Higgs Boson Decay into a Pair of Leptons

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Abstract. The decay of a Higgs boson into a pair of W bosons $h \rightarrow W^+W^-$, is a dominant mode for Higgs boson masses above 135 GeV. At hadron colliders, searches for this decay focus on channels in which both W bosons decay leptonically, $h \rightarrow W^+W^- \rightarrow l^+l^- \nu\bar{\nu}$ plus missing energy. We show that semileptonic decays of heavy flavors are an important background to this signal. Lepton isolation provides too little suppression of heavy flavor contributions, and an additional 4 to 8 orders-of-magnitude suppression must come from physics cuts. An increase of the cut on the the minimum transverse momentum of non-leading leptons in multileptonevents is one effective way to achieve the needed suppression, without appreciable loss of the Higgs boson signal.

Keywords: Higgs, W Pairs, Leptons, Backgrounds, Heavy Flavors

PACS: 14.80.Bn, 13.85.Qk, 13.85.Rm, 13.38.-b

INTRODUCTION

In hadron collisions, the cleanest signature for the Higgs boson decay $h \rightarrow W^+W^-$ is two isolated opposite-sign leptons plus missing transverse energy ($E_T$) from the neutrinos in $W \rightarrow l \nu$. One class of reducible backgrounds involves processes with heavy-flavor (HF) hadrons in the final state, such as $Wc$, $Wb\bar{b}$, and $b\bar{b}$, where at least one lepton comes from the decay of a HF hadron (a hadron that includes either a bottom or charm quark). In this report I summarize a recent study [1] in which we demonstrate that isolation does not sufficiently suppress these HF backgrounds. Rather, the size of the heavy-flavor background is determined by details of the applied physics cuts, and current analyses must be improved to remove this background to $h \rightarrow W^+W^-$. We provide a full simulation of the backgrounds for $h \rightarrow W^+W^- \rightarrow l^+l^- E_T$, following the analysis chains of two studies: one by the DØ Collaboration [2] from which a limit is set on $h \rightarrow WW$ at the Tevatron, and one by the ATLAS Collaboration [3] that estimates the reach at the LHC. The heavy-flavor background could be overwhelming with the default cuts at the LHC, but we propose a new, more restrictive cut that would significantly reduce the background. We emphasize the value of direct measurements of the magnitude and kinematic variation the heavy-flavor background in the Tevatron and LHC data. Space restrictions limit this brief summary to our LHC investigation.

HEAVY FLAVOR BACKGROUND AT THE LHC

The issue for the heavy flavor backgrounds is the extent to which lepton isolation and subsequent kinematic physics cuts can suppress them. The nature of the challenge at the LHC is illustrated by a comparison of $\sigma \times B(h \rightarrow WW^* \rightarrow l^+l^- \nu\bar{\nu}) \sim 0.7 \text{ pb}$ for $m_h = 150$ to 190 GeV, with the size of $\sigma_{b\bar{b}}^\text{inclusive} \sim 5 \times 10^8 \text{ pb}$. Isolation in $b \rightarrow lX$ even
at the 0.5% level leaves a HF $l^+l^- E_T$ background that is $10^3$ greater than the signal. We must address questions of both the magnitude and the shape of the backgrounds.

In order to make statements regarding experimental issues, we require a detailed simulation of reconstructed events. We run events through the PYTHIA 6.322 [4] showering Monte Carlo, and feed the output through a heavily modified version of PGS [5] that reproduces the results of the relevant full ATLAS detector simulations to within 10% [6]. This code has a more accurate treatment of geometric effects and efficiencies than ATLFAST. The ATLAS physics cuts described in the ATLAS Technical Design Report (TDR) [3] are then applied to the objects found in PGS. We use MadEvent 3.0 [7] to generate hard events, and we match the cross sections after showering to the differential next-to-leading order (NLO) cross sections. For $Wj j$ and the relevant single-top-quark process, a $K$ factor times a leading-order (LO) distribution is sufficient to retain all angular correlations. Continuum $W^+W^-$ and $h \rightarrow W^+W^- \rightarrow l^+l^- E_T$ are evaluated using PYTHIA routines with $K$ factors.

### TABLE 1.

| Cut level          | $h \rightarrow WW$ | WW | $bbj^*$ | $Wc$ | Single-top | $Wb\bar{b}$ | $Wc\bar{c}$ |
|--------------------|---------------------|----|---------|------|------------|-------------|-------------|
| Isolated $l^+l^-$  | 336                 | 1270 | $>35700$ | 12200 | 3010       | 1500        | 1110        |
| $E_{T l_1} > 20$ GeV | 324                 | 1210 | $>5650$  | 11300 | 2550       | 1270        | 963         |
| $E_T > 40$ GeV     | 244                 | 661  | $>3280$  | 2710  | 726        | 364         | 468         |
| $M_H < 80$ GeV     | 240                 | 376  | $>3270$  | 2450  | 692        | 320         | 461         |
| $|\Delta\phi| < 1.0$ | 136                 | 124  | $>1670$  | 609   | 115        | 94          | 131         |
| $|\Delta\eta| < 1.0$ | 81                  | 83   | $>1290$  | 393   | 68         | 49          | 115         |
| $|\Delta\eta| < 1.5$ | 76                  | 71   | $>678$   | 320   | 48         | 24          | 104         |
| Jet veto           | 41                  | 43   | $>557$   | 175   | 11         | 12          | 7.4         |
| $130 < M_T^l < 160$ | 18                  | 11   | —        | 0.21  | 1.3        | 0.04        | 0.09        |

In Table 1 we show the cross sections we compute for opposite-sign dileptons. The second column shows the signal process $h \rightarrow WW$, and the remaining columns display the backgrounds that we examine, beginning with continuum $WW$ production and followed by several heavy flavor backgrounds. The first level of cuts requires two isolated leptons, each with $p_T l > 10$ GeV and $|\eta| < 2.5$. Isolation of electrons and muons replicates recent ATLAS descriptions [3, 6], and it is applied within the modified PGS detector simulation. Next, a cut is placed on the transverse energy of the reconstructed highest-$E_T$ lepton $l_1$ of $E_{T l_1} > 20$ GeV. A fairly high missing energy of 40 GeV is then required. Spin correlations in $h \rightarrow W^+W^- \rightarrow l^+l^- E_T$ tend to send the leptons in the same direction. Consequently, their invariant mass is low, and ATLAS requires $M_{ll} < 80$ GeV. Likewise, the angle between the leptons should also be small, and an aggressive cut is made on the azimuthal angle between the leptons, $\Delta\phi < 1.0$. The next-to-last cut is a veto of any event having a jet with $E_{T j} > 15$ GeV, and $|\eta_j| < 3.2$. It serves to reject background from $t\bar{t}$ production. Finally, a tight cut is made on the transverse mass $M_T^l$ of the dilepton and missing energy. It appears naively to remove most of the heavy-flavor background.

The final cut on $M_T^l$ is the key to the ATLAS sensitivity. In Fig. 1(a) we see a comparison of the Higgs boson signal, the continuum $WW$ background, and the heavy-flavor backgrounds. The HF backgrounds are more than an order of magnitude larger than the
previously calculated backgrounds for $M_{ll}^T < 110$ GeV. As a result of the physics cuts and lepton isolation, the $bb$ background has been suppressed by 11 orders of magnitude. It is unlikely that the tail of this distribution cuts off sharply at 125 GeV. It would be difficult to believe an excess observed in the region $M_{ll}^T < 160$ GeV without a measurement of this HF background. Even for a 200 GeV Higgs boson, the median transverse mass is below 140 GeV, leading to poor mass resolution if events are observed.

FIGURE 1. (a) Opposite-sign dilepton transverse mass distribution for a 160 GeV Higgs boson, the continuum $WW$ background, and the sum of heavy-flavor backgrounds (HFB) at ATLAS. The inset shows a blow-up of the signal region. (b) Same as (a) but after the cut on the next-to-leading lepton $p_T l_2$ is raised from 10 GeV to 20 GeV.

Fortunately, we can reduce the HF background to a manageable level by pushing the $M_{ll}^T$ mass peak associated with the heavy-flavors below 110–120 GeV. The distribution in $E_T$ of the leading lepton in the $W$+jets and single-top samples is fairly insensitive to small increases in the $E_T$ threshold near 20 GeV. This feature is not surprising since the leptons come from real $W$ decays. The leading lepton from $b$ or $c$ decay falls faster, but an increase in the cut will not improve the overall significance. On the other hand, the next-to-leading lepton has an exponentially falling background as a function of $E_T$. An increase of the minimum transverse energy cut on additional leptons from 10 GeV to 20 GeV reduces the background by roughly a factor of 20, while maintaining about 2/3 of the signal and continuum $WW$ backgrounds. In particular, the dangerous $bb$ background drops by a factor of 30, the $Wj + X$ backgrounds go down a factor of 10, and single-top-quark production goes down a factor of 5. Such a cut is nearly a “magic bullet” for Higgs boson masses above 140 GeV. An estimate of the effect of this one change in the cuts is shown for the signal and total backgrounds in Fig. 1(b). The leading edge of the heavy-flavor transverse-mass peak is 20 GeV lower than with the default cuts. The downward shift of this leading edge, along with the lower overall magnitude of the background, protects the Higgs boson signal region from uncertainties in the modeling of the heavy-flavor background. The residual HF background will still be measurable at lower $M_{ll}^T$, and it provides a control sample.

Our analysis demonstrates that despite small efficiencies, heavy-flavor decays into leptons are a potentially serious background. An increase in the transverse-energy cut of
secondary leptons is effective at reducing the background, but every level of cuts is significant. Some of the proposed cuts are sensitive to actual detector performance, noise, and the underlying event — none of which will be known until data are accumulated. Extrapolations of the magnitude and shape of the HF background using Monte Carlo techniques have large inherent uncertainties. We recommend that the HF background be measured with cuts as close as possible to the final sample. At the LHC the HF background is large enough that it can be studied in the $M_{ll}$ distribution and fully controlled.

DISCUSSION

Although our study focuses on $h \rightarrow W^+W^-$, it raises a broader question of the potential danger of heavy-flavor leptons in multi-lepton analyses. For example, trilepton searches for supersymmetry typically have soft additional leptons. There could be a significant impact on analyses of these types of signals if lepton transverse momentum cuts must be raised to remove the heavy-flavor leptons.

In investigations at linear colliders, the Higgs boson decay $h \rightarrow W^+W^-$ can be reconstructed fully from hadronic decays of the $W$ in the Higgs-strahlung process $e^+e^- \rightarrow hZ \rightarrow W^+W^-Z$, with $Z \rightarrow q\bar{q}$ or $Z \rightarrow l^+l^-$. The branching fraction $BR(h \rightarrow WW^*)$ can be measured to $\sim 4\%$ accuracy in $e^+e^- \rightarrow hZ \rightarrow WW^*Z$, with $WW^* \rightarrow 4$ jets or $WW^* \rightarrow l\nu + 2$ jets. Studies of the decay mode $h \rightarrow l^+l^-E_{\text{miss}}$ do not appear necessary for access to the $h \rightarrow W^+W^-$ coupling or branching fraction, but there may be interesting additional information to be gained. In $e^+e^- \rightarrow hZ$, with $Z \rightarrow l^+l^-$, and $h \rightarrow W^+W^- \rightarrow l^+l^- + E_{\text{miss}}$, there should be interesting kinematic signatures in the four-charged-lepton final state.

ACKNOWLEDGMENTS

Work in the High Energy Physics Division at Argonne is supported by the U. S. Department of Energy, Division of High Energy Physics, Contract No. W-31-109-ENG-38.

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