



## Higgs Decays to Muons in Weak Boson Fusion

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### Abstract

We investigate the muonic decay of a light Higgs boson, produced in weak boson fusion at future hadron colliders. We find that this decay mode would be observable at the CERN LHC only with an unreasonably large amount of data, while at a 200 TeV vLHC this process could be used to extract the muon Yukawa coupling to about the 10% level, or better if significant improvements in detector design can be achieved.

### I. INTRODUCTION

Hadron colliders such as the Fermilab Tevatron or CERN LHC are machines well suited to direct observation of a Higgs boson or other remnants of electroweak symmetry breaking and fermion mass generation. In particular the LHC promises fairly complete coverage of Higgs decay scenarios [1,2], including general MSSM parameterizations [1,3], and even invisible Higgs decays [4]. This would not be possible without the use of Weak Boson Fusion (WBF) production channels [3,5–7]. Observation of a resonance in some expected decay channel is, however, only the beginning of Higgs physics. One needs to study as many properties and decay channels of the Higgs-like resonance as possible – not only at a future Linear Collider [8] but also at the LHC [9] and even higher energy colliders – to finally claim understanding of the mechanism of electroweak symmetry breaking sector.

An especially difficult task is to show that the Higgs boson has Yukawa couplings not only to the third generation quarks and leptons but also to the lighter fermions. In the case of quarks, associated production with top and bottom flavors [10] probes the large Yukawa couplings, as does the dominant decay to bottom quarks for a light Higgs boson. For quarks other than the third generation, one might be able to tag decays to charm at a Linear Collider [8] or other  $e^+e^-$  machine. In the case of lepton Yukawa couplings, WBF Higgs production and subsequent decay to tau pairs [3,11] probe the third generation Yukawa coupling. However, no proposed  $e^+e^-$  collider will accumulate a large enough sample of Higgs events to probe the

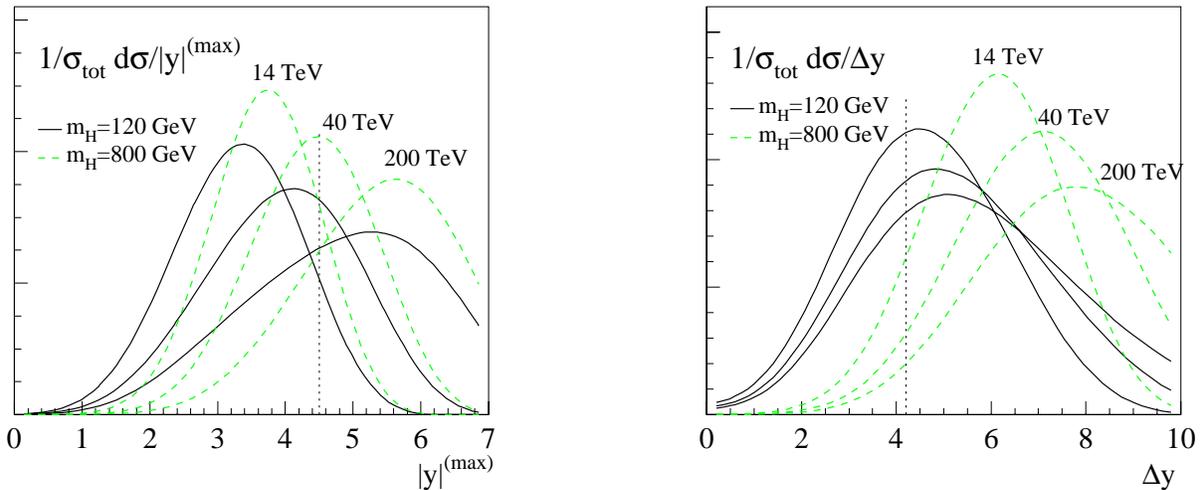


Figure 1. Maximum jet rapidity (left) and dijet rapidity difference (right) for the WBF signal. No cuts are applied on the Higgs decay products. All distributions are normalized to the total cross sections. For the low Higgs mass the different collider energies follow the same pattern as for the heavy Higgs boson. The dotted lines indicate the cuts applied in the LHC analyses [3,5]. All curves are obtained for transverse jet momenta above 30 GeV.

decay to muons <sup>1</sup>. We show that even at the LHC the size of the Higgs sample is most likely too small to observe a Higgs Yukawa coupling to muons. On the energy frontier, however, a very Large Hadron Collider (vLHC) [12] with center-of-mass energy of between 40 and 200 TeV will be perfectly well suited for this task. The number of accumulated Higgs bosons with a WBF signature is large enough and easily distinguishable from background.

## II. WEAK BOSON FUSION SIGNATURE

Over the last few years the importance of the Weak Boson Fusion (WBF) Higgs boson signature at the LHC has been extensively demonstrated [3–6,9]. The main feature, namely a large number of observables which distinguish the signal from typical QCD-induced backgrounds, will have even higher priority at hadron colliders beyond the LHC. There, weak boson and top quark production cross sections in association with jets, the largest backgrounds, will be many orders of magnitude larger than new physics signals and in many cases render those unobservable. Before we study one Higgs decay channel in detail we give an overview how the typical WBF signature is going to change from LHC to vLHC energies.

We first recall the selection criterion for WBF at the LHC. It involves minimum transverse energies for

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<sup>1</sup>A Linear Collider with an integrated luminosity of 1 ab<sup>-1</sup> will produce fewer than 100000 Higgs bosons. The branching fraction to muons leaves a sample of fewer than 25, before efficiencies and background reduction – at least an order of magnitude too few to be utilized.

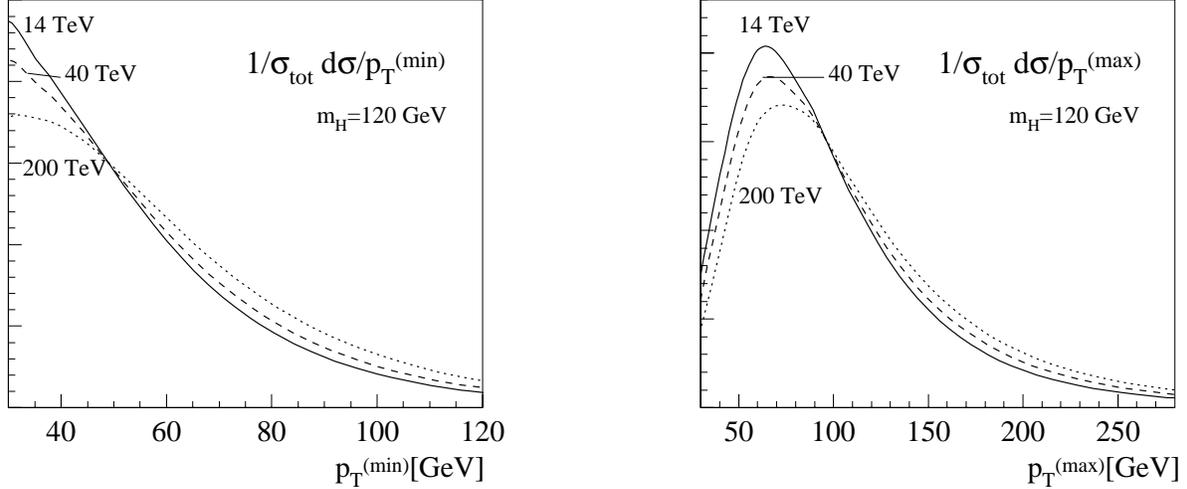


Figure 2. *Minimum (left) and maximum (right) transverse momentum of the tagging jets for a possible Higgs signal at the LHC (solid), 40 TeV vLHC (dashed), or 200 TeV vLHC (dotted). The curves are for a light Higgs boson,  $M_H = 120$  GeV; the shape of the curves does not change significantly for a heavier Higgs (in contrast to Fig.1). Events are created only with transverse jet momentum above 30 GeV, and no cuts are applied on the Higgs decay products.*

the jet as well as a particular geometry, reflected by the jet rapidities:

$$p_{T_j} \geq 20 \text{ GeV} \quad \Delta R_{jj} \geq 0.6 \quad |\eta_j| \leq 4.5 \quad |\eta_{j_1} - \eta_{j_2}| \geq 4.2 \quad \eta_{j_1} \cdot \eta_{j_2} < 0 \quad (1)$$

These cuts distinguish forward jet events from central QCD jet production and are limited only by the design of the detector. If the hadronic calorimeter is bound by values of  $|\eta_j| \leq 5$  and the forward jets have a finite non-negligible spread, jets with a central rapidity of bigger than 4.5 will not be observed precisely enough. In Figure 1 we show that most of the signal in a WBF Higgs production event at the LHC lies inside this detector range. For a vLHC with energies of 40 or 200 Tev this picture changes drastically. Although it is still possible to accumulate a large sample of WBF Higgs events, the cut on maximum jet rapidity removes a significant fraction of the signal events. As such, extending the rapidity reach of the hadronic calorimeters will be a major challenge for vLHC detectors, if one wants to make maximal use of WBF signatures. This holds true for heavier Higgs bosons as well. Fig. 1 suggests that increasing the required rapidity separation of the jets (rapidity gap) by up to one unit would be extremely useful to suppress QCD backgrounds more effectively. We cannot anticipate whether or not this is technically feasible.

The transverse momentum spectrum of the tagging jets is displayed in Fig. 2. It hardens slightly with increased collider energy, but is of course driven by the mass of the emitted weak boson,  $W, Z$ . The case of a heavy Higgs is not displayed, as the maximum values of the curves coincide with those of the light Higgs cases. The minimum transverse momentum necessary to detect a tagging jet will increase for higher  $\sqrt{s}$  due to increased low- $p_T$  jet activity from the underlying event, and from minimum bias assuming higher luminosity running at a machine with larger  $\sqrt{s}$ , so in the plotted sample for the vLHC we include events only above  $p_T = 30$  GeV, as compared to 20 GeV in the usual LHC analyses. In the following analysis we conservatively assume a CMS-like detector with the tagging criteria of Eq.(1) and an increased minimum  $p_T$  value of 30 GeV.

Another issue is that of the minijet veto, where events with additional soft, central jets of  $p_T > 20(30)$  GeV at the LHC (vLHC) are discarded. Earlier studies found that the minijet veto survival probability depends almost exclusively on the tagging dijet invariant mass ( $m_{jj}$ ), and we find that the values determined for the LHC are essentially unchanged for vLHC energies as well. However, we recognize that our determination of central jet activity ignores minimum bias from high luminosity running, as well as the underlying event, and as such the survival probabilities will ultimately have to be measured at the respective collider. Measuring these rates at the LHC should give a good prediction for the vLHC for equivalent luminosity running. Our minijet veto survival probability estimates therefore serve only as a guide for what one might expect in practice.

### III. HIGGS DECAY TO MUONS

Since the search for a Higgs boson decaying to muons is generally rate limited one would naively try to look for Higgs bosons produced in gluon fusion. However, for a light Higgs boson the invariant mass peak is close to the  $Z \rightarrow \mu\mu$  mass peak and therefore overwhelmed by background events. For larger Higgs masses the peak moves away from the  $Z$  pole, but the cross section drops sharply. Only in the MSSM does the  $\tan\beta$  enhancement bring this channel back into the picture. WBF, as we will show below, allows us to suppress the reducible and the irreducible backgrounds to a manageable level.

In the following analysis we look for tagging dijet production in WBF, with the acceptance cuts Eq.(1) and an additional minimum transverse momentum of the tagging jets of 30 GeV at the vLHC. The dominant backgrounds are:

- QCD  $Zjj$  production followed by the decay  $Z \rightarrow \mu^+\mu^-$ . Before cuts this is the dominant  $Z$  background. It consists of radiation of a  $Z$  boson off initial state and final state quarks. We include photon interference effects in the dilepton production.
- Electroweak (EW)  $Zjj$  production with a subsequent decay  $Z \rightarrow \mu^+\mu^-$ . This background includes the signal diagram where the Higgs line is replaced by a  $Z$  boson, which makes it particularly hard to remove using kinematical cuts. Again, photon interference effects are included. After cuts both  $Z \rightarrow \mu^+\mu^-$  backgrounds will typically be of similar importance [3].
- $W^+W^-jj$  production, where the neutrinos are aligned, so their missing transverse energy cancels to the level of  $\cancel{p}_T < 30$  GeV. This value for the missing momentum is essentially below the resolution of the detector and is therefore treated as zero.
- $t\bar{t} + jets$  production where the missing transverse momentum is small, as for the  $WWjj$  background. Either the bottom quarks from the top quark decays or the additional jets are tagged as forward jets [13]. It has been shown that  $t\bar{t}j$  is expected to be the most severe of these, followed by  $t\bar{t}jj$  and a negligible contribution from  $t\bar{t}$  [3].
- $b\bar{b}jj$  production with both bottom quarks decaying to muons. Again the missing transverse momentum cancels and the transverse jet momentum is unusually large. Without any cuts this background is many orders of magnitude larger than the signal, but kinematically very different.

$\sqrt{S}$ [TeV]	$M_H$ [GeV]	$\sigma_H$ [fb]	$\sigma_Z^{EW}$ [fb]	$\sigma_Z^{QCD}$ [fb]	$S/B$	significance $\sigma$	$\Delta\sigma/\sigma$	$\mathcal{L}_{5\sigma}$ [ $\text{fb}^{-1}$ ]
14	115	0.25	3.57	0.40	1/9.1	1.7	60%	2600
14	120	0.22	2.60	0.33	1/7.5	1.8	60%	2300
14	130	0.17	1.61	0.24	1/6.5	1.7	65%	2700
14	140	0.10	1.11	0.19	1/7.5	1.2	85%	4900
40	115	0.56	4.52	1.03	1/6.2	3.2	35%	750
40	120	0.52	3.32	0.79	1/5.3	3.3	35%	700
40	130	0.39	2.11	0.53	1/4.3	3.2	35%	750
40	140	0.25	1.51	0.41	1/5.0	2.4	50%	1400
200	115	2.57	39.6	5.3	1/10.1	5.3	20%	270
200	120	2.36	29.2	4.0	1/8.0	5.7	20%	230
200	130	1.80	18.7	2.7	1/6.9	5.3	20%	260
200	140	1.14	13.4	2.0	1/7.9	4.0	27%	500

TABLE I. Final results of the  $H \rightarrow \mu^+ \mu^-$  analysis. Cross sections are with cuts but no minijet veto or efficiency factors included. Efficiencies included for the statistical significances and percentage uncertainties are 60% for ID of all final states combined, and additionally 68% for mass bin capture of the signal resonance only. The Gaussian significance is given for an integrated luminosity of  $300 \text{ fb}^{-1}$ . The modified cuts beyond the WBF acceptance cuts at the LHC, Eq.(1), are described in the text.

To extract the backgrounds we make use of two distributions: as usual the invariant mass of the tagging jet pair in WBF tends to be larger than for the QCD background. We therefore cut

$$m_{jj} > 500 \text{ GeV} \quad (\text{LHC}) \qquad m_{jj} > 1000 \text{ GeV} \quad (\text{vLHC}) \quad (2)$$

and thereby reduce the  $t\bar{t}, b\bar{b}$  and QCD  $Zjj$  production backgrounds. Both muons have to be visible in the detector, which means  $|\eta_\mu| < 2.3$  and  $p_{T_\mu} > 10 \text{ GeV}$ . Additionally, one of the two muons must have  $p_{T_\mu} > 20 \text{ GeV}$ , to avoid issues of triggering. We note that typically both muons have considerably more  $p_T$  than these cuts, so increasing this cut slightly does very little to either signal or backgrounds. Moreover, the muons must lie in the rapidity region between the two tagging jets, with good separation in rapidity from the jets:  $|\Delta\eta_{\mu j}| > 0.6$ . We also require the muon invariant mass to lie in a window centered on the known Higgs boson mass;  $M_H \pm 1.6 \text{ GeV}$ , which is anticipated to capture 68% of the signal cross section, an efficiency factor we take into account. This reduces the non- $Z/\gamma^*$  backgrounds by almost two orders of magnitude, since they have an essentially flat distribution in the muon invariant mass. Finally, we apply a minijet veto survival probability of 0.9 for the signal, 0.3 for the QCD background and 0.75 for EW background. Two more efficiencies have to be folded into the cross sections: 90% for the detection of each muon and 86% for each tagging jet.

After these cuts we find that the  $W^+W^-jj$  cross section (QCD+EW) at the LHC has dropped to  $\lesssim 0.007 \text{ fb}$ ,  $t\bar{t} + jets$  to  $\lesssim 0.004 \text{ fb}$ , and the  $b\bar{b}jj$  background to  $\lesssim 0.003 \text{ fb}$ . From this point on we will consider only the irreducible  $Z/\gamma^* \rightarrow \mu^+ \mu^-$  backgrounds which are typically  $\mathcal{O}(1\text{fb})$ , i.e. two to three orders of magnitude dominant at the LHC. At a vLHC of  $\sqrt{s} = 200 \text{ TeV}$ ,  $t\bar{t}+jets$  becomes slightly less than 10% of the  $Zjj$  backgrounds, small enough to ignore for the purposes of this demonstrative analysis.

Beyond the simple kinematic cuts discussed above there are several distributions which distinguish the two major backgrounds and the signal. Unfortunately, none of them used as a cut leads to a sufficiently

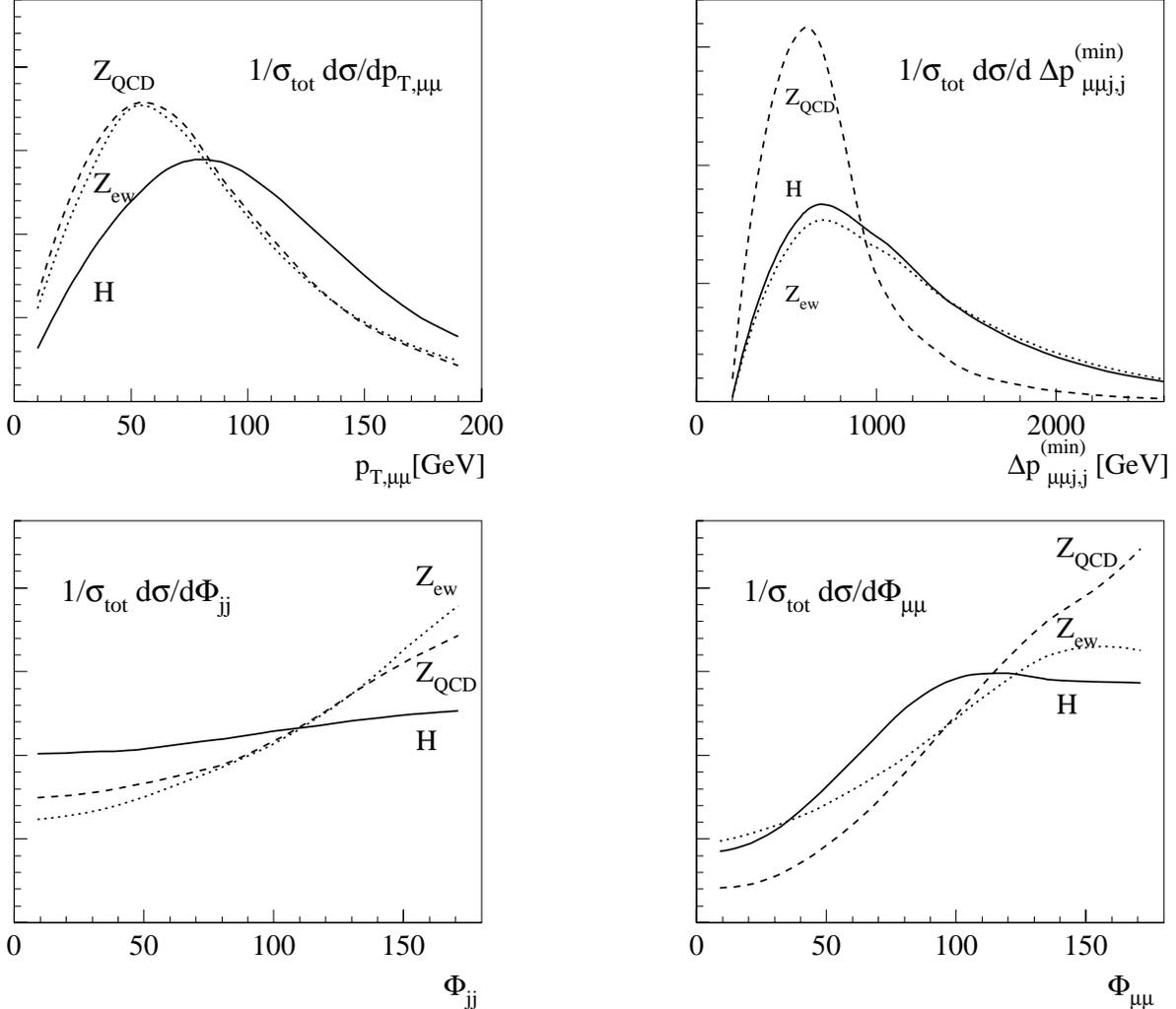


Figure 3. Several normalized distributions for a 120 GeV Higgs signal and the  $Zjj$  backgrounds. They are discussed in the text in more detail; none of them is used for Table I, but may prove useful in a neural net analysis.

large increase in the statistical significance. In particular for the lower energy scenario the analysis does not behave according to Gaussian but according to Poisson statistics. This means that even an improvement in  $S/\sqrt{B}$  will not automatically lead to an improvement in significance. However, these distributions may be of use in a neural net analysis, which can search for more complicated correlations and improve upon the statistical significance found by use of hard cuts only. Furthermore, for a measurement of the Yukawa coupling of a Higgs boson to muons an increase in  $S/B$  is desirable. Even though none of the cuts will enhance the significance considerably, they will lead to a huge improvement in  $S/B$ , in particular at a high energy collider.

Four of these distributions are depicted in Fig. 3. The first is the transverse momentum of the muon pair. It is generally larger for the signal, since the resonance is produced centrally and not in radiation off an incoming parton or a forward tagging jet. Moreover, the Higgs mass gives a slightly higher over-all energy scale. The upper right plot shows a distribution of the momentum imbalance in the final state. The variable

is constructed from the final state momenta as  $|\vec{p}_{\mu\mu} + \vec{k}_{j1} - \vec{k}_{j2}|$  in the parton rest frame. If the Higgs or  $Z$  boson is radiated off a tagging jet one expects one of the tagging jets to balance the other jet- $\mu\mu$  system: the variable  $\Delta p_{\mu\mu j,j}$  will be small for one of the two jet-boson combinations. This behavior is precisely what the Fig. 3 (second panel) shows for the QCD  $Zjj$  background. The initial state radiation in contrast leads to less-central tagging jets and is likely to be removed by the central lepton and the forward jet cuts. In the lower two plots of Fig. 3 we display the azimuthal angle distributions for the tagging jets and the muons. The jet azimuthal angle distribution for the SM and the MSSM is flat, an observation that can actually be used to determine the coupling structure of the Higgs to the  $W, Z$  bosons [9]. The slight preference of larger angles is an artifact of the cuts. For both QCD and EW  $Zjj$  backgrounds the distribution is peaked at larger angles.

## SUMMARY

For an intermediate mass Higgs boson we have shown that one can observe decays to muons at future hadron colliders, which allows for a measurement of the Higgs-muon Yukawa coupling. Since in this mass range the minimal supersymmetric Higgs boson will only have a slightly enhanced branching fraction to muons, this analysis covers the Standard Model as well as its minimal supersymmetric extension MSSM. This decay mode would also be accessible at the LHC, given a large amount of integrated luminosity, however this begs the question of rate loss from minimum bias minijet rejection at very high luminosity running. As such, practical measurement of the Higgs-muon Yukawa coupling would be viable probably only at a second-stage vLHC. Our estimated statistical uncertainty of about 20% on the cross section measurement corresponds to about a 10% measurement of the Yukawa coupling. Systematic uncertainties are of negligible concern, as the uncertainty on the production rate will be known to less than 5% from uncertainties due to QCD corrections and in the  $HVV$  coupling, and the  $Zjj$  backgrounds will be known to even better precision via a sideband analysis of their rates. Furthermore, we have suggested how this analysis may be improved using tools such as a neural network, or by improvements in detector technology which would reduce signal loss from incomplete rapidity coverage of the event sample, as well as greater suppression of the QCD background.

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