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