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Using colour portraits in identifying the quark-antiquark pairs in heavy boson decays

Preliminary

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Abstract

In searching for new heavy particle states and in studying properties of W-pairs, the colour flow between primary partons should provide an efficient tool in identifying the correct quark-antiquark pairs and in rejecting the background events. This approach is tested in a Monte Carlo based analysis of $e^+e^- \to W^+W^-, H^+H^-$, h^0A^0 and h^0Z^0 events with four quarks. The colour portrait is shown to provide useful complementary information to conventional methods in LEP 2 physics analysis.

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1 Introduction

We have recently investigated colour structure of $e^+e^- \to q\bar{q}g$ Mercedes events by using a new event-by-event method which is based on the interjet particles, i.e. particles not uniquely connected with a single jet of particles, to calculate weights of connectedness of the pairs of parton directions [1]. In multijet events with more than three identified parton directions, it is useful to study the colour connecetd parton-parton system in its rest frame, i.e. in the frame in which the two partons fly apart in opposite directions. According to colour dipole models, such as the Lund model, a colour field is strung between the two partons and results in a small sum of transverse momenta of the produced particles relative to the axis connecting the two colour charges (Figure 1). Similar colour dipoles could also form in cluster models like Herwig [2] or VNI [3]. A method using this effect has been proposed in Ref. [4]. We have studied applications of the colour flow reconstruction approach to different LEP 2 physics tasks. Since correct pairing of the decay products of a heavy particle appears to be the key to a clean experimental analysis of pair production of W's, H^+H^-, h^0A^0, h^0Z^0 etc., it is of vital importance to find the optimum way of identifying the decay products. The used strategy is the following: 1) find the parton profile of the event, 2) find the most probable colour flows between the parton directions, 3) combine the colour connected pairs of partons in order to distinguish particles such as W-bosons. The colour flow reconstruction can be also used in another important task in these analyses, the QCD background rejection. Finally, we have investigated possibilities to use the approach for extracting W^+W^- events with kinematical configurations most sensitive to colour reconnection effects.

2 Reconstructing colour portraits of multiparton final states

2.1 Background

Hadrons are supposedly produced in a process where the field created by colour charges polarises and arranges itself into colour neutral clusters which turn into observable particles. The initial hard parton directions should be observed as jets of energetic hadrons. However, the softer ones (the interjet particles) cannot be uniquely identified with any single hard parton direction. It is well known experimentally that the parton directions can be measured with better accuracy than their energies. The colour flow between the identified parton directions is an observable which should be measurable through the interjet particles, for reviews see [5].

In the following, we first aim at finding the hard parton directions, then reconstruct possible hypotheses for the colour flow structure (the antenna pattern) of the event and, finally, for each hypothesis, boost all the particles into the rest frames of each potential colour dipole, calculate the transverse momenta of the particles relative to the connection axis, assign the particles to the dipoles, then choose the hypothesis giving the minimum average sum of p_t's.

In defining the parton directions, several options are available. We prefer to use the energy flow, i.e. the hard particle tracks and energy deposit information in an iterative process described in Ref. [1]. One may also choose to use a conventional jet clustering algorithm. In the following analysis we utilise, for the sake of convenience in event analysis, the Durham jet clustering algorithm [6] for defining the parton directions. We then impose a four constraint fit which imposes energy and momentum conservation for the events to compensate for possible detector inefficiencies.

2.2 Analysis of heavy boson pair production

In analysing heavy particle production in channels of the type $e^+e^- \to W^+W^-$, H^+H^-, h^0A^0, $h^0Z^0 \to$ hadrons, one has to be able to 1) select the correct quark-antiquark pairs created in the decays and 2) reject the QCD background processes in an effective and least biased way. A bias introduced in the selection process is usually corrected by using a Monte Carlo parametrisation of the data. Since no consensus on modelling the colour reconnection processes exist, it is of primary interest to find selection procedures which do not depend on the model assumptions and which have high purity for events in the kinematical regions of interest regarding the colour reconnection phenomena.

There are three possible colour configurations, antenna patterns, in event candidates of the type $e^+e^- \to W^+W^- \to$ hadrons reconstructed as 4-jet events (see Figure 1). Our task is to find the most probable colour configurations for these events to be able to identify the correct quark-antiquark pairs and to reject the QCD background events. After defining the hard parton directions, the parton profile of the event, we boost, for each hypothesis, all the particles into the rest frame of each candidate pair, calculate the p_t's relative to the connection axis, and assign the particles to the pair giving the minimum sum of p_t's. Finally, the colour configuration giving the minimum average p_t of all the particles is chosen.

3 Monte Carlo event analysis

3.1 Track selection

For the charged tracks the following conditions were required: (1) Vertex Detector - Inner Detector tracks and Vertex Detector tracks without z (longitudinal coordinate along the beam direction) information are rejected, (2) track length is required to be within 20 cm - 400 cm, (3) track polar angles with respect to the beam direction are required to be within $10^o - 170^o$, (4) transverse impact parameter is required to be less than 4 cm and (5) the track momentum larger than 0.2 GeV/c, and (6) the track momentum, rescaled by using the calorimetric information, is required to satisfy $dp/p < 1$. For the neutrals it is required that the registered energy is larger than 0.5 GeV. In case of the hadron calorimeter information, it is required that the registered energy exceeds 0.7 GeV and that the showers registered in the STIC calorimeter deposit signals in more than a single cell.

3.2 4-jet events

Identifying the correct jet-jet pairs

For testing the performance of the method in identifying the correct jet-jet pairs resulting from a heavy boson decay, we have used Monte Carlo event samples of the following type: $e^+e^- \rightarrow W^+W^-$ and H^+H^- ($M_{H^-} = 60\ GeV/c^2$) generated by PYTHIA [7] and h^0A^0 ($m_{h^0} = 65\ GeV/c^2$, $m_{A^0} = 85\ GeV/c^2$, $tan\beta = 2$), h^0Z^0 ($m_{h^0} = 90\ GeV/c^2$) produced using the HZHA generator [8]. As a reference sample, we use QCD background events simulated by the PYTHIA event generator. All the samples were produced at the c.m.s. energy of 184 GeV with the fully hadronic decays only and processed by the complete DELPHI detector simulator [9]. We require the reconstructed c.m.s. energy, $\sqrt{s'}$, to be $\sqrt{s'} > 130\ GeV$ and the visible energy , E_{vis}, to be $E_{vis} > 110\ GeV$ in order to reject the events with large missing energies and/or momenta. By these selections the fully hadronic W^+W^- or Higgs event samples are reduced by 6% - 8%. In the QCD background sample these selection criteria efficiently reject the ISR events. In order to define the hard parton directions, the parton skeleton of the event, we utilise the Durham clustering algorithm [6]. In the following analysis we use only the events in which four parton directions are identified. For optimising the event selection efficiency we fix the Durham test variable, y_{cut}, at $y_{cut} = 0.007$ which leads to four jet rates of $63\% - 66\%$ in W^+W^- and Higgs samples. In the QCD background sample 8% of the events passing the ISR cuts are reconstructed as four jet events. For the selected samples of four jet events we impose energy and momentum conservation through a 4C fit for correcting possible detector inefficiencies.

For investigating the jet pairing efficiencies we need to assign the reconstructed jets of hadrons to the primordial quark-antiquark pairs resulting from the heavy boson decays. In our analysis, we identify a jet with a quark by considering the relative angular separation with respect to the Monte Carlo generated quark direction. A final state jet is identified with a quark which exhibits the smallest angular separation with respect to the jet. In case of an ambiguity the whole event is rejected [10]. The combined event selection efficiency is 54% for the H^+H^- sample, 53% for the h^0A^0 sample, and 56% for the hadronic W^+W^--events.

In the four jet final states there are three possible ways to combine the two jet-jet pairs to form a pair of bosons, i.e. there are three possible colour configurations of the event. In Fig. 2 the average p_t sum is plotted for all potentially connected pairs of jets together with the correct pairs known from the Monte Carlo simulation. It is seen that in the rest system of each pair the average p_t's are small and typically of the order 400 MeV/c. The method of identifying the correct colour configurations is based on the utilisation of the relatively soft interjet particles. The efficiency of the method increases as a function of the increasing Lorenz boost of the quark-antiquark system, i.e. for fixed heavy boson masses we expect higher efficiencies at higher c.m.s. energies. In Figure 3 all the six jet-jet masses (solid lines) and the two jet-pair masses (dashed lines) selected by minimising the average p_t relative to the colour connection are shown together with their relative fractions of the over-all jet-jet mass distribution in H^+H^-, h^0A^0 and W^+W^- event samples. For each data sample the transverse energy method prefers the correct simulated mass, i.e. the method tends to select the correct jet-jet pairing. The efficiency of identifying the correct pair, as calculated from the known Monte Carlo history of the jets, is 59% for the H^+H^- events, 54% for the h^0A^0 final states and 47% for the W^+W^- pairs [11]. In the h^0Z^0 final states, with a 90 GeV h^0, the h^0Z^0 pair is produced close to the threshold which causes the p_t method to become less efficient.

For the W^+W^- and H^+H^- event analysis the condition of minimum mass difference is often used in choosing the correct jet-jet pairs. In the following, we compare the approach based on the most probable colour configurations with the usual procedure based on the minimum mass difference. By choosing the jet-jet pairs which minimise the mass difference between the two reconstructed heavy boson candidates, we obtain the correct pairing efficiency of 83% in the H^+H^- sample and 61% in the W^+W^- sample. Note that for the h^0A^0 pairs with non-equal h^0 and A^0 masses the mass difference method cannot be used. For h^0Z^0 events at threshold minimising mass difference is also not efficient because of bosons being off-shell.

In order to investigate possible correlations of the two methods, we divided the W^+W^- events into two subsamples in which (1) the minimum mass difference identified the correct jet-jet pairing and (2) in which this failed. In sample (1) we obtained for the efficiency of the p_t method 49% while this efficiency was 45% for sample (2). This indicates that the two methods tend to be uncorrelated with each others and the p_t method therefore complements the pairing information given by the mass difference between the two jet-jet pairs.

Rejecting QCD four jet background

Out of the QCD processes which could be reconstructed as four jet events, the dominant and most difficult one to be separated from boson pair decays is a back-to-back quark-antiquark pair with two hard gluons. In the other background processes with gluons emitted by a single quark or one hard gluon splitting into quarks or gluons the secondary partons are relatively softer and not likely to be seen as separate jets. The $q\bar{q}gg$ process represents a colour configuration which is significantly different from the heavy boson decays (see Figure 1). In these events, the colour dipoles are formed between the two quark-gluon systems and between the two gluons. Intuitively, the colour connections could be formed most easily between the partons which are closest to each others in space-time [12].

At c.m.s. energies close to the pair production threshold, the angular separation of a quark-antiquark pair resulting from a heavy boson decay cannot be small, i.e. no colour connection is expected between the jet-jet pairs with small interjet angles. Since the opposite is predicted for the QCD background events, the colour flow reconstruction method provides an efficient way of rejecting the $q\bar{q}gg$ background. Our background analysis is based on comparison of the average p_t of a jet-jet pairing which exhibits the smallest interjet angle to the minimum average p_t in the event. For the QCD background events the probability of these two selection criteria to coincide or to have a small difference should be larger than for heavy boson pair events. In Figures 4 and 5 a difference between these two average p_t's calculated for the QCD background events and, on the other hand, for the W^+W^- (Fig. 4) and h^0Z^0 (Fig. 5) events is clearly observed. By using this measure as a discriminant variable, we obtain the background rejection efficiency shown in Figure 6.

A commonly adopted method in rejecting QCD backgrounds in W^+W^- or Higgs boson analyses is based on using a function of the minimum jet energy, $min(E_{jet})$, and the minimum jet-jet angle, $min(\alpha_{jet-jet})$. We plot the product $D = min(E_{jet}) \cdot min(\alpha_{jet-jet})$ in Figure 4 and 5 and the rejection efficiency of the D-variable in Figures 6a and 6b together with the efficiencies obtained by using the p_t method. The rejection power of the D-variable is seen to be stronger than the one obtained by using the p_t method. However, since the average p_t sum provides us with complementary information of the pairings, we can combine the two methods in defining a signal probability function as the normalised product of the two rejection factors (Figure 6).

3.3 3-jet events

It is interesting to investigate the special event configurations where two of the four final state jets fuse into a single jet of hadrons (Figure 1b). These events may be especially sensitive to the colour reconnection phenomena and, therefore, cause mass shifts and/or multiplicity depletion of soft interjet particles. In Table 1 we list the rejection factors for the different event selection criteria used for extracting the three-jet like final states in $e^+e^- \to W^+W^- \to q\bar{q}q\bar{q}$ and for rejecting the background events due to non-hadronic, i.e. $e^+e^- \to W^+W^- \to q\bar{q}l\nu, l\nu l\nu$ and due to the QCD events. We used data samples generated by PYTHIA [7] and processed by the complete DELPHI detector simulator [9].

The following successive selection criteria are considered: 1) $\sqrt{s'} > 150\ GeV$ for rejecting the events with an energetic radiative photon events, 2) visible energy $E_{vis} > 125\ GeV$, to select the hadronic decays, 3) no lepton with energy $E > 20\ GeV$ and no particles within a 10^o cone around the candidate, 4) acoplanarity < 0.06, 5) missing momentum $p_{miss} < 40\ GeV/c$, 6) number of jets is 3 ($y_{cut} = 0.01$), 7) the angle between the fastest and second fastest parton direction, α_{12}, is required to be between $120^o < \alpha_{12} < 160^o$ and the angle between the fastest and slowest parton direction, α_{13}, is required to be between $100^o < \alpha_{13} < 150^o$, 8) the transverse momentum sum of the particles in the parton-pair rest frame should be the minimum one with respect to the other pairings in an event, 9) the hadronic mass $W_{mass} > 70\ GeV/c^2$, 10) the value of the test variable, y_{cut}, determined at the limit of resolving four jets by the Durham algorithm, is required to be within $0.0015 < y_{cut} < 0.0085$. The total integrated luminosity collected by DELPHI in 1997 and 1998 is expected to be $200 pb^-1$ which results in order of 3000 WW W^+W^- events. With this statistics a sample of 64 three-jet like W^+W^- hadronic events with two of the jets fused together (93% of the events have two (anti)quarks closer than 45^o to each other) should be observed (see Fig. 1b). With the same set of selection criteria 20 background events due to the QCD continuum, and no semileptonic W^+W^- event remain (Table 1).

Table 1. The rejection factors for the different event selection criteria used for extracting the three jet final states in $e^+e^- \to W^+W^- \to q\bar{q}q\bar{q}$ and for rejecting the background events due to non-hadronic, i.e. $e^+e^- \to W^+W^- \to q\bar{q}l\nu, l\nu l\nu$ and due to the QCD events.

Cut	W^+W^-			QCD
	$q\bar{q}l\nu$ & $l\nu l\nu$	$qq\bar{q}\bar{q}$ $\alpha_{min} < 30^o$	$qq\bar{q}\bar{q}$ $\alpha_{min} > 30^o$	
General event selection	1.0	1.0	1.0	1.1
$s' > 150$	6.4	1.2	1.3	3.7
$E_{vis} > 125$	2.2	1.1	1.1	1.4
Leptons	5.7	1.0	1.0	1.0
Acoplanarity < 0.06	1.0	1.1	1.9	1.1
$P_{miss} < 40$	1.3	1.0	1.0	1.0
$N_{jet} = 3$	1.4	1.4	3.3	3.0
Jet angles	3.1	1.6	1.6	3.9
P_T minimisation	2.5	1.5	2.0	4.4
$W_{mass} > 70$	1.4	1.1	1.2	1.7
$0.0015 < y_{cut}^{3\to4} < 0.0085$	2.7	1.2	1.4	1.5
Acceptance in %	0.02%	14.9%	2.1%	0.1%
Expected N_{ev}	0	41	23	23

4 Discussion and Conclusions

We have demonstrated that analysis of the colour structures of multijet events can be used as an alternative method of choosing the correct jet-jet pairs and rejecting QCD background in analysis of production and subsequent decay of heavy objects at LEP 2 (W^+W^-, H^+H^-, h^0A^0 and h^0Z^0 - pairs).

This approach provides valuable complementary information to the conventionally used jet pairing method which is based on the minimum mass difference between the boson pairs and can be utilised in events with two heavy bosons of different masses. We are currently studying possible ways of combining the two approaches.

We have shown that this method can be used for separation between $q\bar{q}gg$ events and heavy boson pair production and can be combined with conventional methods resulting in improved rejection efficiency. Further studies of the improvement require applying the method to a complete analysis.

With the new approach three-jet like W^+W^- events, i.e. hadronic events with two overlapping jets, can be investigated for the first time, enabling further studies on colour reconnection phenomena.

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[10] This does not, naturally, apply to the QCD background events.

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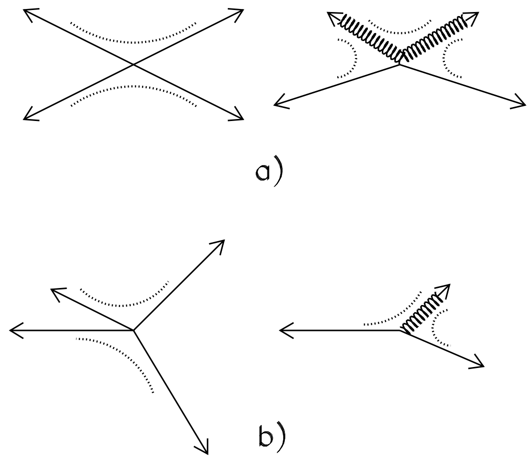

Figure 1: Illustration of the event portraits resulting from (a) a pair of heavy bosons decaying into four quarks and the corresponding QCD background event with a quark-antiquark pair and two hard gluons (4-jet events), (b) a pair of quarks emitted from the heavy boson decays fuse into a single jet of particles and the corresponding QCD background event with a quark-antiquark pair and a single hard gluon.

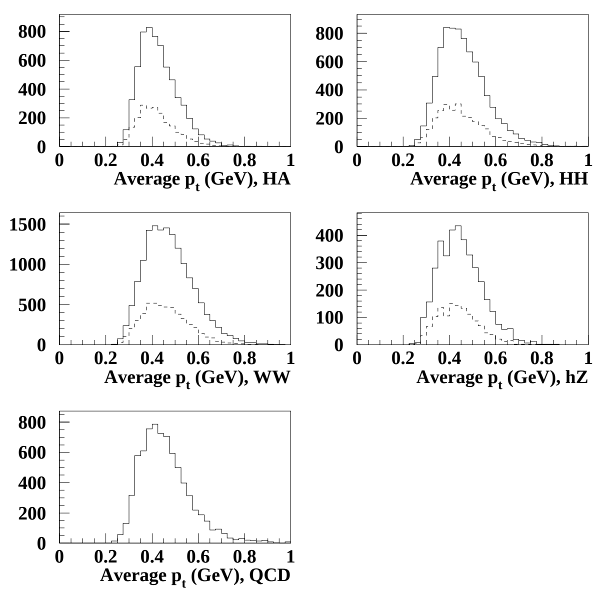

Figure 2: Average p_t sums of particles in the rest frames of all jet-jet pairs (solid lines) and in the correct jet-jet pairs (dashed lines) emitted from the heavy boson decays in $e^+e^- \to H^+H^-$, h^0A^0, W^+W^-, h^0Z^0 and in the QCD 4-jet hadronic events.

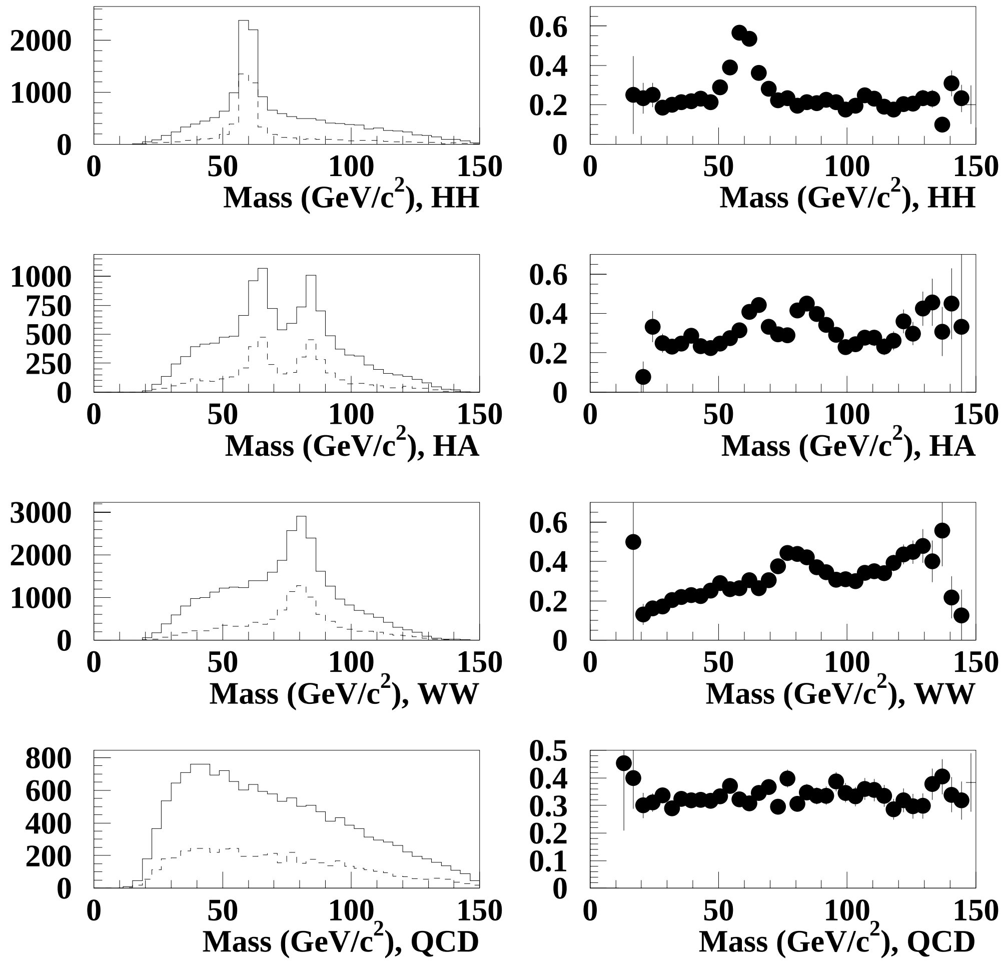

Figure 3: Effective jet-jet mass distributions for all jet-jet pairs (solid lines) and for the two pairs per event selected by using the minimum average p_t sum method (dashed lines) in the $e^+e^- \to H^+H^-$, h^0A^0, W^+W^- and in the QCD 4-jet hadronic events. On the right hand side the relative efficiency of the method is shown as the ratio between the two distributions.

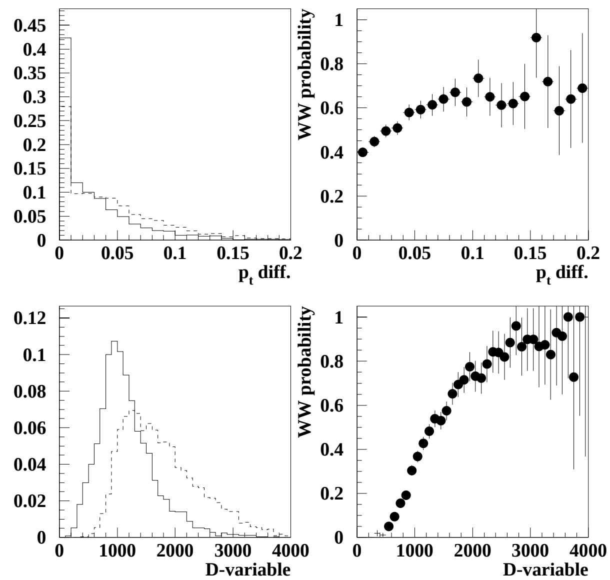

Figure 4: The difference between the average p_t sums calculated for the W^+W^- and QCD 4-jet events together with the W^+W^- p_t discrimination probability calculated as the ratio between the two distributions (upper distributions); and the D-variable and its W^+W^- discrimination probability calculated for the same events (lower distributions).

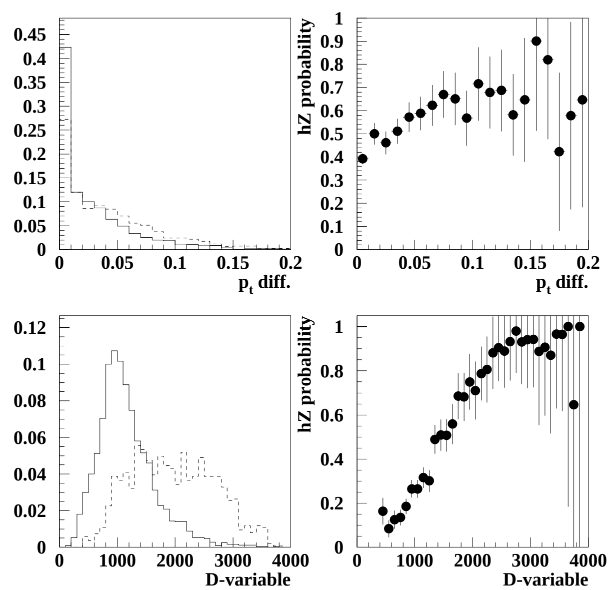

Figure 5: The difference between the average p_t sums calculated for the H^0Z^0 and QCD 4-jet events together with the H^0Z^0 p_t discrimination probability calculated as the ratio between the two distributions (upper distributions); and the D-variable and its H^0Z^0 discrimination probability calculated for the same events (lower distributions).

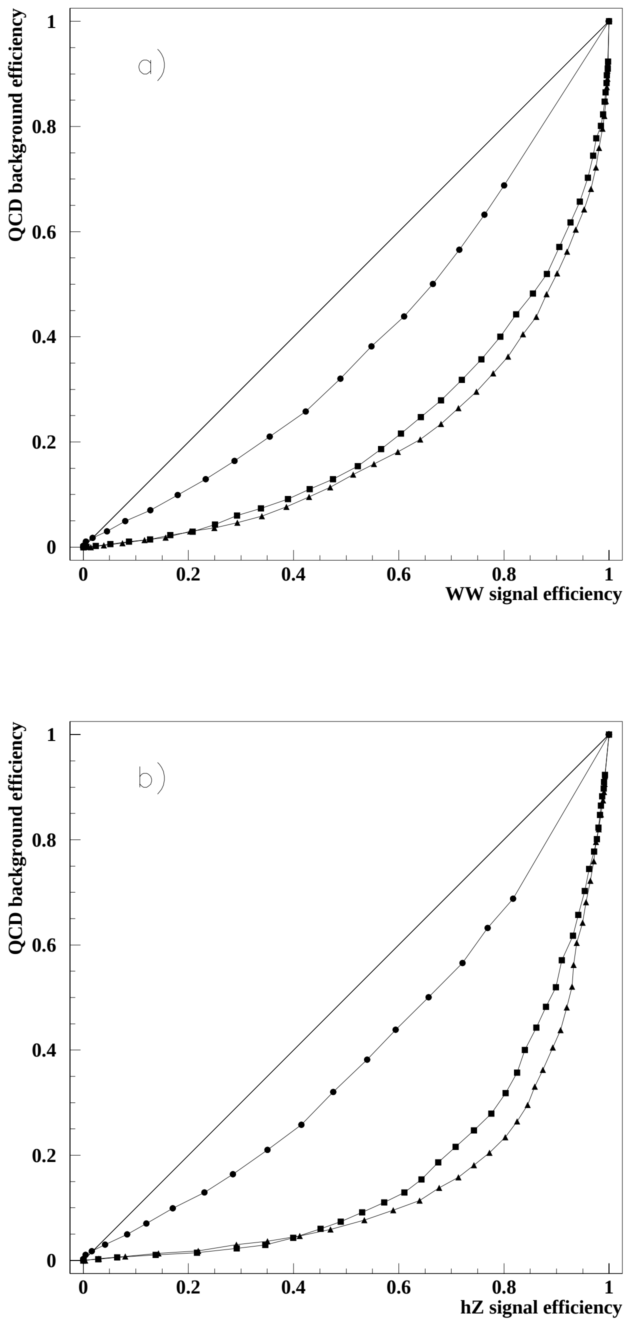

Figure 6: (a) The QCD background rejection efficiency vs. the W^+W^- signal efficiency calculated for the average p_t sum method (solid circles), for the D-variable method (solid squares) and for the combination of the two methods (solid triangles). (b) The QCD background rejection efficiency vs. the H^0Z^0 signal efficiency calculated for the average p_t sum method (solid circles), for the D-variable method (solid squares) and for the combination of the two methods (solid triangles).