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UNUSUAL CHARGED HIGGS SIGNALS AT LEP-2

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ABSTRACT

We have made a detailed study of the signals produced at LEP-2 from charged scalar bosons whose dominant decay channels are into four fermions. The event rates as well as kinematics of the final states are discussed when such scalars are either pair-produced or are generated through a tree-level interaction involving a charged scalar, the W and the Z. The backgrounds in both cases are discussed. We also suggest the possibility of reconstructing the mass of such a scalar at LEP-2.

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1 INTRODUCTION

A major part of the activities in high energy physics today concerns the signatures of the Higgs boson which is responsible for electroweak symmetry breaking in the Glashow-Salam-Weinberg model, popularly known as the standard model (SM). The SM symmetry breaking sector contains a complex scalar doublet, from which one neutral physical state ultimately remains while the others are gauged away to give masses to the weak vector bosons. This scalar decays primarily into either a pair of vector bosons or into a fermion-antifermion pair, depending on its mass. A number of search strategies have accordingly been formulated at both electron-positron and hadronic colliders [1] for this scalar.

There is, however, a parallel stream of activities, going on for quite some time now, to find out whether there is some new physics beyond the standard model. One aspect of this type of effort is to see the phenomenological implications of a larger scalar sector. This includes the possibility of models with two or more Higgs doublets. Also, scenarios with higher scalar representations of SU(2) cannot *a priori* be ruled out. In fact, some such representations could be theoretically advantageous for example, triplet scalars can give us a natural explanation of left-handed Majorana masses for neutrinos [2]. The important thing to note is that in certain situations, the dominant decay modes of some physical scalars could be different from those predicted by the SM. If these happen to be the lightest scalar states, then our first encounter with elementary spin-zero particles may very well be through some of these new channels. For example, as we shall see below, there is a distinct possibility of scalars with no tree-level fermion-antifermion interaction [3]. Such scalars, in a certain mass range, may decay dominantly into four fermions [4]. Also, some of them may be produced [5] through a tree-level interaction involving a charged scalar, the W and the Z, something that is disallowed in the SM and its extensions into two or more Higgs doublets. In this paper, we discuss some of these unusual signals of a charged scalar at LEP-2.

In section 2 we outline the theoretical scenarios in which these non-standard signals of a scalar may be observed. Sections 3 and 4 are devoted respectively to the signals of pair-produced charged scalars and those produced through the $H^{\pm}W^{\mp}Z$-coupling. We conclude the discussion in section 5.

2 THEORETICAL MOTIVATIONS

As we have already stated, there are two crucial components in the unusual interactions of a scalar, namely (i) the absence of tree-level fermion-antifermion interactions, and (ii) the presence of a tree-level $H^{\pm}W^{\mp}Z$-coupling. We give below some specific examples of models where one or both of the above features are present. For further details of these models, we refer the reader to the existing literature.

(a) A two Higgs doublet model can be constructed [6] where only one doublet couples to fermions(f) with isospin both $\frac{1}{2}$ and -$\frac{1}{2}$. This is one of the options available to ensure that there is no flavour-changing Yukawa coupling at the tree-level [7]. In this case, in general, physical states are formed after the two doublets mix. It can be shown that one of the two neutral physical scalars ceases to have any $f\bar{f}$-coupling if the mixing angle is either 0 or $\pi/2$ (caused by some discrete symmetry in the potential). But the charged scalar will still have a fermionic coupling. On the other hand, if there are more than two doublets, (for example, those in the Weinberg model of CP-violation) [8], charged Higgs physical states totally decoupled from fermions can be envisioned. However, none of these doublet extensions allows a tree-level $H^{\pm}W^{\mp}Z$-interaction.

(b) A model with a Higgs doublet together with a complex ($Y = 2$) triplet has been proposed to explain the origin of left-handed Majorana masses for neutrinos. Such a Higgs structure can be built within a left-right symmetric scenario [2]. The introduction of a triplet makes it possible to have a tree-level $H^{\pm}W^{\mp}Z$-interaction, although the physical charged Higgs state need not in general be decoupled from fermion-antifermion pairs [9]. It should be noted here that all triplet (and higher) representations imply a departure from unity in the tree-level value of the ρ-parameter, defined as $\rho = \frac{m_W^2}{m_Z^2 cos^2\theta_W}$. With just one complex triplet, such a contradiction with experiments [10] can be avoided by assuming that the vacuum expectation value (VEV) of the neutral member of the triplet is very small compared to the doublet VEV, as a result of which the triplet contributes negligibly to the W-and Z-masses. Such a solution, however requires fine tuning.

(c) A more aesthetic way out of the problem with ρ is to postulate [11] that there is more than one triplet (or higher representation), arranged in such a manner that their *net contribution*

to ρ is 1. One way to do this is to have one complex ($Y = 2$) and one real ($Y = 0$) triplet along with the conventional doublet. Moreover, one has to assume that the VEV's of the neutral components of the two triplets are equal, as a consequence of a custodial symmetry. This allows the triplet to contribute substantially to the gauge boson masses without affecting the value of ρ. It has been shown [12] that the scalar potential can be constructed to obey such a custodial symmetry upto arbitrary orders, although it requires fine-tuning (to the same extent as that in the SM itself [13]) to maintain the symmetry when gauge couplings are switched on. This scenario also implies a tree-level $H^{\pm}W^{\mp}Z$ vertex. In addition, it leads to a 5-plet of scalar physical states ($H^{\pm\pm}, H^{\pm}, H^0$) under the $SU(2)$ custodial symmetry which have no overlap with the doublet, and hence have no fermion-antifermion couplings at all [14].

Among the above examples, (a) has feature (i) only, (b) has feature (ii) only, and (c) has both. In the remaining discussion, we shall not make any specific model assumption. However, we shall consider the signals of a charged Higgs which has both of the above features.

Here we are concerned with signals at the LEP-2. Consequently our attention will be focussed on a charged scalar of mass between 45 and 80 GeV approximately. There are two ways in which such an object can be formed in e^+e^- annihilation, namely, pair production, via s channel γ and Z exchange and associated production via the $H^{\pm}W^{\mp}Z$-interaction. The second possibility has already been studied [4, 15], although [15] discusses it more in the context of the next linear collider (NLC). In what follows, we will give details of the signals in the first case, and will do some further analysis of the signals vis-a-vis backgrounds in the second case also. Being in the aforesaid mass range, the charged scalar can decay either into four fermions at the tree-level, mediated by a virtual W and a virtual Z, or into a fermion-antifermion pair at the one-loop level. The relative strengths of these two channels are independent of the strength of the $H^{\pm}W^{\mp}Z$ coupling, which occurs identically in both decay widths. It has already been shown [4], contrary to earlier claims, that the tree-level process is dominant once the Higgs is as massive as about 50 GeV. Therefore, for such masses as can be looked for at LEP-2, we assume a 100% branching ratio for the four-fermion decay

of a singly charged scalar in our analysis.[1]

3 PAIR-PRODUCTION OF CHARGED SCALARS

A charged scalar can be pair-produced in e^+e^- annihilation through s-channel diagrams mediated by the Z and the γ. The production cross-section is model-independent [16]. In Figure 1 we show this cross-section as a function of the charged Higgs mass for centre-of-mass energies 176 GeV and 192 GeV respectively. The corresponding cross-sections for associated charged Higgs production via the $H^{\pm}W^{\mp}Z$ vertex are also shown. We can see from the Figure that the latter can be quite sizable. However, since these numbers are for maximal mixing between the doublet and exotic Higgs representation(s), this mechanism dominates over pair-production only if the mixing angle is large. This is allowed only in option (c) discussed in section 2.

For the charged scalars of our interest, each can decay (via a virtual W and a Z) into four fermions, which can be (a) two quark-antiquark pairs($q\bar{q}q\bar{q}$), (b) a quark-antiquark and a lepton-antilepton pair($q\bar{q}$ $\ell^+\ell^-$), and (c) two lepton-antilepton pairs($\ell^+\ell^-\ell^+\ell^-$). Though the final states with increasingly higher number of leptons have cleaner signatures, one pays a heavy price in terms of branching ratios. When two charged scalars are involved, one can hope to get a sufficient number of events only by studying the final states with the largest branching ratios. For this, at least one of them has to decay purely hadronically. The other will either go to four jets, or to two jets (via the virtual Z) and a lepton and a neutrino (via the virtual W). While the former of these has a total branching ratio of about 25%, that for the latter case is approximately 14% (including leptons of both positive and negative charges). It is straightforward to see that all the other final states will give experimentally insignificant rates. (By 'leptons' here we mean electrons and muons).

In Figures 2(a, b) we present the multijet cross-sections, calculated in a parton level Monte Carlo simulation, as functions of the charged Higgs mass for a centre-of-mass energy of 176 GeV. In Figure2(c) we present the same thing but at a higher centre-of-mass energy

[1]In principle, if there are triplets, a singly charged scalar can decay into two leptons if lepton number violation is allowed. We disregard that possibility here.

of 192 GeV. We have used a jet-merger criterion that two jets are merged into one if $\Delta R \leq 0.7$, where $\Delta R^2 = \Delta\phi^2 + \Delta\eta^2$, $\Delta\phi$ and $\Delta\eta$ being the separations in azimuthal angle and pseudorapidity of the initial partons. We find that even though the final state nominally has 8 partons, it has jet multiplicities 6-8 as a result of jet-merging. As we can see from the Figure, the largest cross-section is in the 6-jet final state irrespective of the Higgs masses and centre-of-mass energies considered here. One should note that in the Figure 2(a) cross-sections have been obtained without using any invariant mass cut, whereas in the Figure 2(b) and Figure 2(c) we have demanded that the invariant mass of no combination of jets lies within $m_W \pm 5$ GeV. We will explain the need for such a cut later.

In Figure 3 we show the distribution in ΔR between different jet pairs before merging. This shows that the jets coming out of the two oppositely charged scalars are clearly separated into two hemispheres; if one labels the jets from one scalar by the numbers 1 to 4 and those from the other by 5 to 8, then ΔR within the same set tends to peak between 0.5 and 1, while the peak between opposite sets is observed around 3. As we can see from this Figure, if one puts a judicious cut on the maximum value of ΔR, one can reduce contamination of the decay products of one of the scalars from those of the other, making it possible to think about the measurement of the scalar mass by reconstructing the invariant mass in a given hemisphere.

Figure 2(a) shows an initial rise of the cross-section with m_H, particularly with high jet multiplicities, upto a certain value. The 6-jet events dominate principally in the low Higgs mass region. This is because a higher mass Higgs boson has lower 3-momentum, which causes the four daughter fermions to be more spherically spread out, thereby reducing the probability of merging. This gives rise to more 7- and 8-jet events for a heavier Higgs until phase space suppression of the cross-section takes over. In contrast to Figure 2(a), in Figures 2(b, c) where the invariant mass cut has been used, the 6-jet events dominate over 7 and 8 jet events for the complete range of Higgs masses we are interested in. This is because of the fact that in the 6-jet final state, merging of jets increases the total 6-jet invariant mass, so the peak around $m_W \pm 5$ GeV is smeared out. The energy distributions for the four most energetic jets (after jet merging) have also been shown in Figure 4.

Backgrounds to the above events are most serious for 6 jets. As the number of jets

increases, the direct QCD final states become suppressed. However, the strongest SM backgrounds in this case are 6-jets coming from $W^{\pm}$-pairs produced at LEP-2. These can be as much as 2 to 5 times the signals for, say, $m_H = 55$ GeV, depending on the jet-merging criterion [17]. To remove this background, we have demanded in our parton level Monte Carlo that no combination of jets may have invariant mass in the range $m_W \pm 5$ GeV on both sides. The 7- and 8-jet events are relatively immune to such backgrounds. On the whole, for $\sqrt{s} = 192$ GeV and $m_H \leq 60$ GeV there can be still some 7-odd events even with 7-jets, and upto 15 events with 6-jets (assuming an integrated luminosity of 500pb^{-1} per year), provided that 7 jets can be identified, this should be a reasonable rate. For higher Higgs masses the rate starts falling even further.

When one charged Higgs decays into a pair of jets together with a lepton and $\not{p}_T$, the final states become relatively cleaner from the viewpoint of backgrounds. However, because of branching fractions one has a further suppression of about $(\frac{14}{25})$, as we have mentioned earlier. The event topologies are similar to the case of all jets; a separation into opposite hemispheres can still be seen for the particles coming out of the two scalars. We also impose a lower cut of 2 GeV on the lepton energy throughout, which does not really affect the signal as the lepton energy peaks beyond 10 GeV. The isolations between the charged lepton and the jets have been shown in Figure 5; for a typical jet in the same hemisphere the distribution peaks at a healthy value of $\Delta R \approx 1$, whereas for an oppositely directed jet the peak is around 3. It is also to be noted that the lepton generally emerges at high angles with the beam pipe, as its rapidity distribution shows in Figure 6.

4 SINGLY PRODUCED CHARGED SCALARS

As has been mentioned already, an exotic charged Higgs may also be produced at an e^+e^- collider through a tree-level $H^{\pm}W^{\pm}Z$ vertex. This process has been investigated in some earlier works. Of these, reference [15] gives details of the expected event shapes and the SM backgrounds for an e^+e^- collider with centre-of-mass energy in the range 500 GeV– 2 TeV. Here we focus on them in the special context of LEP-2, in supplement to our earlier study.

There are two channels of production a Z-mediated s-channel graph producing a charged

scalar together with a real or a virtual W, or a WZ-fusion process producing a charged scalar together with $\bar{e}\bar{\nu_e}(e^+\nu_e)$. The latter diagram becomes important for $\sqrt{s} \sim 500$ GeV or above because of s-channel suppression. At LEP-2, the former is found to be play the dominant role. The production cross-section is proportional to $\sin^2\theta_H$, where θ_H is the mixing angle of the doublet Higgs with that belonging to a higher representation. In other words, it gives the fractional contribution of the exotic scalar representation to the W-mass. In models with a custodial symmetry of the type described in section 2, $\sin\theta_H$ can be as high as of the order of unity without any phenomenological contradiction. The results shown in the Figures corresponds to $\sin\theta_H = 1$; for other values the rates can be obtained by suitable scaling. Let us add here for the sake of completeness that in case (b) described in section 2, LEP data impose the restriction $\sin^2\theta_H < 0.009$.

As Figure 1 shows, this kind of production has higher cross-sections compared to pair-production for larger values of the scalar mass, provided that $\sin\theta_H$ is large. Again, the event rates are maximum when out of the 6 fermions in the final state, at least 4 are hadrons. In Figure 7 the cross-sections are shown for the multijet signals, where, again, the same jet-merging criterion has been employed. Although the 4-and 5-jet final states do not stand much of a chance of detection against QCD backgrounds, it should be noted that the 6-jet events have higher rates than those in the previous section so long as $\sin\theta_H$ is large. Remembering that the invariant mass cuts are applied here, this seems to be a rather optimistic situation for the exotic Higgs signals. When either the associated W or the virtual W in Higgs-decay gives rise to a pair of leptons, the events become even cleaner, although a corresponding suppression of approximately $(\frac{2}{7})$ with respect to the hadronic channel in the overall rate is inevitable.

Reference [15] identifies the following SM processes as major backgrounds to the $H^{\pm}W^{\mp}Z$-induced production: (a) $e^+e^- \longrightarrow W^+W^-Z$, (b) $e^+e^- \longrightarrow e^+e^-W^+W^-$ and (c) $e^+e^- \longrightarrow e^+W^-Z\nu$. However, these can be serious only when the centre-of-mass energy is large enough and the Higgs can actually decay into a real W and a Z. For the scalar mass range that we are concerned with at LEP-2, background (a) is not kinematically allowed. Also, so long as $m_H \leq m_W$, (b) and (c) can be removed by demanding that no fermion pair reconstructs to the W or the Z-mass. This includes both invariant mass reconstruction and, for leptons

with neutrinos, Jacobian peaks in the transverse plane. In a similar way $e^+e^- \longrightarrow W^+W^-\gamma$ or $e^+e^- \longrightarrow ZZ\gamma$ does not pose a serious threat; moreover, a simple estimate shows their cross-sections to be on the order of 10^{-3}pb. Another potential source is when a Z-pair is produced in e^+e^- collision. One of these Z's may go to a pair of jets, while the other may go to a $\tau^{\pm}$-pair. Further decays of the tau's may mimic the $jets + lepton + \not{p}_T$ or the multijet signal. However, without any cuts, the signal is higher than the backgrounds by at least a factor of 2. In addition, the softness of the products of tau-decay provides a way of suppressing them by suitable kinematic cuts.

5 CONCLUSIONS

We have performed a detailed analysis of the types of events expected at the LEP-2 if there happen to charged scalars in the mass range of 50-80 GeV, which do not have tree-level fermion-antifermion couplings. On the whole, the rates of single production from the $H^{\pm}W^{\mp}Z$-vertex are large provided that the contribution of non-doublet VEV's to the gauge boson masses is dominant. On the other hand, if that contribution is small, then one has to depend primarily upon pair-production which has smaller rates. But then the high multiplicity of final state particles seem to help the signals in rising above the backgrounds once appropriate cuts are imposed.

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Figure Captions

Figure 1 : Total cross-section (1) for $e^+e^- \to H^\pm W^\mp$ in pb (a) at $\sqrt{s} = 176$GeV and (b) at $\sqrt{s} = 192$GeV; (2) for $e^+e^- \to H^+H^-$ in pb (c) at $\sqrt{s} = 176$GeV and (d) at $\sqrt{s} = 192$GeV as a function of charged Higgs mass.

Figure 2(a) : Multijet cross-section (without invariant mass cut as discussed in the text) for $e^+e^- \to H^+H^- \to jets$ in pb at $\sqrt{s} = 176$GeV as a function of charged Higgs mass. (a) 6-jets, (b) 7-jets and (c) 8-jets in the final states respectively.

Figure 2(b) : Multijet cross-section (with invariant mass cut as discussed in the text) for $e^+e^- \to H^+H^- \to jets$ in pb at $\sqrt{s} = 176$GeV as a function of charged Higgs mass. (a) 6-jets, (b) 7-jets and (c) 8-jets in the final states respectively.

Figure 2(c) : Multijet cross-section (with invariant mass cut as discussed in the text) for $e^+e^- \to H^+H^- \to jets$ in pb at $\sqrt{s} = 192$GeV as a function of charged Higgs mass. (a) 6-jets, (b) 7-jets and (c) 8-jets in the final states respectively.

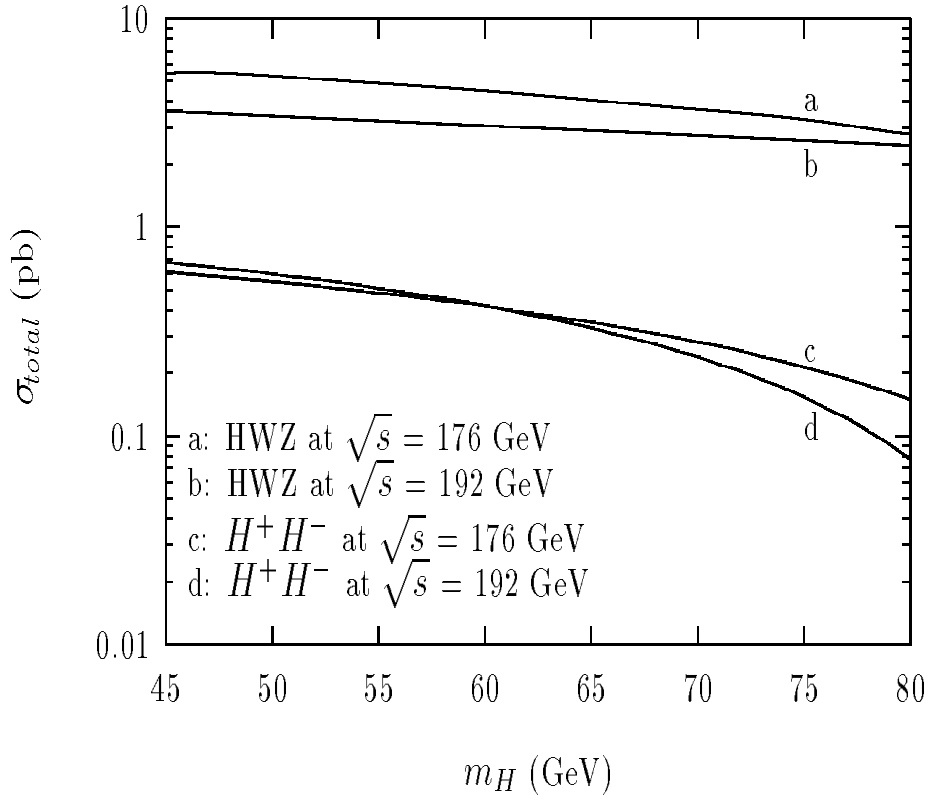
Figure 3 : Isolation between different jet pairs for $e^+e^- \to H^+H^- \to jets$ at $\sqrt{s} = 192$GeV and $m_H = 55$GeV. ΔR between two jets from same hemisphere: (a) and (b); ΔR between two jets from opposite hemispheres: (c) and (d).

Figure 4 : Jet energy distributions for the four most energetic jets for $e^+e^- \to H^+H^- \to jets$ at $\sqrt{s} = 192$GeVand at $m_H = 55$GeV.

Figure 5 : Isolation between different jet pairs and between a charged lepton and jet for $e^+e^- \to H^+H^- \to jets + \ell + \nu$ at $\sqrt{s} = 192$GeV and $m_H = 55$GeV. ΔR: between two jets(a), jet and charged lepton (b) from same hemisphere; and a jet and charged lepton (c) from opposite hemisphere.

Figure 6 : Lepton rapidity distribution for $e^+e^- \to H^+H^- \to jets + \ell + \nu$ at $\sqrt{s} = 192$GeV and $m_H = 55$GeV.

Figure 7 : Multijet cross-section (with invariant mass cut) for $e^+e^- \to H^\pm W^\mp \to jets$ in pb at $\sqrt{s} = 192$GeV as a function of charged Higgs mass. (a) 5-jets, (b) 6-jets and (c) 4-jets in the final states respectively.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σ_{total} (pb)
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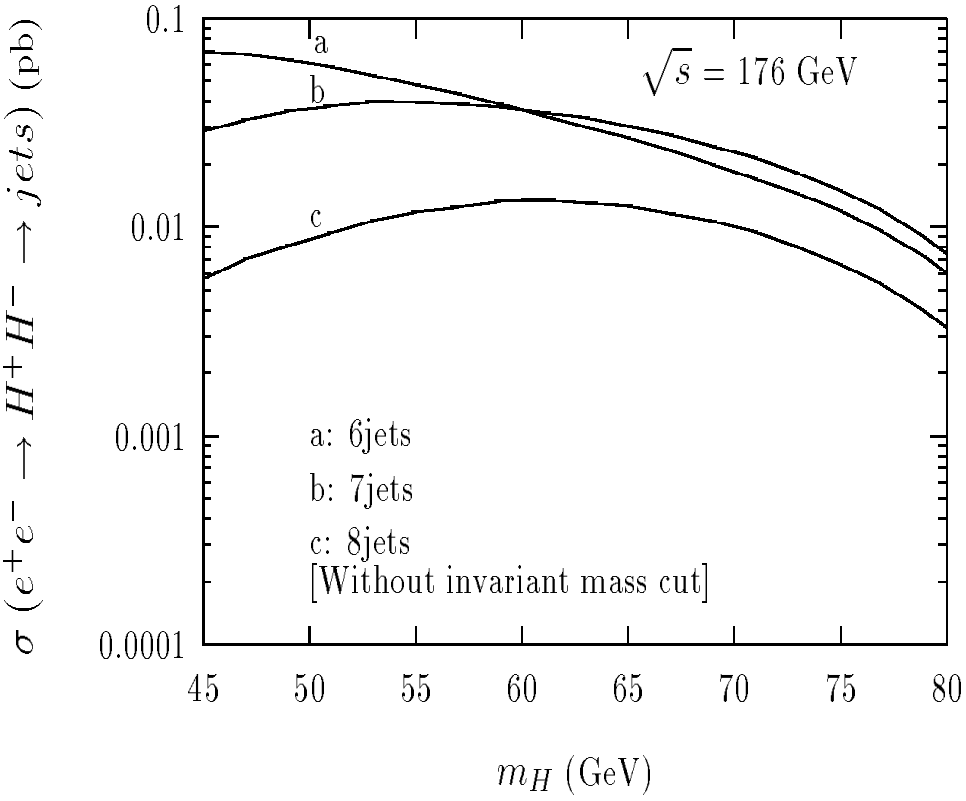
a: HWZ at $\sqrt{s}$ = 176 GeV
b: HWZ at $\sqrt{s}$ = 192 GeV
c: H^+H^- at $\sqrt{s}$ = 176 GeV
d: H^+H^- at $\sqrt{s}$ = 192 GeV

Fig. 1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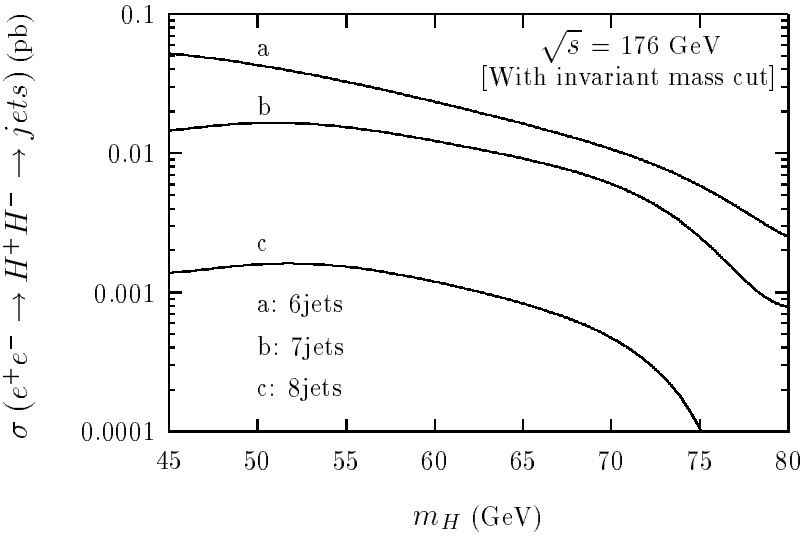
$\sqrt{s}$ = 176 GeV
a: 6jets
b: 7jets
c: 8jets
[Without invariant mass cut]
$\sigma\ (e^+e^- \to H^+H^- \to jets)$ (pb)
m_H (GeV)

Fig. 2(a)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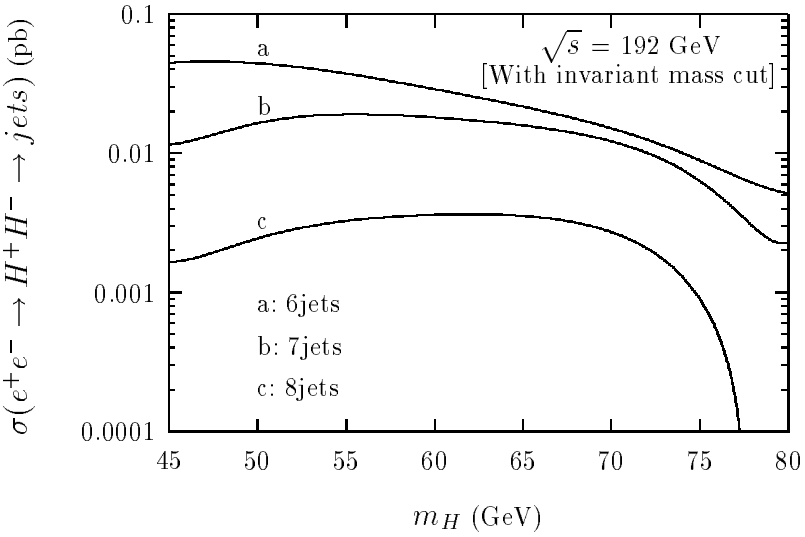
$\sqrt{s}$ = 176 GeV
[With invariant mass cut]
a: 6jets
b: 7jets
c: 8jets
$\sigma\,(e^+e^- \to H^+H^- \to jets)$ (pb)
m_H (GeV)

Fig. 2 (b)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$\sqrt{s}$ = 192 GeV
[With invariant mass cut]
a: 6jets
b: 7jets
c: 8jets
$\sigma(e^+e^- \to H^+H^- \to jets)$ (pb)
m_H (GeV)

Fig. 2 (c)

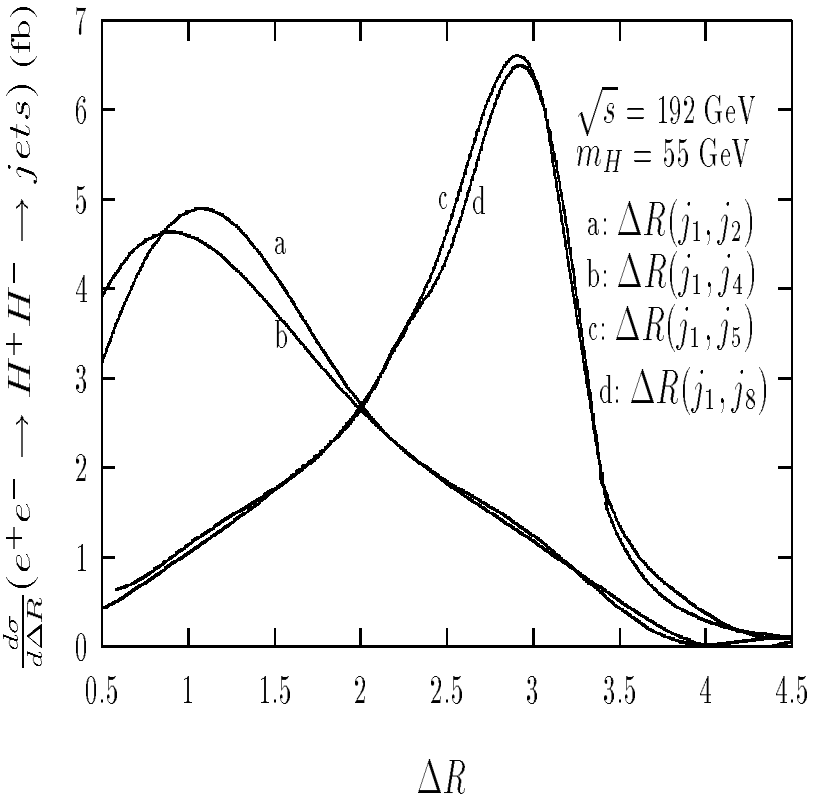
$\frac{d\sigma}{d\Delta R}(e^+e^- \to H^+H^- \to jets)$ (fb)
ΔR
$\sqrt{s}$ = 192 GeV
m_H = 55 GeV
a: $\Delta R(j_1, j_2)$
b: $\Delta R(j_1, j_4)$
c: $\Delta R(j_1, j_5)$
d: $\Delta R(j_1, j_8)$
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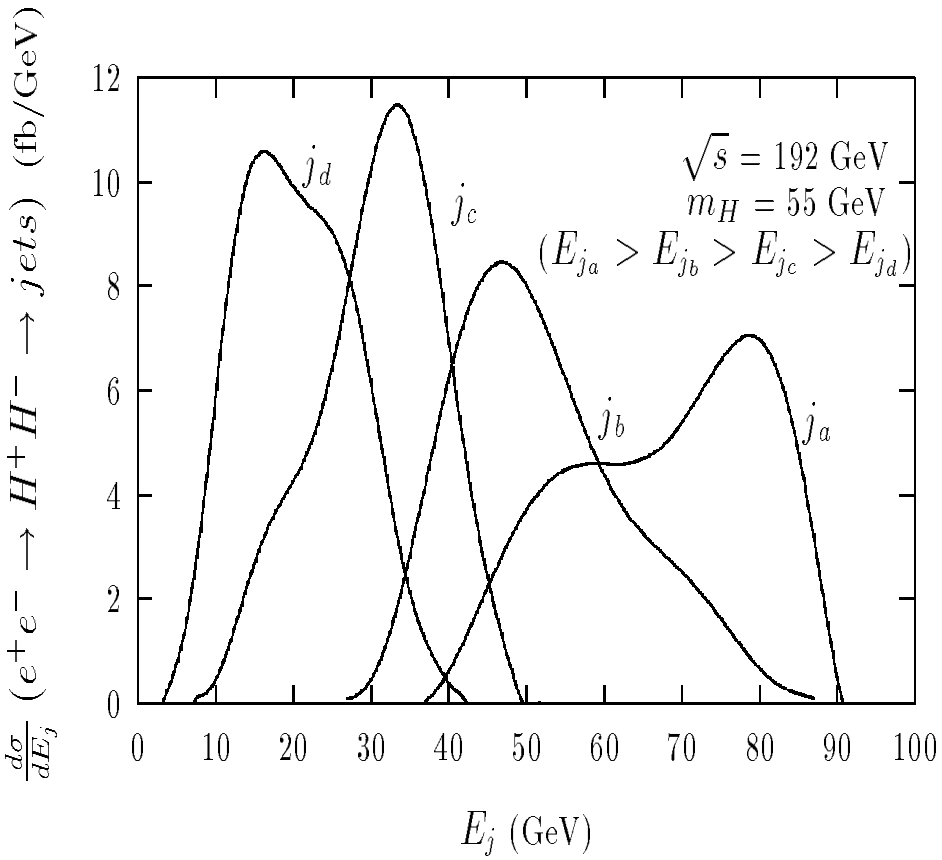
Fig. 3


$\frac{d\sigma}{dE_j}$ $(e^+e^- \to H^+H^- \to jets)$ (fb/GeV)
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10
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30
40
50
60
70
80
90
100
E_j (GeV)
j_d
j_c
j_b
j_a
$\sqrt{s}$ = 192 GeV
m_H = 55 GeV
$(E_{j_a} > E_{j_b} > E_{j_c} > E_{j_d})$

Fig. 4

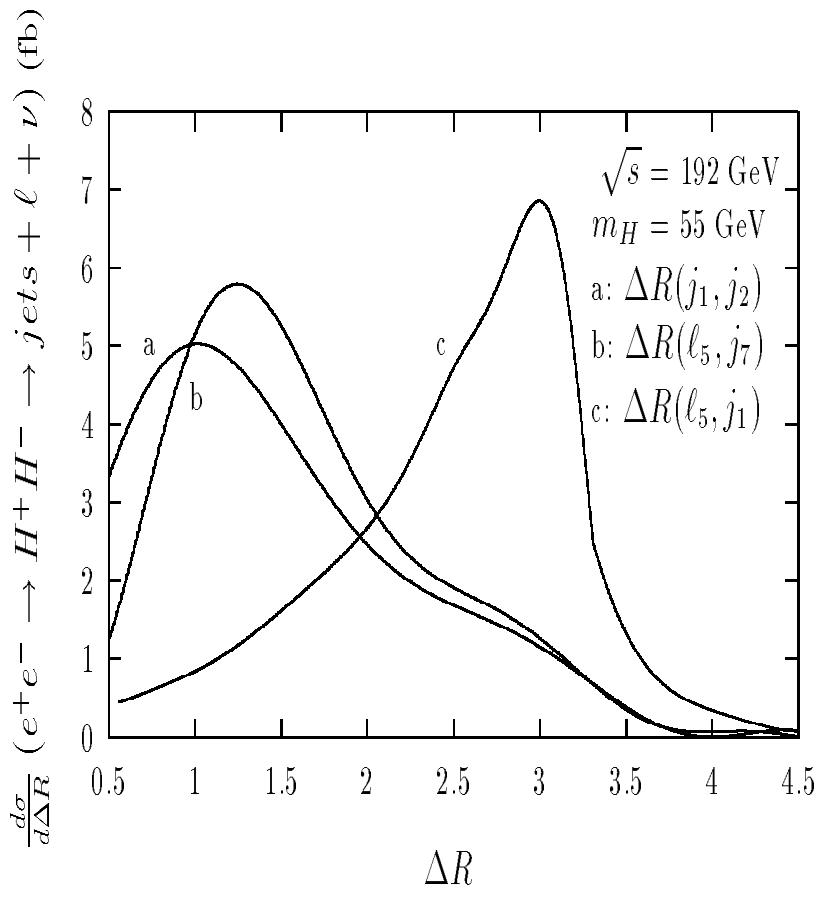
$\frac{d\sigma}{d\Delta R}$ $(e^+e^- \to H^+H^- \to jets + \ell + \nu)$ (fb)
ΔR
$\sqrt{s}$ = 192 GeV
m_H = 55 GeV
a: $\Delta R(j_1, j_2)$
b: $\Delta R(\ell_5, j_7)$
c: $\Delta R(\ell_5, j_1)$
a
b
c
0
1
2
3
4
5
6
7
8
0.5
1
1.5
2
2.5
3
3.5
4
4.5

Fig. 5

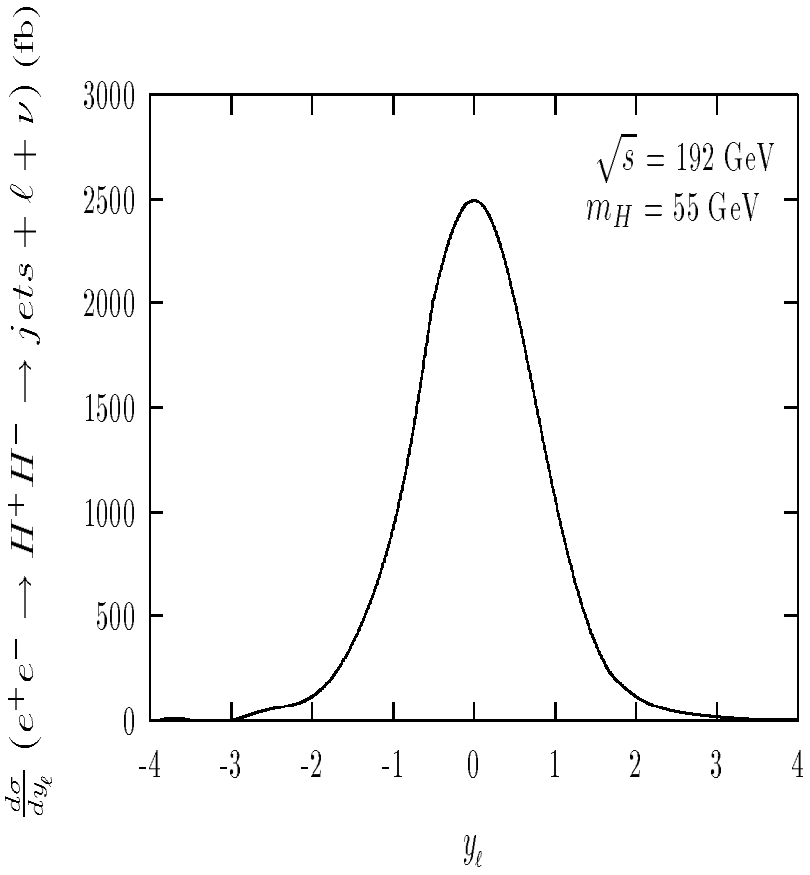
$\frac{d\sigma}{dy_\ell}$ $(e^+e^- \to H^+H^- \to jets + \ell + \nu)$ (fb)
3000
2500
2000
1500
1000
500
0
-4
-3
-2
-1
0
1
2
3
4
y_ℓ
$\sqrt{s}$ = 192 GeV
m_H = 55 GeV

Fig. 6

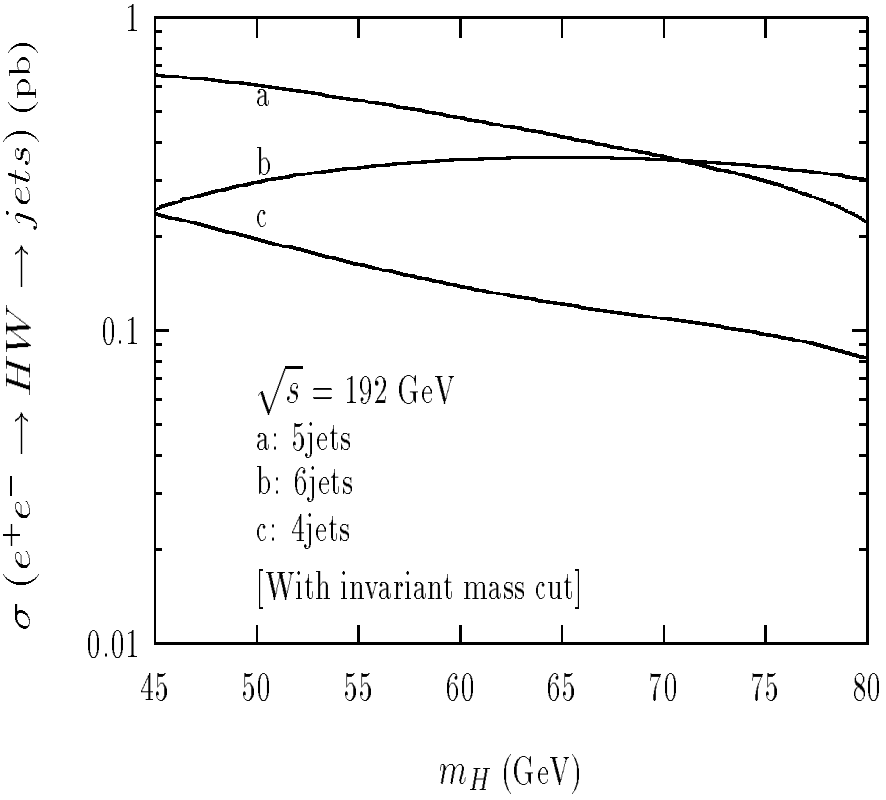
1
0.1
0.01
45
50
55
60
65
70
75
80
a
b
c
$\sqrt{s}$ = 192 GeV
a: 5jets
b: 6jets
c: 4jets
[With invariant mass cut]
$\sigma\ (e^+e^- \to HW \to jets)$ (pb)
m_H (GeV)

Fig. 7