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Heavy flavour tagging and QCD tests in four-jet events at LEP1

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Abstract

We present a theoretical review of the possibilities offered by heavy flavour tagging in testing QCD features in 4-jet events at LEP1. Attention is focused mainly on the properties of the angular variables which are used in the experimental analyses to measure the colour factors of the strong interactions. We also comment on a possible settlement of the ongoing controversy about the existence in LEP1 data of SUSY events involving light gluinos. Integrated and differential rates of interest to phenomenological analyses are given and various tagging procedures are discussed.

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1. Introduction

The LEP1 era has now ended. Regarding QCD tests, the legacy passed on by the experiments ALEPH, DELPHI, L3 and OPAL is indeed a convincing indication that the $SU(3)$ gauge group of the Standard Model ($\mathcal{SM}$) is the theory that describes the strong interactions [1]. By studying the process $e^+e^- \to Z \to$ hadrons decisive results have been achieved: the QCD coupling 'constant' α_s has been determined from jet rates and shape variables; both its flavour independence and running have been verified; multi-jet distributions reproduce QCD predictions to second order in α_s; many models proposed as alternatives to ordinary QCD have been ruled out; the triple gluon vertex coupling has been verified to be in agreement with QCD; finally, the colour factors that determine the gauge group responsible for strong interactions have been measured [2]. However, as far it concerns the latter measurements, somewhat less conclusive results have been obtained.

In the 'colour factor analyses' in 4-jet samples, the basic idea is to measure the fundamental colour factors of QCD, that is, C_A and C_F and T_F, which are determined from the $SU(N_C)$ generators $(T^a)_{ij}$ and from the structure constants f^{abc}. Explicitly, one obtains $C_A = N_C$, $C_F = (N_C^2 - 1)/2N_C$, and $T_F = 1/2$. In ordinary QCD (i.e., $N_C = 3$): $C_A = 3$ and $C_F = 4/3$. In order to determine C_A, C_F and T_F[1], one compares the theoretical predictions to the data by leaving the colour factors as free parameters to be determined by a fit. The comparison is made by resorting to differential spectra of variables based on angular correlations between jets, which are usually ordered in energy and where the two most energetic jets are 'identified' with the primary quarks (i.e., from the Z decay). Some of the most widely used are the Bengtsson-Zerwas angle χ_{BZ}, the Körner-Schierholz-Willrodt angle Φ_{KSW}, the 'modified' Nachtmann-Reiter angle θ^*_{NR} [3] and the angle between the two least energetic jets θ_{34} (i.e., from the gluon splitting). The distributions in these quantities are different for $Q\bar{Q}gg$ and $Q\bar{Q}q\bar{q}$ events. This is decisive as, in general, the main difference between QCD and alternative models is the predicted relative contributions of the two subprocesses[2]. This leads to different shapes of the angular distributions of the full 4-jet sample and thus to different predictions for the values of C_A, C_F and/or T_F (see, e.g., Ref. [4]). Ultimately, in fact, C_F, C_A and T_F represent nothing else than the relative strengths of the interactions $q \to qg$, $g \to gg$ and $g \to q\bar{q}$, respectively.

The present status of the colour factor analyses [2, 5] is that, although the experimental measurements agree well with ordinary QCD, it is not possible to rule out its Supersymmetric version. In fact, such a theory includes in the spectrum of the fundamental particles the spin 1/2 partner of the gluon, the *gluino* $\tilde{g}$, which could be produced at LEP1 in $Q\bar{Q}\tilde{g}\tilde{g}$ events (via $g^* \to \tilde{g}\tilde{g}$), provided it is not too heavy. Since gluinos are coloured fermions, their contribution would enhance the part of the 4-jet cross section with angular dependence similar to that of $2Q2q$ events. Naively, one could alternatively say that N_F is (apparently) increased, such that an experimental measurement could reveal SUSY signals in the form of an enhancement of T_R. In detail, gluinos with a mass $\gtrsim 2$ GeV yield an expectation value for T_F/C_F within one standard deviation of the measured one [5].

Like the QCD gauge boson, the gluino is neutral, it is its own anti-particle (i.e., it is a Majorana fermion) and its coupling to ordinary matter is precisely determined in terms of the QCD colour matrices and α_s [6]. However, whereas $m_g \equiv 0$, the gluino mass $m_{\tilde{g}}$ is an arbitrary parameter, and so is the lifetime $\tau_{\tilde{g}}$. In particular, in the theory it is natural for gluinos to be much lighter (a few GeV) than squarks if their mass is induced radiatively and if dimension-3

[1] Better, ratios among them: e.g., C_A/C_F and T_R/C_F, where $T_R = N_F T_F$, with N_F number of active flavours.

[2] E.g., the $2Q2q$ contribution to the total 4-jet rate at the Z peak is only about 5% in QCD but up to 30% in certain Abelian models [4].

SUSY breaking operators are absent from the low energy dynamics [7]. Thus, if gluinos are so light, they should be produced at LEP1 [8]. Recently, there has been a renewed interest in this possibility, especially motivated by the (small) discrepancy between the value of α_s determined by low energy deep-inelastic lepton-nucleon scattering and the one measured by the e^+e^- CERN experiments [9]. In this respect, it has been speculated that the evolution of α_s is being slowed down by a contribution to the β function due to light gluinos. The latest experimental constraints still allow for the existence of relatively long lived and light gluinos, in the parameter regions [10]: (i) $m_{\tilde{g}} \lesssim 1.5$ GeV and $\tau_{\tilde{g}} \lesssim 10^{-8}$ s; (ii) $m_{\tilde{g}} \gtrsim 4$ GeV and $\tau_{\tilde{g}} \gtrsim 10^{-10}$ s.

In our opinion, if one adopts energy ordering of the jets (as it has been done so far), the effectiveness of the experimental analyses in putting stringent bounds on the measured values of C_A, C_F and T_R is largely reduced. In fact, the angular variables introduced above are most useful for emphasizing QCD features if one can distinguish between quark and gluon jets and assign the momenta of the final states to the corresponding particles[3]. It was this consideration that motivated two of us to advocate in Ref. [11] the use of 4-jet samples with two of the jets clearly identified as originating from heavy flavour quarks. In this way, it is at least possible to distinguish some quark jets, namely those which originate from b-quarks, from gluon jets, thus identifying the particles in the final states and defining the angular variables in the proper manner. A direct consequence of this approach is that one gains a greater discriminating power between events with different angular behaviour. Furthermore, an intrinsic advantage of the heavy flavour selection is that the $Q\bar{Q}gg$ event rates are reduced more (by a factor of 5) than the $Q\bar{Q}q\bar{q}$ ones (which are divided by 3), such that their relative differences can be more easily studied. The final aim is to assess whether with b-tagging techniques one is able to reduce the confidence level regions around the experimental measurements, in such a way to eventually shed new light on the possibility that SUSY signals are present in LEP1 data.

Such techniques have been rapidly developed by the LEP1 collaborations in the past years [12], and have become an excellent instrument to study heavy flavour physics. Their main features are well summarized, e.g., in Refs. [13]: in particular, we remind the reader that the method offering the best performances is the lifetime tagging by detecting a secondary decay μ-vertex. Yet, the crucial point in b-tagging-based analyses is that the total statistics in $2b2$jet events is greatly reduced compared to that available when no quark identification is exploited, not merely because only flavour combinations involving b's are retained (and these are even mass suppressed [14]) but also because the (single) tagging efficiency at LEP1 is rather low, $\varepsilon \lesssim 40\%$ (for purities close to 1). Typically, one has to consider that the initial rate of $2b2$jet events from pure QCD is of the order $\mathcal{O}(8000)$ events per experiment: for $\approx 4 \times 10^6$ hadronic Z decays, $\Gamma_{b\bar{b}}/\Gamma_{\rm had} \approx 22\%$, $R_4 \approx 10\%$ and $\varepsilon \approx 30\%$, where R_4 is the 4-jet fraction, and considering two tags. Note that the statistics could well be increased by considering the data of all experiments altogether and/or by relaxing the requirements of high b-purity (see discussion in Ref. [11]). Indeed, experimental studies of b-tagged 4-jet events have been already reported [15] (showing that a considerable reduction of the systematics can be achieved) and others are in progress [16].

Independently of the results of the new analyses, there are however other possibilities offered by the μ-vertex devices to settle down the debate about colour factor measurements at LEP1. This is clear if one considers that long-lived gluinos might yield 4-jet events with detectable displaced vertices, as already recognised in Ref. [17] and exploited in Ref. [18]. In the rest of this contribution, we briefly summarise the computational techniques, the tagging procedures and the main results already reported in Refs. [11, 19].

[3] When ordering in energy, one has to bear in mind that in $Z \to Q\bar{Q}gg$ decays for only half of the events the two lowest energy partons are both gluons [4] !

2. Calculation

In carrying out the analyses described here we made use of the FORTRAN matrix elements already discussed in Ref. [14] and presently used for experimental simulations [5], upgraded with the inclusion of the gluino production and decay mechanisms (see also Ref. [20]). The programs do not contain any approximations, the intermediate states γ^* and Z being both inserted, and the masses and polarisations of all particles in the final states (of the two-to-four body processes) retained. The availability of the last two options is especially important if one considers, on the one hand, that in b-tagged samples all final states are massive, and, on the other hand, that in proceeding to experimental fits one could well select restricted regions of the differential spectra of the angular variables, where the rates are likely to strongly depend on the spin state of the partons[4].

In the analyses we are reporting about we have adopted four different jet-finding procedures: the JADE scheme (J) and its "E" variation (E), and the most recent Durham (D) and Geneva (G) algorithms [21]. We will present rates only for some of these, as none of the results drastically depends on the choice of the jet recombination scheme and/or the value of the jet resolution parameter, $y_{\rm cut}$. As it concerns the exact definitions of the angular variables used here, these can be found in Ref. [11][5]. Anyhow, to make clear the rest of the paper, we point out the following (with reference to the formulae of Ref. [11]). When heavy flavour identification is implied, labels 1 & 2 refer to the two tagged jets whereas 3 & 4 to the two remaining ones. If no vertex tagging is assumed, jets are labelled according to their energy, $E_1 \geq E_2 \geq E_3 \geq E_4$. The numerical values adopted for quark masses and $\mathcal{SM}$ parameters can be found in Ref. [14].

3. Results

3.1 Angular variables

The first two figures illustrate the improvement that can be achieved by using heavy flavour tagging (two lower plots), compared to the results obtained when energy ordering is used (two upper plots). Distributions are normalised to one. The label 'Abelian' for the $2Q2g$ contribution refers to rates obtained in a particular Abelian model of QCD[6], in which the self-interaction of gluons is absent [23] (see Ref. [11] for details). Note that the $Q\bar{Q}q\bar{q}$ subprocess is identical in both models. The following aspects must be emphasised in Figs. 1–2.

(i) Concerning the angles χ_{BZ} and Φ^*_{KSW}, the discrimination power between the behaviour of the $Q\bar{Q}gg$ and $Q\bar{Q}q\bar{q}$ components slightly improves (more for the second variable). In the case of the first one, the original symmetric behaviour implied by the definition is restored.

(ii) Another remarkable feature of Fig. 1 is that when b-tagging is exploited, the differences between the Abelian and the non-Abelian behaviour of the $2Q2g$ component are dramatically emphasised, for both angles. In the case of the χ_{BZ} variable these differences disappear when energy ordering is used. It should also be stressed that this is not the case for the Φ^*_{KSW} angle only because we are using here an 'improved' definition of this variable (which shows sensitivity

[4] For this reason we have not used the results published in literature for the gluino decay rates, as these are averaged over the helicities of the unstable particle. Instead we have recomputed the relevant Feynman decay amplitudes by preserving the gluino polarisation and by matching the latter with the corresponding one in the production process [19].

[5] We stress that the Φ^*_{KSW} angle is actually a modification of the original one Φ_{KSW} , proposed by two of us (see Ref. [11] for further details).

[6] We are aware that this model has been already ruled out in other contexts [22], but we regard it as a useful tool to demonstrate the sensitivity of the introduced angular variables to the features of QCD.

to the gauge structure even without any flavour tagging), the original one being less sensitive to such differences.
(iii) Regarding the θ^*_{NR} angle, once again the original symmetry is restored, such that this clearly helps to differentiate the $2Q2g$ and $2Q2q$ subprocesses. In contrast, the behaviour of the two different gauge interactions in the $2Q2g$ subprocess remains identical.
(iv) Finally, for the angle θ_{34}, the improvement concerns the enhanced separation between the two different gluon behaviours, more than a discrimination between gluon and quark properties.

3.2 Mass effects

Fig. 3 shows the effect on the relevant differential spectra of the inclusion of the b-quark mass in the computations. The angular distributions corresponding to b-contributions are compared to those involving massless d-quarks (q represents here a massless flavour). (Differences are even more dramatic when comparing $b\bar{b}b\bar{b}$ and $d\bar{d}d\bar{d}$ distributions, though the former flavour combination corresponds to a suppressed contribution.) In particular, it is worth noticing that the (QCD) $Q\bar{Q}gg$ spectra is less affected by mass effects than the $Q\bar{Q}q\bar{q}$ ones and that the Bengtsson-Zerwas and the (modified) Körner-Schierholz-Willrodt angles are more mass sensitive than the (modified) Nachtmann-Reiter and the angle between the two untagged jets. In general, it must be stressed that mass effects are not negligible and should be included in phenomenological analyses exploiting heavy flavour tagging. In contrast, when energy ordering is adopted (that is, when all quark flavours are retained in the four-jet sample), the above effects are largely reduced (see Ref. [14]). In this case, in fact, the most part of quark combinations in the final state involves massless particles. Results have been shown for the case of the E scheme, as this is the algorithm for which mass suppression is somehow larger. However, similar effects are visible also in the other three cases: J, D and G.

3.3 Gluino tagging

When dealing with tagging a secondary vertex possibly due to gluino decays, several points must be addressed [19]. First of all, one has to confine oneself to secondary vertex analyses only[7], however this technique has a larger efficiency than any other method [13]. Second, the vertex has to be inside the detectors, so that only gluinos with $\tau_{\tilde{g}} \lesssim 10^{-9}$ s can be searched for [18]. Nonetheless, this represents an appealing opportunity, as a substantial part of the mentioned $(m_{\tilde{g}}, \tau_{\tilde{g}})$ window could be covered by the experiment. In this respect, we exploit a sort of 'degeneracy' in lifetime between b-quarks and gluinos, assuming that when making secondary vertex tagging one naturally includes in the $2b2$jet sample also SUSY events, in which a $\tilde{g}$ behaves as a b. We call such approach 'minimal trigger' procedure, as we propose a tagging strategy that does not take into account any of the possible differences between gluinos and b-quarks in 4-jet events with two secondary vertices (thus, in the following, we will generally speak of 'vertex tagging'). There are in fact at least three obvious dissimilarities.
(i) Their charge is different, such that one could ask that the jet showing a displaced vertex has a null charge. This would allow one to isolate a sample of pure SUSY events. However, we remind the reader that to measure the charge of a low energy jet in 4-jet events has not been attempted before and that the procedure would certainly have very low efficiency (in isolating a very broad hadronic system in an environment with high hadronic multiplicity).

[7] Thus neglecting other forms of heavy flavour tagging: such as the high p_T lepton method, as gluinos do not decay semileptonically.

(ii) Gluino lifetimes much longer than that of the b are still consistent with experiment (note that $\tau_b \approx 10^{-12}$ s), such that recognising a displaced vertex with decay length $d \gg 3$ mm (that of the b) would allow one to immediately identify gluinos. Unfortunately, most of the b-tagged hadronic sample at LEP1 has been collected via a bi-dimensional tagging (see, e.g., Ref. [24]). Thus, different d's could well appear the same on the event plane. Furthermore, tagging a $d > 3$ mm vertex would allow one to separate gluinos with $\tau_{\tilde{g}} > \tau_b$, but this would not be helpful if $\tau_{\tilde{g}} \leq \tau_b$.
(iii) Other than in lifetime, b-quarks and gluinos can differ in mass as well, such that one might attempt to exploit mass constraints to separate SUSY and pure QCD events. However, on the one hand, one could face a region of m_b-$m_{\tilde{g}}$ degeneracy and, on the other hand, one should cope with the ambiguities related to the concept of mass as defined at parton level and as measured at hadron level.
We emphasise that measuring the charge of the vertex tagged jet, attempting to disentangle different decay lengths or measuring partonic masses could well be further refinements of the procedure we are proposing, and that their exploitation certainly does not spoil the validity of the latter. In addition, all these aspects necessarily need a proper experimental analysis, which is beyond the scope of a theoretical study.

The steps of our analysis are very simple. Under the assumption that b's and $\tilde{g}$'s are not distinguishable by vertex tagging, one naturally retains in the sample all SUSY events (whereas the ordinary QCD components are reduced as mentioned earlier). Then, it is trivial to notice that there exist clear kinematic differences between the $Q\bar{Q}gg$, $Q\bar{Q}q\bar{q}$ and $Q\bar{Q}\tilde{g}\tilde{g}$ components. This is shown in Fig. 4, where we plot the quantities $Y_{ij} = M_{ij}^2/s \equiv (p_i + p_j)^2/s$, where $ij = 12$ or 34 and $s = E_{\rm cm}^2 \equiv (M_Z)^2$. The behaviour of the curves is dictated by the fact that gluinos are always secondary products in 4-jet events, whereas quarks and gluons are not (lower plots). When no vertex tagging is exploited, such differences are washed away (upper plots). The value $m_{\tilde{g}} = 5$ GeV is assumed for reference, the shape of the distributions being qualitatively the same regardless of it. Therefore, if one simply asks to reject events for which, e.g., $Y_{12} > 0.2$ and/or $Y_{34} < 0.1$, one gets for the total rates of the three components the pattern exemplified in Fig. 5. From the drastic predominance of $2Q2g$ events in the complete 'unflavoured' sample (no vertex tagging, top left), one first obtains that the total rates of ordinary QCD events are significantly reduced compared to those of SUSY events (after vertex tagging, top right), and eventually that the $Q\bar{Q}\tilde{g}\tilde{g}$ fraction is always comparable to that of $Q\bar{Q}gg + Q\bar{Q}q\bar{q}$ events (when also the kinematic cuts are implemented, bottom left): and this is true *independently* of the gluino mass, of the jet algorithm and of the $y_{\rm cut}$ value used in the analysis (see Ref. [19]).

Therefore, after our event selection, SUSY signals would certainly be identifiable, as a clear excess in the total number of 4-jet events with two displaced vertices. Thus, the final goal will be to definitely assess the presence of gluinos at LEP1 or contradict the latter, at least over appropriate regions of masses and lifetimes[8]. We finally stress that, as we are concerned here with total rates and not with differential distributions, the event number should be sufficient to render the analysis statistically significant[9] and that the usual ambiguities related to the fact that gluino effects on the total number of 4-jet events are comparable in percentage to the systematic uncertainties due to the jet hadronisation process and/or the $y_{\rm cut}$ selection procedure

[8] And this should certainly be done after the appropriate MC simulations, including the details of the detectors and of the tagging procedure as well as a generator where $m_{\tilde{g}}$ and $\tau_{\tilde{g}}$ enter as free parameters to be determined by a fit.

[9] In this respect we acknowledge that many of the aspects of our approach were already employed in Ref. [18], the tagging procedure sketched there being however well beyond the statistical possibilities of the LEP1 experiments.

are much less severe in our approach[10]. However, since the key point of the present approach is to exploit the $b/\tilde{g}$ vertex degeneracy, a highly enriched heavy flavour sample should be selected in this case.

3.4 Gluino decays

Before closing, we should mention that a further aspect must be kept into account when attempting our analysis. It concerns the kinematics of the gluino decays. In the most sponsored SUSY framework [6], the dominant gluino decay modes are $\tilde{g} \to q\bar{q}\tilde{\gamma}$ and $\tilde{g} \to g\tilde{\gamma}$, where $\tilde{\gamma}$ represents a 'photino' (better, the Lightest Supersymmetric Particle, which is a superposition of the SUSY partners of the neutral gauge bosons of the theory). Furthermore, the $q\bar{q}\tilde{\gamma}$ channel is, in general, largely dominant over the $g\tilde{\gamma}$ mode [6].

The crucial point is that in both cases the gluino decays into a jet with missing energy. It is not our intention to discuss the possibility of selecting such a signature, as we are mainly concerned here with the fact that the energy left to the hadronic system E_h is above the experimental cuts in minimal hadronic energy, which are used to reduce the backgrounds (e.g., in Ref. [5] the threshold was set equal to 3 GeV). In Fig. 6 (first three plots) we show the E_h spectra after the gluino decay, in both the channels. Two kinematic decay configurations are considered: a massless photino, and a massive one (i.e., $m_{\tilde{\gamma}} = 1/2 m_{\tilde{g}}$). The message is that in the most likely SUSY scenario (i.e., three-body decay dominant and massless photino) all gluino events should be retained in the event selection. Conversely, Fig. 6 illustrates the percentage of these which will pass the adopted trigger requirements. Finally, in the bottom right plot of Fig. 6 we show the dependence of the SUSY rates on the value of $m_{\tilde{g}}$. Below $m_{\tilde{g}} \approx 5$ GeV, the mass suppression is always less than a factor of 2.

4. Summary and conclusions

In this paper we have stressed the importance of using at LEP1 samples of 4-jet events, in which two of the jets show a displaced vertex. This could help to improve some of the experimental tests of QCD and to possibly settle down the ongoing dispute about the existence of SUSY events in the data. Those presented are theoretical results, which should be in the end verified by detailed MC simulations. However, it is our opinion that they indicate that the matter raised and procedures similar to the ones outlined here would deserve experimental attention.

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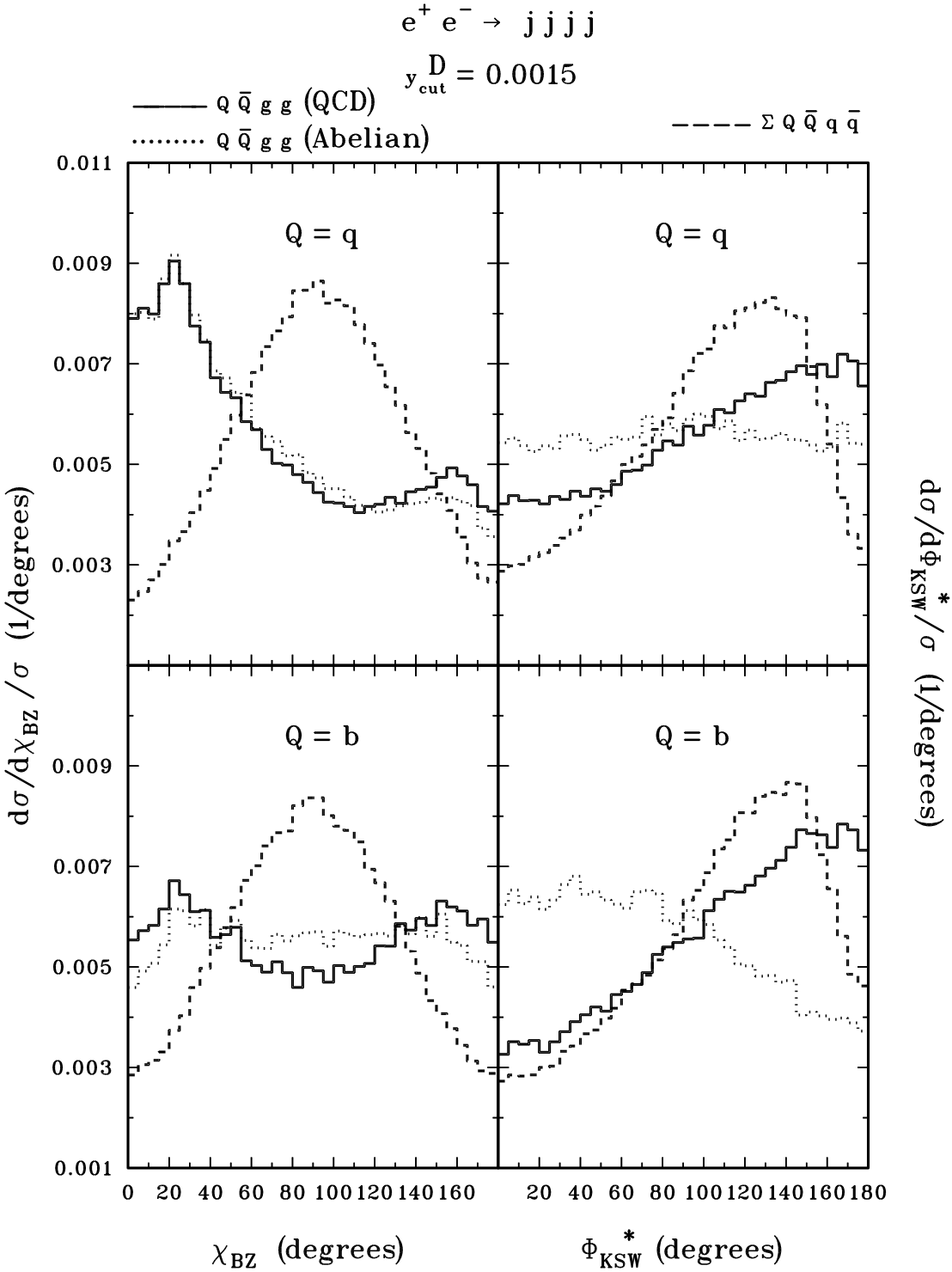

Fig. 1

Distributions in the angles χ_{BZ} and Φ^*_{KSW} for the $Q\bar{Q}gg$ (QCD and Abelian) and $Q\bar{Q}q\bar{q}$ components in 4-jet events, in the D scheme with $y^D_{\rm cut} = 0.0015$, without ($Q = q$) and with ($Q = b$) b-tagging.

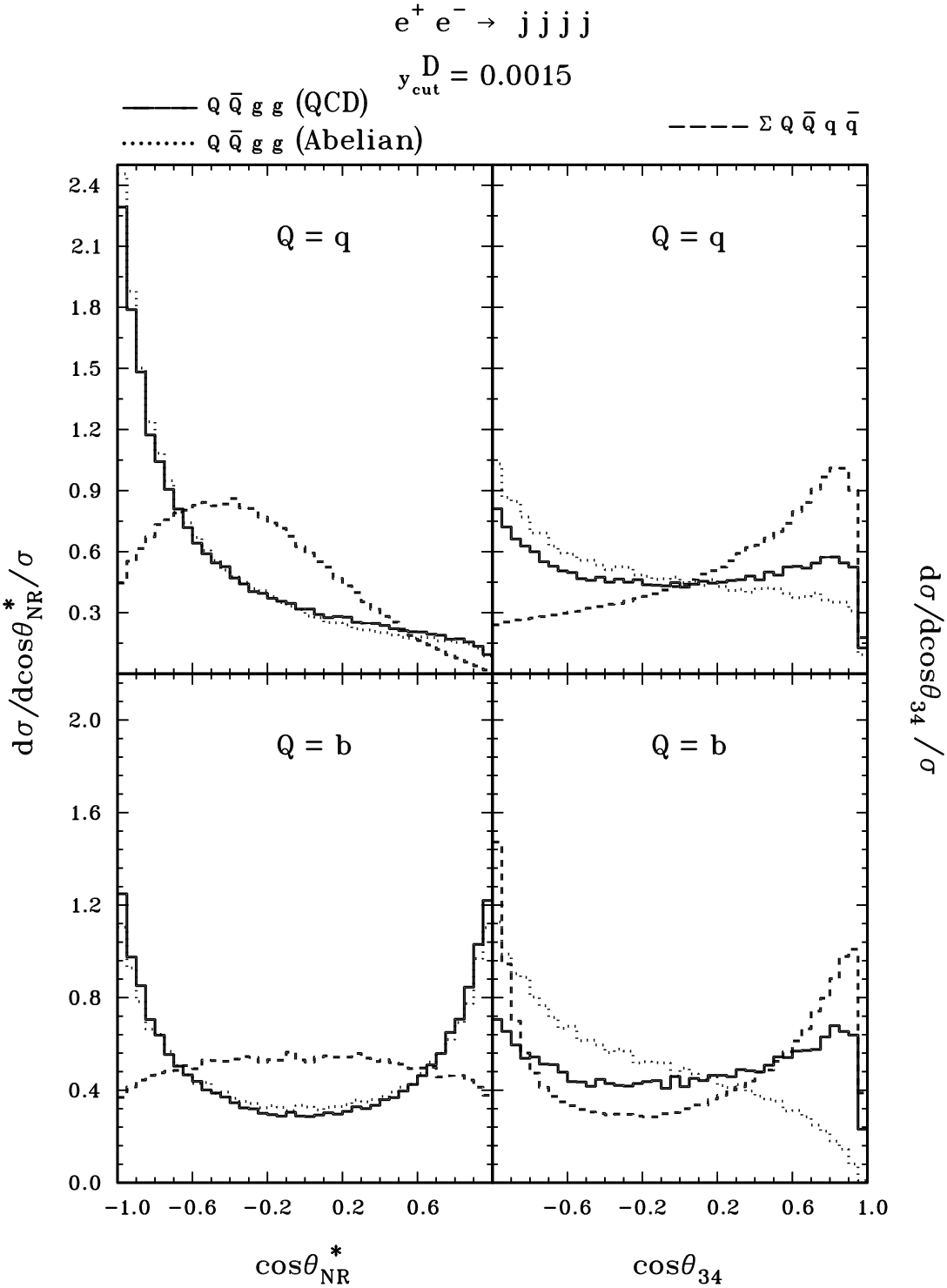

Fig. 2

Distributions in the cosine of the angles θ^*_{NR} and θ_{34} for the $Q\bar{Q}gg$ (QCD and Abelian) and $Q\bar{Q}q\bar{q}$ components in 4-jet events, in the D scheme with $y^D_{\rm cut} = 0.0015$, without ($Q = q$) and with ($Q = b$) b-tagging.

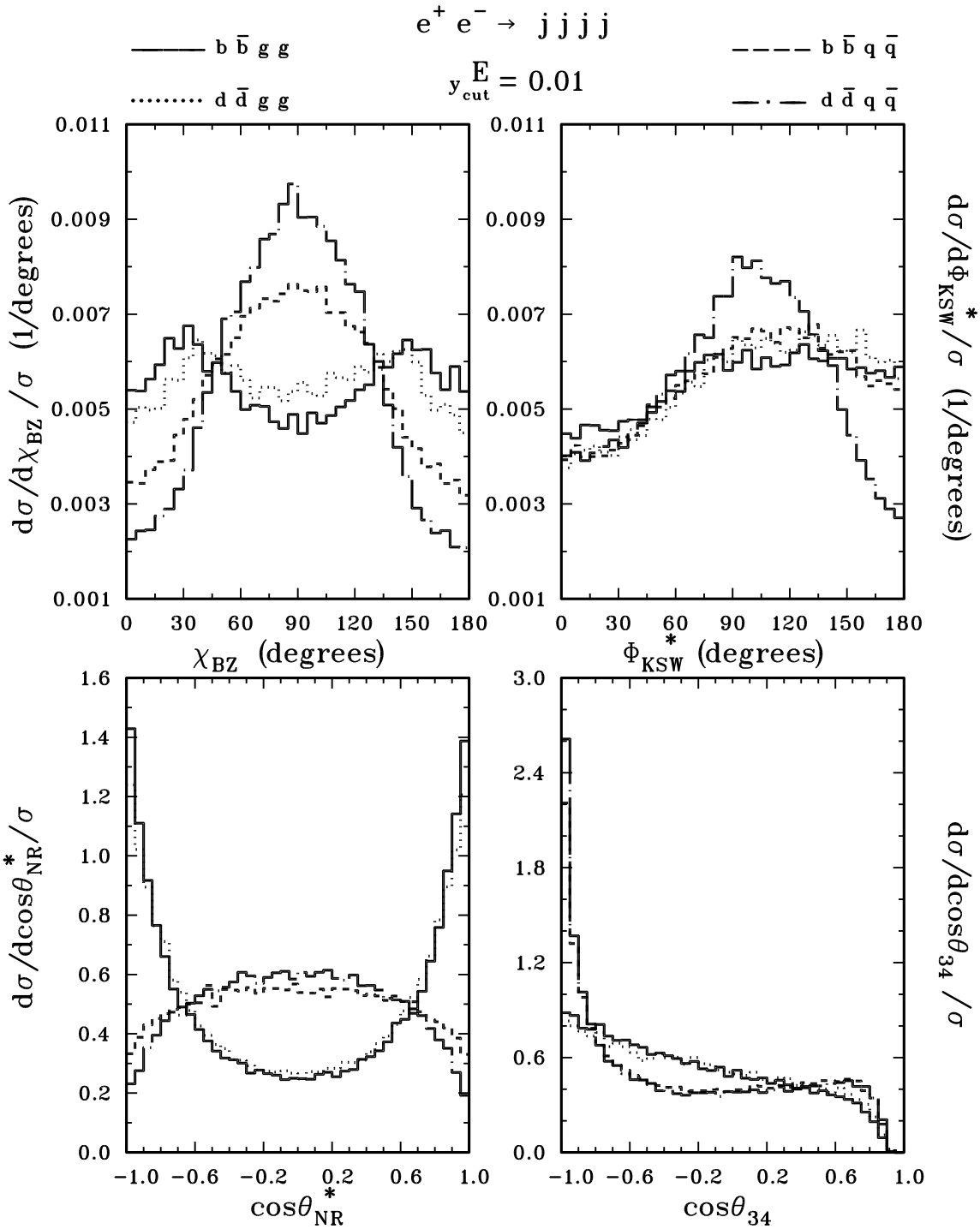

Fig. 3

Distributions in the angles χ_{BZ} and Φ^*_{KSW} and in the cosine of the angles θ^*_{NR} and θ_{34}, for the $Q\bar{Q}gg$ and $Q\bar{Q}q\bar{q}$ components in 4-jet events, in the E scheme with $y^E_{\rm cut} = 0.01$, where $Q = b, d$ and q is a massless quark.

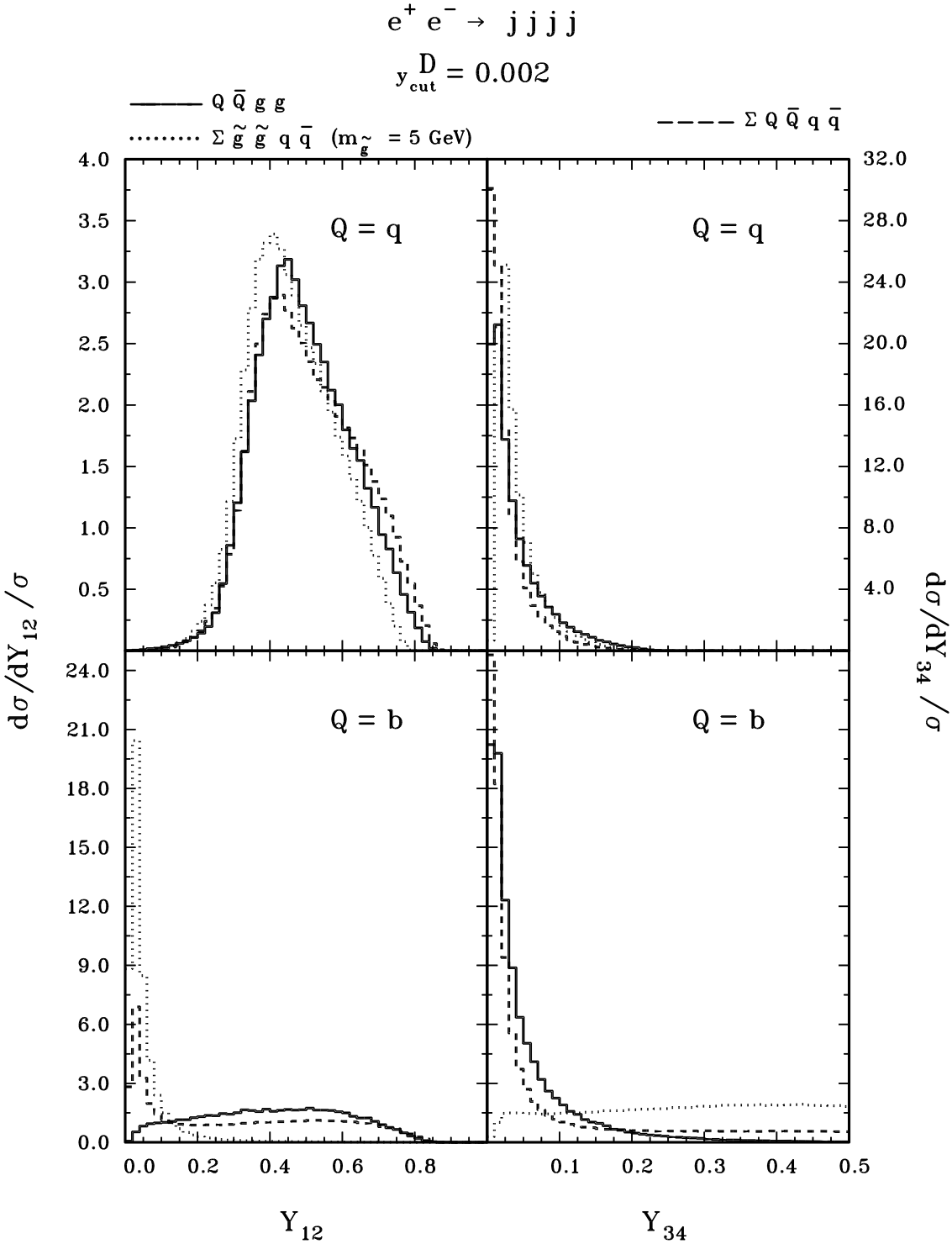

Fig. 4

Distributions in the rescaled invariant masses $Y_{ij} = M_{ij}^2/s$, where $ij = 12, 34$, for ordinary QCD and for SUSY 4-jet events, in the D scheme with $y_{\rm cut}^D = 0.002$, without ($Q = q$) and with ($Q = b$) vertex tagging. Here, $m_{\tilde{g}} = 5$ GeV.

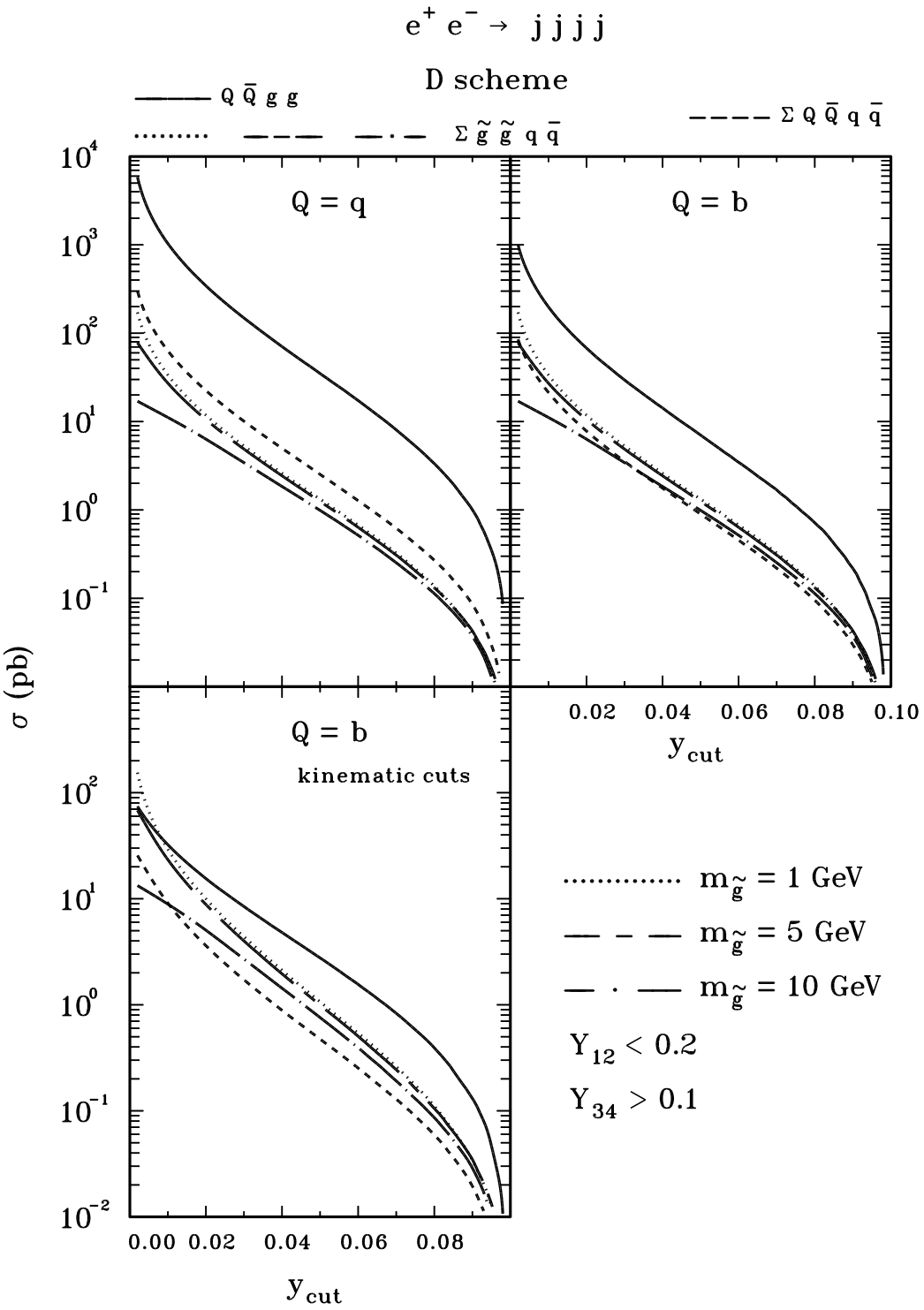

Fig. 5

Total cross sections of ordinary QCD and of SUSY 4-jet events, in the D scheme, without ($Q = q$) and with ($Q = b$) vertex tagging, and after the kinematic cuts, for three different values of $m_{\tilde{g}}$.

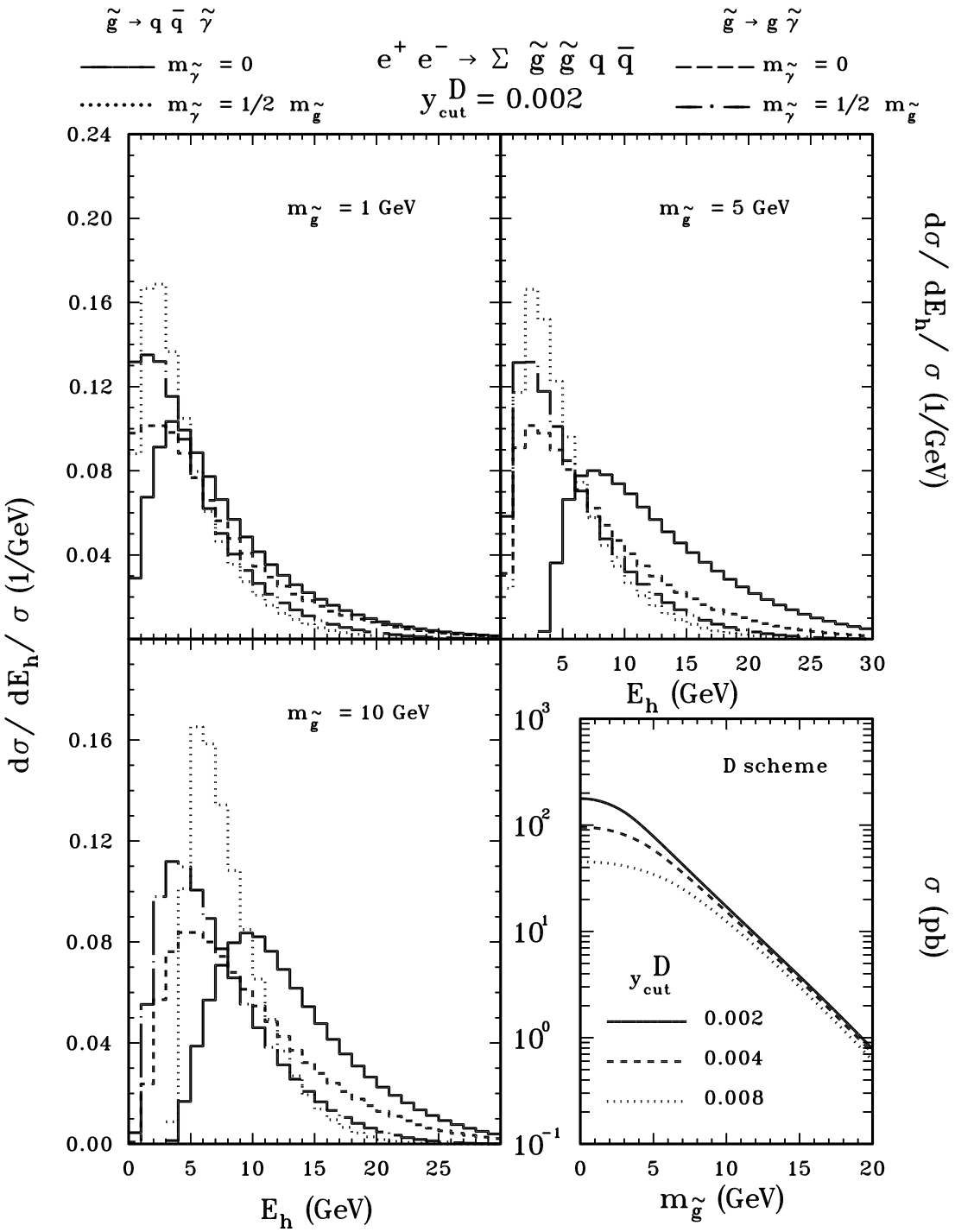

Fig. 6

Differential distributions in the hadronic energy of the 'gluino jet' after the two possible SUSY decays, in the D scheme, for various combinations of $m_{\tilde{g}}$ and $m_{\tilde{\gamma}}$; and total cross section of gluino events in 4-jets, as a function of $m_{\tilde{g}}$ and for three different values of $y^D_{\rm cut}$.