TAGGING THE HIGGS

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ABSTRACT

We study the effects of jet tagging at small angles on signal and background cross-sections in the production of a heavy Higgs boson in pp collisions at LHC/SSC energies, in which the Higgs decays, via a W^+W^- pair into a charged lepton, a neutrino and a pair of jets. The use of the tagging conditions is shown to improve the signal-to-background ratio by about two orders of magnitude. A more detailed analysis of the decay products can substantially enhance this ratio. We point out that the energy-asymmetry of the jets may be very helpful in this respect. Our conclusion is that a 1:1 signal-to-background ratio is feasible at both the LHC and the SSC.

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Establishing the existence of the Standard Model Higgs boson, and studying its properties, will be one of the main goals of the next generation of colliders. In particular, if the Higgs is "heavy", that is for m_H larger than about 200 GeV, it will be produced most copiously at hadron colliders such as the SSC or LHC [1]. If no ultraheavy top quark or heavy new fermion is kinematically accessible (as we shall assume in the following), the dominant decay modes of the Higgs are $H \rightarrow W^+W^-$ and $H \rightarrow ZZ$, in a ratio of approximately 2:1 [1]. Due to the enormous QCD background, isolating the subsequent decay of the bosons into four jets is hopeless [2]. Unfortunately, semileptonic decays such as $H \rightarrow VV \rightarrow jjll$ have smaller branching ratios while the QCD background to these processes (in which two normal QCD jets 'fake' a $V=W$ or Z) is still bigger by a factor of about one hundred, even after relatively stringent cuts [3]. While it is of course possible to isolate a corner of phase space where the signal-to-background ratio is more favourable [4], imposing such very tight cuts can easily reduce the signal even more.

In reference [5] it was stressed that the purely leptonic decay $H \rightarrow ZZ \rightarrow ll' ll'$ provides, in principle, an extremely clean signature with very moderate background: unfortunately the branching ratio for this process is small, about $1/3 \times (2 \times 0.03)^2 = 0.0012$ (throughout this paper, l stands for either e or μ). While this mode is evidently going to be looked for, it would be very nice to have a handle on the semileptonic decay as well, since this has a much larger branching ratio of about $2 \times (1/3) \times (2/3) \times (2/9)$, i.e. about 20%. In [5] it was pointed out that the ZZ mode in Higgs decay differed from its main background, continuum production of Z pairs, in that a heavy Higgs is predominantly made in W/Z fusion, depicted in fig.1, in which the quark radiating the virtual boson survives in the final state.

It was argued that these quarks might be tagged; the background to such a process is suppressed by a factor of α_s^2 , and moreover the p_T spectrum of the scattered quarks, described by the boson propagator $(p_T^2 + \mathcal{O}(m_V^2))^{-1}$, is expected to be significantly harder than that of QCD bremsstrahlung, with a spectrum which rather goes like p_T^{-2} . It was concluded that indeed double tagging would drastically improve the signal-to-background ratio in the ZZ decay mode.

In the present paper we aim at extending the tagging method in order to determine (as was conjectured already in [5]) whether it can also provide a handle on the semileptonic decay of the Higgs. We estimate the Higgs signal and the QCD background and find that a S/B ratio of about 1:3 is very well possible. A more detailed look at the resulting event topologies (which will be discussed in the last part of this paper) even suggests that S/B ratios of 1:1 should be attainable, while the event rate is still a good deal higher than that for the purely leptonic mode. We shall now describe our calculation in some detail, and then proceed to discuss the results.

The cross section for the production and decay of a heavy Higgs boson can be computed at various different levels of refinement. The simplest one, using the so-called equivalent-boson approximation [6], is not well suited to our purpose because it neglects the p_T behaviour of the scattered quarks. Since the fusing W's or Z's are explicitly off-shell, it is dangerous (as was discussed in [7]) to employ the extended set of Feynman diagrams which contains also non-Higgs graphs, as discussed in [8]. The complete (large) set of graphs, including non-fusion graphs necessary to regulate the off-shell effects has been computed [9], but its evaluation is

very slow and cumbersome; moreover we are here only interested in the behaviour of the cross section in the resonance region, which is sufficiently well described by the single graph of fig.1. We therefore adopt the following recipe. First, we pick a value for q_H^2 , the mass squared of the resonating Higgs boson, distributed according to a Breit-Wigner shape with width Γ_H (the total Higgs width) around the nominal Higgs mass value m_H . Then, we compute the amplitudes for the production of a stable, on-shell Higgs boson, as first given by Cahn and Dawson [6]. Finally, we let the Higgs decay into a W pair with subsequent semileptonic decay. This can be done by either letting the W's decay independently, assuming them to be 100% longitudinally polarized; or by using a decay correlation weight w_{dc} given by

$$w_{dc} = \frac{144 (p_e \cdot p_u)(p_\nu \cdot p_d)}{m_H^4 - 4m_H^2 m_W^2 + 12m_W^4},$$

where $p_{e,\nu,u,d}$ are the momenta of the charged lepton, antineutrino, up-quark jet and down-antiquark jet, respectively (or the corresponding antiparticles). These procedures give essentially the same results; in the following we shall use the latter.

The computation for the background process is much more involved. Ideally, one would use the complete matrix elements for the process $pp \rightarrow Wjjjj$. Calculating these is an enormous task, but within reach of modern computational techniques. Lacking these matrix elements at present, we have to use an approximation. The two 'tagging jets' come out with large

rapidities and energies (as we shall see) and can therefore be expected to be reasonably well described by the Altarelli-Parisi splitting functions. For 'bremsstrahlung' jets with rapidity in some interval $\Delta\eta$ these are given by

$$P_{q \rightarrow q}(z) = \frac{4}{3} \cdot \frac{\alpha_s \Delta\eta}{\pi} \cdot \frac{1+z^2}{1-z},$$

$$P_{g \rightarrow q}(z) = \frac{1}{2} \cdot \frac{\alpha_s \Delta\eta}{\pi} [z^2 + (1-z)^2],$$

$$P_{q \rightarrow g}(z) = \frac{4}{3} \cdot \frac{\alpha_s \Delta\eta}{\pi} \cdot \frac{1+(1-z)^2}{z},$$

$$P_{g \rightarrow g}(z) = 6 \frac{\alpha_s \Delta\eta}{\pi} \left[z(1-z) + \frac{1-z}{z} + \frac{z}{1-z} \right].$$

Here the 'momentum fraction' z which is left in the parton after it has emitted the 'tagging jet' is only unambiguously defined in the collinear limit: in our case, z can be taken to be either the fraction of energy or of longitudinal momentum, or some linear combination of these; the differences between the various choices are expected to be of order $\langle p_T^2 \rangle / s$, where s is the overall CM energy of the original partons - a small number.

After emission of the two 'tagging jets' we are left with a 'central system' which in the present case goes into W_{jj} . The matrix elements for parton-parton $\rightarrow W_{jj}$ are known [10]: however, care must be taken to ensure that the momenta used as input in these expressions are on-shell, else gauge invariance is spoiled and the results will lose their meaning. The momenta of the two partons after tagging jet emission can in principle be made massless in two ways. We might neglect the parton transverse momentum after tagging jet emission, so that the conservation of overall transverse

momentum is slightly violated, but with the advantage that the transverse phase spaces decouple: or we might rescale the space-like part of the two partons after emission in their CM frame, keeping their energies fixed, which will slightly alter the parton directions in the lab frame. We have chosen the first option for simplicity: in either case, deviations from the exact result are expected to be of the order of $\langle p_T^2 \rangle/s$, and hence not a problem for the moment.

At this point we want to stress that doing the calculations this way cannot, of course, be the final answer. However, it is only worthwhile to do a more complete background calculation once it has been verified that our tagging scheme in fact works. Therefore we do not worry too much about the above ambiguities: they tend anyway to be much smaller than the other well-known theoretical ambiguities in this problem (choice of QCD scale, structure functions etc.).

In order to examine the validity of this approximation to the matrix element, we have studied a 'toy process', in which a W particle, i.e. a W boson with a mass of 500 GeV, with the real W 's couplings to the fermions, is produced in pp collisions at 17 TeV: the total cross section for this is 25.9 nb. Subsequently, we computed the cross section for $pp \rightarrow W'jj$ where the two jets are required to have rapidities in a given interval and a given minimum energy (these cuts seem to us more reasonable than a cut on p_T at large rapidities). This we did once using the exact matrix elements for Wjj mentioned above, and once using the splitting function approach: a comparison of the results gives an idea of the trustworthiness of our approximation. In fig.2 we give the results in the form of the ratio between the 'exact' and the 'approximate' results for tag jet energy thresholds $E_{\min}$

of 500 GeV and 1 TeV, and rapidity intervals from η_0-1 to η_0+1 , for different values of η_0 . It is seen that for very high rapidities the approximation becomes extremely good, as expected: for realistic rapidities such as the interval 3-5 the approximation is systematically too low. It turns out that this is because a sizeable fraction of the total cross section is coming from tagging jets with quite large p_T : for instance, with $\eta_0=4$ and $E_{\min}=500$, about 30% of the events will contain at least one tagging jet with a p_T of more than 100 GeV. At $E_{\min}=1$ TeV the p_T tends to be of course still larger, and the approximation correspondingly worse. At this point it should be noted that when we vary the definition of z , or treat the kinematics exactly, as mentioned above, the resulting cross sections are the same within the statistical error: it seems difficult to define an approximation that gives a better result automatically. Rather, this breakdown of the approximation is due to the presence of a large number of subprocesses that cannot be formulated as 'bremsstrahlung' of quark or gluon jets, e.g. processes like $uu \rightarrow W'ud$. Removing these from the exact expression decreases the difference between the exact and approximate results by about 50%; the remaining discrepancy is due to the contributions from Feynman graphs in which, for instance, the W' is emitted before bremsstrahlung has taken place. We conclude from this that the approximation can reasonably be expected to be good to within a factor of 2 if we use the cuts $\eta_0=4$ and $E_{\min}=1$ TeV on the tag jets; moreover our background estimates will tend to be on the low side. Since the above splitting function algorithm is precisely that on which the existing shower Monte Carlo programs for initial-state radiation are based, they would be expected to be in agreement with our approximation rather than with the exact result. One should keep in mind throughout this paper that the background can be expected to have

to be multiplied by a factor of about 2 eventually. While this is unfortunate this systematic error is not larger than e.g. the scale ambiguity in α_s , which enters to the fourth power in this problem, or possible changes in structure functions. An independent check of this type was presented in [5] where a similar comparison was made for the process $pp \rightarrow ZZj$ (in that case, of course only one splitting function was used). An agreement of better than 10% was found, in qualitative agreement with our conclusions here.

In our toy model, the cross section after the tagging cuts comes out to about 2.86 pb (using the exact matrix element), which implies a reduction of the W' cross section by a factor of about 10^4 . Apart from the occurrence of two additional powers of α_s , this reduction is also due to the fact that by requiring a minimum energy for the two tagging jets we automatically force the whole system to have much higher invariant mass than when no tag jets are observed. In the case of Higgs production, in contrast, the scattered quarks already tend to come out with sizeable energy, so the reduction in rate will be much less severe. Before we proceed to present our results for the Higgs analysis we would like to stress that, since the QCD background is so much reduced by the tagging condition, the Higgs production from gluon fusion will also be almost completely eliminated. Our results are therefore completely insensitive to any choice of value for the top quark mass (except of course for changes in the W, Z branching ratios, see above).

We shall now discuss the effects of the various cuts that we employ. For definiteness, we shall assume for the moment $m_H = 500$ GeV and a pro-

ton-proton CM energy of 17 TeV. In this case the total cross section for Higgs production (neglecting the contribution from gluon fusion) is 0.74 pb, corresponding to 1467 events of the type $lvjj$ per 10^{40} cm^{-2} of integrated luminosity. In our calculations we shall assume that the $lvjj$ system has an invariant mass within one unit of Γ_H from the nominal Higgs mass m_H , both in the signal and the QCD background. For a relatively light and hence narrow Higgs we replace this window by 20 GeV to each side of m_H , to take the experimental resolution into account [5]. In fig.3^b we have depicted for this case the rapidities of the tagging jets and in fig.3^a those of the 'central' jets, i.e. those jets that in our Monte Carlo program come from the W decay. As expected the tagging jets typically make very small angles with the beams, while the central jets (and leptons) are produced more or less isotropically. We therefore impose an upper limit of 2 on the absolute rapidity of both central jets; for the QCD background we moreover require the two QCD jets to make up an invariant mass to within 5 GeV of the W mass. These 'central cuts' reduce the signal to about 986 events, while the background yield is about 10^5 events - this is the 'factor of 100' swamping of the Higgs signal reported earlier [3].

For the 'tagging cuts' it is seen that a minimum and maximum absolute rapidity of 3 and 5, respectively, are adequate. We have chosen to employ a rapidity gap of 1 between the central and tagging jets in order to avoid misidentifying the two types. We also, as mentioned, require a E_{min} cut on the tagging jets, which we put at 1000 GeV. For the accuracy of the background estimate it would be nicer to take, say, 500 GeV, but as it turns out, this would enhance the signal (by a factor of about 2) much less than the background (by a factor of about 7). As can be seen in Table 1, after the tagging cuts the signal and the background have become of the same order of magnitude.

Once a S/B ratio of about unity has been established it becomes worthwhile to look for a more detailed event structure which may allow us to discriminate real hadronic W decays from 'fake' ones due to QCD. It might be argued that the decays of two W's coming from a Higgs decay are more correlated than those containing QCD jets. However it turns out that such correlations are extremely weak: for instance, the azimuthal correlation between the $e\nu$ decay plane and the plane formed by the two jets (in the Higgs rest frame) is given by

$$\frac{1}{\sigma} \cdot \frac{\partial \sigma}{\partial \phi} = 1 + a(m_W/m_H) \cos 2\phi ,$$

$$a(x) = \frac{2x^4}{1 - 4x^2 + 12x^4} ,$$

where ϕ is the angle between the two planes. For a 500 GeV Higgs the ϕ dependence is negligible, given the meager statistics. Another example is the correlation between the two polar decay angles of the W's: we find

$$\langle \cos \theta_1 \cdot \cos \theta_2 \rangle = -\frac{1}{9} a(m_W/m_H) ,$$

where $\theta_{1,2}$ are the polar angles of the e^- and the up-type jet in the rest frames of the W^- and W^+ , respectively (both results can be derived immediately from the decay correlation defined above). We conclude that we must look at the hadronic W decay itself and not at correlations between it and the leptonic decay.

We propose to use the jet-energy asymmetry, defined as

$$A = \frac{|E_1 - E_2|}{E_1 + E_2},$$

where E_1 and E_2 are the two jet energies, evaluated in the Higgs rest frame (this frame is defined as soon as the v momentum is obtained). It can easily be shown that, for small m_W/m_H , the expected distribution $d\sigma/dA$ of A for W decays where the W comes from a Higgs decay, is given by

$$\left(\frac{\partial \sigma}{\partial A} \right)_{\text{Higgs}} \propto 1 - A^2,$$

whereas a simple model calculation leads us to expect that for most QCD events the distribution will rather look like

$$\left(\frac{\partial \sigma}{\partial A} \right)_{\text{QCD}} \propto \frac{1}{1 - A^2}.$$

This is indeed borne out by the Monte Carlo: in fig. 4 we give the distributions of A in the two cases. If we make an 'asymmetry cut' by requiring A to be smaller than .5, only about 30% of the signal is lost while the background is reduced by a factor of about 6. The situation is summarized in Table 1, where we have compared the signal and background at each stage. After all cuts have been applied, 30.6 events are left in the Higgs channel, while the QCD events number about 17.5 (but we should keep the

factor 2 in our approximation in mind). We conclude that a combination of tagging and an asymmetry cut will in fact work to isolate a good sample of Higgs events already at LHC; note that the corresponding sample of 'gold-plated' $H \rightarrow ZZ \rightarrow 4$ leptons events is expected to be about 5.3 (where we have included a realistic rapidity cut of $-2 < \eta < 2$ on each charged lepton).

In Table 2 we present the results (after all cuts) for various Higgs masses and CM energies, accompanied for completeness by the expected number of 'gold-plated' ZZ channel events.

In conclusion, we have demonstrated that tagging the bremsstrahlung jets associated with heavy Higgs production provides a powerful way of reducing a serious QCD background to the $H \rightarrow WW \rightarrow jjlv$ decay channel. This is precisely what was conjectured in [5]. A signal to background ratio of 1 per cent is increased to order one to one. Although there is necessarily a substantial reduction in the signal, the number of Higgs events which survive should be sufficient for detection at LHC energies up to Higgs masses of order 1 TeV.

There are several deficiencies in the present analysis. The exact background matrix elements for W^*jjjj production are not yet known. We have used an approximation to the matrix element and shown that it works satisfactorily for a toy process with similar kinematics. As a result of this comparison we estimate that we are probably underestimating the background by a factor of two. There are as always additional theoretical uncertainties of the same order. More positively, we have made no serious attempt to "optimise" the cuts. Rather we have chosen representative values for the cuts which appear reasonably optimal. A more comprehensive study should yield a significant improvement. Our present detector config-

uration envisages a central detector covering 15-165 degrees in polar angle to detect the central leptons and jets from Higgs decay, and a forward detector covering 0.8 - 5 degrees for tagging jets with energy of at least 1 TeV. It is clearly important to find out whether this latter configuration is feasible in practice.

The present study should therefore be regarded as a "first look" at what promises to be an extremely important detection scenario for heavy Higgs bosons.

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cuts applied	Higgs signal	QCD background
none	1476 ± 7	-
central	986 ± 6	$(1.01 \pm 0.02) 10^5$
+ tagging	42.5 ± 0.3	131 ± 13
+ asymmetry	30.6 ± 0.3	17.5 ± 0.9

Table 1: Expected numbers of semileptonic Higgs and background events for an integrated luminosity of 10^{40}cm^{-2} , under the influence of the cuts discussed in the text, at 17 TeV, $m_H = 500 \text{ GeV}$.

m_H (GeV)	17 TeV		40 TeV	
	Higgs	QCD	Higgs	QCD
300	52.9 ± 2.0 (11.0)	58.4 ± 2.7	318 ± 18 (32.5)	713 ± 22
500	30.6 ± 0.3 (5.3)	17.5 ± 1.9	205 ± 8 (20.4)	214 ± 8
700	19.6 ± 0.4 (3.2)	12.4 ± 0.9	162 ± 7 (13.9)	140 ± 8

Table 2: Expected numbers of $lvjj$ events for an integrated luminosity of 10^{40} cm^{-2} , for the Higgs signal and the QCD background, after the cuts described in the text. The errors are the statistical errors from the Monte Carlo calculation only. In brackets: the number of events expected in the channel $H \rightarrow ZZ \rightarrow 4$ charged leptons.

FIGURE CAPTIONS

fig.1: The Feynman graph for WW or ZZ fusion into an on-shell Higgs boson.

fig.2: Ratio between the exact and approximate results in the process $pp \rightarrow W'jj$, as a function of the cuts on the rapidities and the energies of the jets.

fig.3: Rapidity distributions of the central jets (3^a) and the tagging jets (3^b) in the process $pp \rightarrow H+jj \rightarrow l\nu jj+jj$.

fig.4: The jet energy asymmetry distribution for the Higgs signal (solid line) and the QCD background (dashed line).

Fig. 1

Fig. 2

Fig. 3

Fig. 4