Missing heavy flavor backgrounds to Higgs boson production

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Abstract

We investigate characteristics of the signal and backgrounds for Higgs boson decay into $WW$ at the Fermilab Tevatron and CERN Large Hadron Collider. In the lepton-pair-plus-missing-energy final state, we show that the background receives an important contribution from semileptonic decays of heavy flavors. Lepton isolation cuts provide too little suppression of these heavy flavor contributions, and an additional 4 to 8 orders-of-magnitude suppression must come from physics cuts. We demonstrate that an increase of the minimum transverse momentum of nonleading leptons in multilepton events is one effective way to achieve the needed suppression, without appreciable loss of the Higgs boson signal. Such a cut would impact the efficiency of searches for supersymmetry as well. We emphasize the importance of direct measurement of the lepton background from heavy flavor production.

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I. INTRODUCTION

The quest to understand the mechanism of electroweak symmetry breaking is a central goal of high energy physics. Experiments at the Fermilab Tevatron and CERN Large Hadron Collider (LHC) approach this goal by searching for a new scalar particle, the Higgs boson \( H \), over a broad range of possible masses. Electroweak precision data suggest that a standard model-like Higgs boson should have a mass between 114 GeV and 219 GeV \(^1\), while the mass of a supersymmetric Higgs boson should be less than about 140 GeV. The measurement of Higgs boson decays into \( W^+W^- \) is expected to provide the largest significance of any final state when \( 135 < M_H < 219 \) GeV \(^2, 3\).

The cleanest signature for \( H \to W^+W^- \) is two isolated opposite-sign leptons plus missing transverse energy (\( E_T \)) from the neutrinos in \( W \to l\nu \) \(^2, 3\). Detailed simulations of backgrounds to this channel from physics processes (mostly continuum \( W^+W^- \) production) and fake rates have been performed for the Tevatron \(^4, 5\) and the LHC \(^6\). One class of reducible backgrounds involves processes with heavy-flavor (HF) hadrons in the final state, where at least one lepton comes from the decay of a HF hadron (a hadron that includes either a bottom or charm quark). It has been assumed that these backgrounds are removed by lepton isolation selections. In this paper we demonstrate that isolation does not sufficiently suppress this background. Rather, the size of the heavy-flavor background to lepton signatures is determined by details of the applied physics cuts, and current analyses do not successfully remove this background to \( H \to W^+W^- \).

A rough estimate of the heavy-flavor background can be obtained from the probability that a muon from \( B \) meson decay passes isolation and basic acceptance. Using the PYTHIA code \(^7\) to model production of central (\(|\eta_B| < 2\) \( B \) hadrons with transverse momentum \( p_{TB} > 10 \) GeV, and running events through the default PGS \(^8\) detector simulation, we compute an efficiency of \( 8 \times 10^{-3} \) for finding an isolated muon with \( p_{T\mu} > 10 \) GeV, and \( |\eta_\mu| < 2 \) (the D\( \phi \) Collaboration independently computed an efficiency of about \( 5 \times 10^{-3} \) in a complete detector simulation of the same process with similar cuts \(^8\)). This efficiency is dominated by the transverse momentum spectrum of the initial \( B \) hadrons, and the fragmentation function of \( B \to \mu + X \), with isolation playing a less important role. The difference in the rates for muons before and after D\( \phi \)-like isolation cuts shows that isolation itself retains 10–50\% of all muons (depending on the initial \( B \) momentum). While an

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overall acceptance of $10^{-2} - 10^{-3}$ is small, the initial cross sections involving heavy flavors are many orders-of-magnitude larger than the predicted signal. At this level, these heavy-flavor backgrounds would swamp or at least equal the largest backgrounds considered so far. It is essential to understand quantitatively whether and how heavy-flavor backgrounds are important in the region of interest for Higgs boson searches.

There are two classes of heavy flavor backgrounds that contribute to the dilepton plus $E_T$ final state. The first category includes processes that contribute equally to like-sign lepton and opposite-sign lepton final states: $Wb\bar{b}$, $Wc\bar{c}$, and s-channel single-top-quark production. The second class of events is more problematic in that, up to mixing effects, it contributes only to opposite-sign lepton final states: $b\bar{b}$, $c\bar{c}$, $Wc$, $Wb$, and t-channel single-top-quark production. The $b\bar{b}$ process is especially worrisome, because an acceptance of $10^{-10}$ would still leave a sizable background.

In this paper, we present a full simulation of the backgrounds for $H \rightarrow W^+W^- \rightarrow l^+l^-E_T$. We focus on two analyses: one by the DØ Collaboration [4] that sets a limit on the $H \rightarrow WW$ cross section at the Tevatron, and one by the ATLAS Collaboration [6] that estimates their reach at the LHC. A third analysis by the CDF Collaboration [5] is also studied, but it produces neither a Higgs boson signal nor heavy-flavor backgrounds because of extremely tight cuts. We limit our treatment of the CDF analysis to its potential for suppressing some of the backgrounds at DØ or ATLAS. If a CDF analysis is produced with sensitivity to the $H \rightarrow WW$ channel, it will encounter the same issues as DØ.

We begin in Sec. II with a description of our simulation technique. We then proceed with a deconstruction of each cut applied in the DØ analysis and its effect on the heavy-flavor background. We demonstrate that the overall $l^+l^-E_T$ background could be as much as a factor of two larger than current estimates. We discuss the inherent weaknesses in a Monte Carlo estimate of the heavy-flavor background, and we emphasize the value of direct measurements of its magnitude and kinematic variation in the Tevatron data. In Sec. III we examine this background at the LHC, following the ATLAS analysis chain in detail. We show that the heavy-flavor background could be overwhelming with the default cuts. We propose a new, more restrictive cut that would significantly reduce the background, and we argue that the residual background can be measured in situ. We conclude with a discussion of heavy-flavor lepton backgrounds in general.
II. HEAVY FLAVOR BACKGROUND AT D0

The D0 Collaboration searched for Higgs boson decay through $W^+W^-$ into opposite-sign leptons [4]. We follow the complex analysis cuts because the suppression of the heavy-flavor background (HFB) comes not just from the isolation cuts, but from the sequence of physics cuts tuned to extract the Higgs boson signal from the $WW$ and $Z$ backgrounds. A side effect of those cuts is to reduce the heavy-flavor background, but our goal is to understand the sensitivity at each stage.

In order to make statements regarding experimental issues, we require a detailed and believable simulation of reconstructed events. We accomplish this by running events through the PYTHIA 6.322 [7] showering Monte Carlo, and feeding the output through a version of the PGS 3.2 [3] fast detector simulation, modified to match D0 geometries, efficiencies, and detailed reconstruction procedures. The D0 physics cuts are then applied to the objects found in PGS.

The isolation criteria used by the D0 Collaboration differ for muons and electrons [4]. A muon is said to be isolated if there is a hit in the muon chamber, and the sum of the transverse momenta of tracks in a cone $\Delta R < 0.5$ around a leading track is less than $p_T^{\text{trk}} = 4$ GeV. The cone is defined in the plane of azimuthal angle and pseudorapidity by $\Delta R^2 = (\Delta \phi)^2 + (\Delta \eta)^2$. For electrons, $E_T^{\text{EM}}$ is defined to be a core cluster of transverse energy in the electromagnetic calorimeter in a cone of size $\Delta R = 0.2$. $E_T^{\text{had}}$ is the total transverse energy in a surrounding cone of size $\Delta R = 0.4$ minus $E_T^{\text{EM}}$. Isolated electrons satisfy the requirement $E_T^{\text{had}} / E_T^{\text{EM}} < 0.2$; and, if $|\eta_e| < 1.1$, a track must exist with $E_T^{\text{EM}} / p_T^{\text{trk}} < 2$. We apply these isolation definitions in our analysis as a modification of PGS reconstruction.

Strong angular cuts are made in all analyses with multiple leptons. It is vital to maintain the correlations in our modeling. Based on the results of Ref. [9], we use MadEvent 3.0 [10] to generate hard events, and we match the cross sections after showering to the differential next-to-leading order (NLO) cross sections, using the procedure described in Ref. [11]. For $Wjj$ and the relevant single-top-quark events it was shown [9] that a $K$ factor times a leading-order (LO) distribution is sufficient to retain all angular correlations. The $K$ factors for $Wb\bar{b}$ and $Wc\bar{c}$ are $K = 1.5$ [9]; $K = 1.5$ for $Wc$ [12]; and we assume $K = 1.5$ for $Wb$. The ZTOP program provides $K = 1.4$ for $s$-channel single-top-quark production and $K = 1.1$ for $t$-channel production [9, 11]. We use $K = 2.0$ for $b\bar{b}$ production [13, 14], and we
Assume $K = 2.0$ for $c\bar{c}$. Continuum $W^+W^-$ and $H \rightarrow W^+W^-$ are evaluated from PYTHIA routines, with $K$ factors $K = 1.3$ for $W^+W^-$ [15] and $K = 2.0$ for $H \rightarrow WW$. Note that the $K$ factor used for Higgs boson production is obtained after cuts from MCFM [15], and it is larger than that used by the DØ Collaboration.

The heavy-flavor backgrounds we calculate are ultimately suppressed by at least 5 orders-of-magnitude, and a few tricks are required to obtain a significant sample of events for this study. For events with a real $W$, a selection of several hundred events is chosen that pass a loose set of cuts on the hard matrix element: the transverse mass of the lepton and at least one heavy quark are greater than 8 GeV, and both pseudorapidities are less than 3.25. Each event is then processed by PYTHIA and PGS until two isolated leptons are found for each cut level, or a maximum of $10^4$ trials is reached. This procedure provides enough events to capture the effects of isolation and physics cuts (on phase space), and it retains the correlation between isolation and the missing transverse energy $E_T$ cut.

Simulations of $b\bar{b}$ and $c\bar{c}$ are significantly more challenging. Even after preselection, the cross sections change by more than 8 orders-of-magnitude. The largest loss of events is from the $E_T$ cut, since there is intrinsically little missing energy. In order to obtain any events, the procedure is modified to require only one isolated lepton. The probability for finding the lepton at that point in phase space is then squared. Cuts that depend on lepton four-vectors use the identified lepton and any observed heavy-flavor jet in the event. The direction of the jet is retained, and the lepton energy fraction is estimated based on the maximum energy that could go into pions near the lepton and still pass the isolation energy thresholds. The uncertainties of this method are qualitatively large but difficult to quantify. Given the results we obtain at the end, we consider our simulation of $b\bar{b}$ a proof-of-principle that this background must be accounted for, and not a definitive prediction of its size.

Our final results are checked against the published DØ results for $H \rightarrow W^+W^-$ and continuum $W^+W^-$ [4], and they agree to within 10%. The good agreement with a DØ isolation prediction [8], and a thorough study of the effect of variations of detector parameters and reconstruction algorithms, provide some confidence that our analysis is not very sensitive to the detector simulation.
A. Numerical results

The DØ analysis quotes results for the total number of opposite-sign dileptons. We separate the background sample into separate ee, eµ, and µµ subsamples. In order to understand the effect of the analysis chain, we examine each level of cuts for the µ⁺µ⁻ channel in Table I. There are two target cross sections to keep in mind: the \( H \rightarrow W^+W^- \rightarrow \mu^+\mu^- \) signal is 0.6 fb at \( \sqrt{S} = 1.96 \text{ TeV} \) if \( M_H = 160 \text{ GeV} \); and the largest background previously estimated comes from continuum \( WW \) production. We concentrate on backgrounds that end up larger than the Higgs boson signal and comparable to the continuum \( WW \) rate. The single-top-quark production modes and \( Wb \) end up at less than 0.25 fb, but they are included in the final totals below.

TABLE I: Cross sections (in fb) for the \( \mu^+\mu^- \) channel as a function of cuts for the 160 GeV Higgs boson DØ analysis. Isolated muons have \( p_T \mu > 10 \text{ GeV} \), \(|\eta_\mu| < 2\), and satisfy DØ isolation criteria. Interval cuts summarizes the effects of three cuts described in the text that depend on combinations of lepton momenta.

| Cut level               | WW       | b\(\bar{b}\) | c\(\bar{c}\) | Wc      | W\(\bar{b}\) | Wc\(\bar{c}\) |
|-------------------------|----------|-------------|-------------|---------|-------------|-------------|
| Isolated \( \mu^+\mu^- \) | 62       | 7.8 \times 10^6 | 5.3 \times 10^4 | 85      | 36          | 16          |
| \( p_T\mu_1 > 15 \text{ GeV} \) | 61       | 5.8 \times 10^6 | 3.9 \times 10^4 | 82      | 34          | 15          |
| \( E_T > 20 \text{ GeV} \)    | 49       | 208         | 5           | 51      | 19          | 7.5         |
| \( E_{T_{\text{scaled}}} > 15 \) | 42       | 24          | < 0.1       | 38      | 7.7         | 4.4         |
| \( H_T < 100 \text{ GeV} \)  | 42       | 24          | < 0.1       | 38      | 7.7         | 4.3         |
| \( \Delta \phi_{ll} < 2.0 \) | 19       | 24          | < 0.1       | 12      | 3.3         | 1.8         |
| Interval cuts           | 9.3      | 24          | < 0.1       | 3.1     | 2.0         | 0.9         |

The inclusive cross sections begin several orders-of-magnitude larger than Higgs boson production. The first level of cuts requires two opposite-sign (OS) isolated muons with \( p_T\mu > 10 \text{ GeV} \) and \(|\eta_\mu| < 2\). Nearly 1% of bottom or charm quarks has hadronized and subsequently decayed into a muon that passes all isolation criteria. At this point the \( W + X \) cross sections are more than 100 times that of the final Higgs boson signal, and comparable to continuum \( WW \). The \( b\bar{b} \) and \( c\bar{c} \) rates are 3–5 orders-of-magnitude larger. The cut on the leading muon in the analysis is 15 GeV, but this restriction does not reduce the event rate.
significantly, as shown in the Table.

The first significant physics cut is the demand for large missing energy. This cut has little effect on $W + X$ events because there is always at least one high-$E_T$ missing neutrino. For $b\bar{b}$ or $c\bar{c}$ production, however, there is a more significant suppression of the background than even the isolation criteria. The $E_{T\text{scaled}}$ cut, where

$$E_{T\text{scaled}} = \frac{E_T}{\sqrt{\sum_j [\Delta E_j \sin \theta_j \cos \Delta \phi(j,E_T)]^2}},$$

(1)

reduces sensitivity to jet mismeasurements. It acts like a stronger $E_T$ cut that reduces $b\bar{b}$ and $c\bar{c}$ by another order of magnitude.$^1$

The rest of the cuts are only modestly effective since they were designed for different purposes. A cut on the scalar sum of jet-$E_T$ ($H_T$) removes $t\bar{t}$ production, but the processes that concern us rarely have additional jets. The $\Delta \phi_{ll}$ cut expresses the fact that spin correlations cause the charged leptons from Higgs boson decays to align. This cut gains a factor of 2 reduction in the $W + X$ backgrounds, but it is not effective against $b\bar{b}$. The reason is that the $B$ meson system had to be recoiling against missed radiation in order to pass the large $E_T$ cut. This effect forces the leptons to be relatively close in phase space.

Finally, “interval cuts” refer to three different cuts that are tuned to match features of $H \rightarrow WW$, but do not excessively impact the heavy-flavor backgrounds here. The cuts are

$$20 \text{ GeV} < M_{ll} < m_h/2,$$

$$m_h/2 + 10 \text{ GeV} < p_{Tl_1} + p_{Tl_2} + E_T < m_h,$$

$$m_h/2 < M_T^ll < m_h - 10 \text{ GeV}.$$  

(2)

Variable $M_{ll}$ is the invariant mass of the dilepton pair, and the transverse mass is

$$M_T^{ll} = \sqrt{2E_T p_T^{ll}[1 - \cos(\phi_{E_T} - \phi_{ll})]}.$$ 

(3)

Since at least one of the muons comes from a heavy flavor decay, it tends to be relatively soft. This muon is soft only because the initial heavy-flavor hadron tends to be soft, and not because it is taking a small fraction of the hadron’s momentum. In most of these events,

$^1$ A recent DØ analysis [16] reduces this cut to $E_{T\text{scaled}} > 7$, a reduction that significantly weakens its power to suppress $b\bar{b}$ and $c\bar{c}$.
the muon has acquired most of the hadron momentum, leaving little surrounding energy in the event on which to cut.

The cut on the sum of the transverse momenta, the second line in the list above, is almost automatically satisfied by phase space considerations. Its largest effect is on the $Wc$ process, where the charm spectrum is fairly soft and so many events fall below the minimum. The transverse mass cut is essentially always satisfied over the large interval allowed. We examine this distribution in detail later.

The final cross sections for a 160 GeV Higgs boson, the $W^+W^-$ continuum, and the heavy-flavor backgrounds are listed in Table II for each final state. Statistical uncertainties are included for the $W + X$ backgrounds, while the $b\bar{b}$ and $c\bar{c}$ uncertainties are large and unknown. We list both like-sign and opposite-sign lepton channels to demonstrate that only some of the backgrounds are symmetric. If the backgrounds were entirely driven by parton-level physics, then there would be no like-sign contribution from $Wc$, since only $W^+\bar{c}$ or $W^-c$ are produced, and mixing is small. However, there is some probability of tagging a jet (especially a wide-angle pion) as an electron, and hence there is an underlying contribution to both LS and OS samples in the $ee$ and $e\mu$ samples, but not the $\mu\mu$ sample. This contamination is small but within the same order of magnitude of an isolated lepton from the charm decay.

In Table II the row containing $b\bar{b}$ production is modeled by two hard processes: $b\bar{b}$ and $b\bar{b}j$, where $j$ stands for an extra jet with $E_T j > 20$ GeV. The isolated muon sample comes almost entirely from $b\bar{b}$, while the isolated electron sample comes almost entirely from $b\bar{b}j$. More electrons appear in the $b\bar{b}j$ sample than the $b\bar{b}$ sample because the $B$ hadrons recoiling against the jet are harder than estimated by $b\bar{b}$ plus showering. Hence, more electrons pass the minimum $E_T$ cut in the isolated electron definition. Sometimes the additional jet is missed and helps the events pass the missing energy cut. While the additional radiation does add some sensitivity to the $H_T$ and mass-window cuts, it is not enough to observe in the Table. Because of the way the calculation is performed, we do not include the effect of finding one lepton from the $b$ decay, and one fake $e$ from additional jets.

The results in Tables I and II imply that the $l^+l^-E_T$ final state for a 160 GeV Higgs boson has an additional background of 16 events from heavy-flavor decays ($W + X$ plus $b\bar{b}$) in 330 pb$^{-1}$ of data, compared to the combined background of 20 events estimated by D$\phi$ (dominated by 12 events from continuum $WW$) [4]. The uncertainty of the contribution
TABLE II: Detailed cross sections (in fb) for like-sign (LS) and opposite-sign (OS) leptons after all cuts for the DØ analysis tuned for a 160 GeV Higgs boson. Cross sections less than 0.25 fb are summed under all else. $c\bar{c}$ contributes 1.4 fb to OS $ee$. Statistical uncertainties are shown where available.

|       | $ee$          | $e\mu$       | $\mu\mu$       |
|-------|---------------|---------------|-----------------|
|       | LS     | OS      | LS     | OS      | LS     | OS      |
| $H \rightarrow WW$ | —   | 0.73 ± 0.04 | —   | 1.26 ± 0.05 | —   | 0.60 ± 0.03 |
| $WW$  | —   | 12 ± 1   | —   | 20 ± 1    | —   | 9.3 ± 0.9    |
| $b\bar{b}(j)$ | —   | 2.1     | —   | 5.6     | —   | 24     |
| $Wc$  | 0.8 ± 0.4 | 2.3 ± 1.1 | 1.1 ± 0.4 | 3.7 ± 1.8 | —   | 3.1 ± 2.2    |
| $Wb\bar{b}$ | 0.4 ± 0.2 | 0.4 ± 0.1 | 2.1 ± 1.6 | 1.3 ± 0.4 | 2.5 ± 1.6 | 2.0 ± 1.1 |
| $Wc\bar{c}$ | 1.4 ± 0.5 | 1.1 ± 0.4 | 1.0 ± 0.2 | 1.6 ± 0.3 | 1.0 ± 0.4 | 0.9 ± 0.2 |
| all else | 0.1 | 1.6 | 0.3 | 0.3 | 0.04 | 0.1 |

from $b\bar{b}$ is large, but even if the $b\bar{b}$ contribution to the background is overestimated by a factor of 10, the remaining heavy-flavor backgrounds (from $W + X$) are fully half as large as the continuum $WW$ rate.

In Table III we demonstrate that the heavy-flavor background is significant in each final state ($ee$, $e\mu$, $\mu\mu$) across the entire range of Higgs boson masses studied by DØ. At this point we might be concerned that there is no apparent excess in the data. However, there is significant uncertainty in the overall normalization of the background. Even a doubling of the background is consistent within 1–2σ when the systematic uncertainties are included. Nevertheless, given the uncertain nature of modeling tails of distributions, it is clear that the relative importance of the backgrounds will only be disentangled by a direct measurement of the heavy-flavor component.

B. Measuring the background

The results of our analysis demonstrate two points: despite small efficiencies, heavy-flavor decays into leptons are a potentially serious background; and the efficiencies are so small, it is difficult to believe any absolute predictions based on Monte Carlo techniques. Therefore,
TABLE III: Cross sections (in fb) at the Tevatron for the $H \rightarrow WW$ signal and heavy-flavor backgrounds (HFB) for each pair of opposite-sign leptons as a function of Higgs boson mass after D$\phi$-like analysis cuts. Continuum $WW$ is also shown for comparison.

| $m_h$ (GeV) | $ee$ | $e\mu$ | $\mu\mu$ |
|------------|------|--------|----------|
| $H \rightarrow WW$ HFB | WW | $H \rightarrow WW$ HFB | WW | $H \rightarrow WW$ HFB | WW |
| 120 | 0.15 | 13 | 7.3 | 0.22 | 23 | 11 | 0.09 | 34 | 5.4 |
| 140 | 0.47 | 12 | 10 | 0.90 | 20 | 16 | 0.41 | 32 | 8.4 |
| 160 | 0.73 | 7.4 | 12 | 1.26 | 12 | 20 | 0.60 | 30 | 9.3 |
| 180 | 0.53 | 5.9 | 11 | 0.88 | 9.8 | 18 | 0.45 | 26 | 9.3 |
| 200 | 0.23 | 4.8 | 8.9 | 0.41 | 7.4 | 16 | 0.19 | 25 | 8.2 |

the background must either be measured *in situ*, or the cuts must be made more restrictive in order to avoid the problem. The latter case will be examined in Sec. III C, but here we examine whether it is possible to measure the background.

Let us return to the two classes of backgrounds from heavy flavor decays. The first class involves processes that have a roughly equal probability of producing like-sign and opposite-sign leptons. These include $Wb\bar{b}$, $Wc\bar{c}$, and $s$-channel single-top-quark production. The simplest choice to measure the backgrounds in this case is to measure the like-sign leptons and use this result as a measure of the background to opposite-sign leptons. The experimental challenge is to accurately predict small variations in efficiencies for the two final states. Nevertheless, this procedure should give a reasonable estimate of the background.

The second class of backgrounds is challenging to measure and, as is evident in Table III, a larger percentage of the total background. There are several processes that contribute only to the opposite-sign final state (up to heavy-flavor meson mixing effects and some wrong-sign charm decays). For a first estimate of the effect of isolation cuts, one could look at a muon triggered sample for a tagged $b(c)$. If a cut is made on missing transverse energy of $E_T > 10$–15 GeV, it should be possible to observe two peaks in the muon $p_T$ spectrum of the $\mu + b$ sample. $B\bar{B}$ production will peak at the muon $p_T$ threshold and exhibit a long tail to larger $p_T$, while $Wb + X$ will peak near 40 GeV. Once isolation criteria are imposed on
this sample, an upper bound on the effect of isolation can be obtained.\textsuperscript{2}

While the muon sample should be fairly clean, the electron plus $b$ sample may be more sensitive to fakes at lower energies. The $e + b$ sample will contain an enhanced fraction of $b\bar{b}(c\bar{c})$, but there will be additional backgrounds from $Z \rightarrow \tau^+\tau^-$, top-quark production, dijets, and $Wj$ events that must be understood.

It is more complicated to estimate the $b\bar{b}$ or $c\bar{c}$ processes because missing energy from escaping neutrinos can help these processes pass the $E_T$ cut. An observation of the acceptance as a function of $E_T$ may help to reduce some background and partially separate $b\bar{b}$ from $Wb/Wc/Wb\bar{b}/Wc\bar{c}$. Unfortunately, these backgrounds are always at the tails of the distributions, and this sort of study is more useful for understanding general physics properties in a detector than for measuring the background to Higgs boson production.

One handle on the background to Higgs boson decay would be to loosen the cuts as little as possible until a more pure sample of background is obtained, and assume that the procedure can be reversed. In Fig. 1 we see the transverse mass distributions for $H \rightarrow WW$, continuum $WW$, and continuum $WW$ plus the heavy-flavor backgrounds that involve a real $W$. Our statistical sample of $b\bar{b}$ events is too small to predict the shape here (but see the ATLAS analysis in Sec. III). The most significant characteristics of the HF backgrounds are that they tend to peak at a slightly lower $M_{ll}$ and have narrower distributions than continuum $WW$. If enough data are collected, and the shape of continuum $WW$ from Monte Carlo is correct\textsuperscript{3}, one can try to make an in situ measurement of the heavy-flavor background. For example, one might look at events above and below 110–120 GeV, and set a limit on the size of the combined heavy-flavor background. A reasonable measurement might be possible with a few inverse femtobarns of data.

C. Cutting away the background

Given the challenge of measuring the heavy-flavor background, the question arises whether it can simply be cut away. One source of inspiration could be the CDF analysis\textsuperscript{4}, but that method also suppresses the signal, so we settle for varying the cuts at each stage of the analysis. The first place to look would be to reexamine the isolation criteria,

\textsuperscript{2} The charm and dijet mistag background should be a small fraction of the total events.

\textsuperscript{3} The residual Drell-Yan and $W$+fake backgrounds must also be included.
FIG. 1: Opposite-sign dilepton transverse mass distribution for a 160 GeV Higgs boson, the continuum $WW$ background, and the sum of all $W + X$ backgrounds with $D\phi$ analysis cuts. The $b\bar{b}$ and $c\bar{c}$ contributions are not included, but they are expected to peak around 80–100 GeV with unknown tails.

but it is difficult to achieve order-of-magnitude suppressions by varying isolation.

Our modest simulations suggest that the HF leptons passing isolation cuts fall into two categories. In the first category, the hadron remnant is outside the $D\phi$ isolation cone $\Delta R > 0.5(0.4)$ for muons (electrons) and so is not counted. An increase of the isolation cone size to 0.7 achieves only a factor of 2 reduction of the backgrounds, but it begins to eat into the good lepton sample we wish to retain. The second category is more problematic. In this case, the hadron remnant is too soft to fail the 4 GeV isolation energy threshold for muons, or the $E_{\text{had}}/E_{\text{EM}} < 0.2$ cut for electrons. These events are more difficult to reject, because the thresholds cannot be lowered by much before sensitivity to the underlying event or minimum ionizing radiation (for muons) increases. More importantly, these events come from the portion of phase space where the lepton takes most of the visible hadron momentum. Even the impact parameter is small.

A better method of cutting the background is to look at the transverse energy $E_{Tl}$ spectra of the leptons. In Figs. 2 and 3 we see the $E_{Tl}$ of reconstructed leptons for $H \rightarrow WW$, continuum $WW$, $Wc$, and $b\bar{b}$. An increase of the cut on the leading lepton from 15 GeV to 20 GeV is useful, but not as beneficial as it might seem, because the $Wc$ leptons peak
above 20 GeV, and even the leading lepton from $b\bar{b}$ is not falling very fast. However, the spectrum of the next-to-leading lepton in Fig. 3 is falling exponentially, whereas the Higgs boson and continuum $WW$ spectra are almost flat up to 40 GeV. An increase of the cut on the next-to-leading lepton close to that of the leading lepton (e.g., make both 20 GeV) virtually removes the $Wc$ and $b\bar{b}$ backgrounds, with a modest reduction of the signal. Of course this increase provides no help against the original continuum $WW$ background.

![Graph](image)

**FIG. 2:** Transverse energy distribution of the leading muon after isolation, with D$\phi$ analysis cuts.

While it appears that there is a way to effectively remove the background from heavy-flavor leptons for the $H \rightarrow WW$ search at the Tevatron, it is not obvious that it is desirable. Given the poor signal to background ratio of about $1/30$ before the addition of the HF backgrounds, we would recommend that more effort be placed on understanding how to extract the HF background from the data. That understanding could then be fed into other multilepton analyses and lay the foundation for studies at the LHC.

### III. HEAVY FLAVOR BACKGROUND AT ATLAS

The Higgs boson is expected to be discovered with a large significance at the LHC. In this Section, we examine the signal and backgrounds for $H \rightarrow WW \rightarrow l^+l^-E_T$ in the ATLAS detector, emphasizing the contribution from leptons that arise from semileptonic decays of heavy flavors.
FIG. 3: Transverse energy distribution of the next-to-leading muon after isolation, with DØ analysis cuts.

The simulation procedure is the same as that used for the DØ analysis in Sec. II. The detector simulation is a heavily modified version of PGS [3] that reproduces the results of the relevant full ATLAS detector simulations to within 10% [17]. This code has a more accurate treatment of geometric effects and efficiencies than ATLFAST. One surprise is that effective $K$ factors after cuts are uniformly smaller at the LHC than at the Tevatron. Using MCFM 4.1 [15] and ZTOP 1.0 [9, 11], we find the $K$ factor for $H \rightarrow WW$ is only 1.25 (compared to 2 at the Tevatron); $K = 1.5$ for $s$-channel single-top-quark production; and all other $K$ factors are approximately 1.0. The net effect is that only the Higgs boson signal is (slightly) enhanced at NLO.

There are two caveats that must be noted. First, the lepton identification and isolation cuts will likely change when data are accumulated and detector response is measured. The large inherent uncertainties in the simulation procedure will not be improved until the detectors are operating. Nevertheless, the results are dominated by detector-independent physics and should be fairly accurate relative to other physics processes.

The second caveat is that we are able to calculate only a lower bound on the $b\bar{b}$ background, and we do not include the $c\bar{c}$ background. The reason is that the ATLAS study imposes extremely tight cuts on the phase space of the leptons that are passed only if strong preselections are made on the events. Rough estimates indicate that the real background
will be at least a factor of 2–3 larger than presented here. However, we demonstrate that
the shape is more of a limiting factor, and we can still draw conclusions regarding the heavy
flavor backgrounds.

In order to compare to the ATLAS study, we follow the cuts described in the ATLAS
Technical Design Report (TDR) [6]. These cuts are similar to those used by D0, but they
have tighter restrictions on angular variables and reconstructed masses. The definitions of
isolation are involved, particularly for electrons, and are spelled-out in Refs. [6, 17]. In Table
IV we show the effect of each level of cuts on the opposite-sign dilepton events.

TABLE IV: Cross sections (in fb) for opposite-sign leptons as a function of cuts for the 160 GeV
Higgs boson ATLAS analysis. \( bbj^* \) production is a lower limit based on limited phase space, and
\( c\bar{c} \) production is not calculated. A dash indicates statistics were too small to estimate.

| Cut level                  | \( H \to WW \) | \( WW \) | \( bbj^* \) | \( Wc \) | single-top | \( Wb\bar{b} \) | \( Wc\bar{c} \) |
|----------------------------|--------------|--------|----------|--------|-----------|-----------|-----------|
| Isolated \( l^+l^- \)      | 336          | 1270   | > 35700  | 12200  | 3010      | 1500      | 1110      |
| \( E_{Tl_1} > 20 \) GeV   | 324          | 1210   | > 5650   | 11300  | 2550      | 1270      | 963       |
| \( E_T > 40 \) GeV        | 244          | 661    | > 3280   | 2710   | 726       | 364       | 468       |
| \( M_{ll} < 80 \) GeV     | 240          | 376    | > 3270   | 2450   | 692       | 320       | 461       |
| \( \Delta \phi < 1.0 \)    | 136          | 124    | > 1670   | 609    | 115       | 94        | 131       |
| \( |\theta_{ll}| < 0.9 \)  | 81           | 83     | > 1290   | 393    | 68        | 49        | 115       |
| \( |\eta_1 - \eta_2| < 1.5 \) | 76          | 71     | > 678    | 320    | 48        | 24        | 104       |
| Jet veto                   | 41           | 43     | > 557    | 175    | 11        | 12        | 7.4       |
| \( 130 < M_{ll} < 160 \) GeV | 18          | 11     | —        | 0.21   | 1.3       | 0.04      | 0.09      |

The first level of cuts requires two isolated leptons, each with \( p_{Tl} > 10 \) GeV and \( |\eta| < 2.5. \)
Isolation of electrons and muons replicates recent ATLAS descriptions [6, 17], and 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 \( E_{Tl_1} > 20 \) GeV. A fairly high missing energy of
40 GeV in then required. Since the leptons from \( H \to WW \) tend to go in the same direction,
the invariant mass is low, and ATLAS requires \( M_{ll} < 80 \) GeV. The angle between the leptons
should also be small, and an aggressive cut is made on the azimuthal angle between them,
\( \Delta \phi < 1.0 \). Next, the dilepton system is required to be forward, with the cut \( |\theta_{ll}| < 0.9 \)
(equivalent to \( |\eta| > 0.73 \)). Then, the leptons are required to be close in pseudorapidity
$|\eta_1 - \eta_2| < 1.5$. The next-to-last cut is a veto of any event with a jet with $E_{T,j} > 15$ GeV, and $|\eta_j| < 3.2$. This cut serves to reject background from $t\bar{t}$ production. Finally, a tight cut is made on the transverse mass of the dilepton and missing energy that naively appears to remove most of the heavy-flavor background.

The most important observations regarding the ATLAS cuts are: the isolation is roughly as effective at ATLAS as at the Tevatron experiments; and the final cut on transverse mass $M_{T}^{ll}$ is the key to the ATLAS sensitivity. In Fig. 4 we see a comparison of the Higgs boson signal, the continuum $WW$ background, and the new heavy-flavor backgrounds. The new backgrounds are more than an order of magnitude larger than the previously calculated backgrounds for transverse masses less than 110 GeV. This observation is important, because the ATLAS transverse mass cut is rather aggressive in the assumption that one can rely on the signal and background distributions to claim discovery when the peak of the distribution is below the cut. Contrast this with D0, which uses $m_h/2$ as a lower limit. A D0-like cut would make $S/B \lesssim 1/30$ for a Higgs boson with mass less than 200 GeV.

![Figure 4](image_url)

**FIG. 4**: Opposite-sign dilepton transverse mass for a 160 GeV Higgs boson, the continuum $WW$ background, and the sum of additional heavy-flavor backgrounds (HFB) at ATLAS. The HFB is a lower limit on $b\bar{b}$ and does not include $c\bar{c}$.

The tail that creeps up to 150 GeV comes mostly from $t$-channel single-top-quark production, which is fairly-well modeled. In Fig. 5 we see the breakdown of the contribution of the HF backgrounds. As a result of the physics cuts and lepton isolation, the $b\bar{b}$ background
(and $c\bar{c}$ if it were included) has been suppressed by 11 orders of magnitude. It is unlikely that the tail of that distribution cuts off sharply at 125 GeV. It would be difficult to believe any excess observed in the region $M_{ll} < 160$ GeV without a measurement of this HF background. We see in Fig. 5 that even a 200 GeV Higgs boson has a median transverse mass below 140 GeV, leading to poor mass resolution even if events are observed.

![FIG. 5: Opposite-sign dilepton transverse mass for individual heavy-flavor backgrounds (HFB) at ATLAS. The $b\bar{b}$ background is a lower limit. $c\bar{c}$ could be at least as large as $b\bar{b}$ production.](image)

![FIG. 6: Opposite-sign dilepton transverse mass for Higgs bosons at ATLAS.](image)
Fortunately, we can reduce the HF background to a manageable level by pushing the $M_T$ mass peak associated with the heavy-flavors below 110–120 GeV. Applying lessons learned from our examination of the DØ and CDF analyses, we look again at the lepton transverse energies. Figure 7 shows that the leading lepton in the $W+\text{jets}$ and single-top samples is fairly insensitive to small increases in the $E_T$ threshold near 20 GeV. This is not surprising, since the leptons come from real $W$ decay. The leading lepton from $b$ or $c$ decay falls faster, but an increase in the cut will not improve the overall significance. It may be desirable to raise the cut to further suppress the poorly modeled $b\bar{b}$ and $c\bar{c}$ components, but there is currently no clear gain from doing so.

![Figure 7: Transverse energy distribution of the leading lepton after isolation at ATLAS.](image)

The next-to-leading lepton in Fig. 8 shows 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 $b\bar{b}$ 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 each of the backgrounds in Fig. 9 and for the signal and total backgrounds in Fig. 10. The leading edge of the heavy-flavor transverse-mass peak is 20 GeV lower than with the default cuts. The 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 $M_T^ll$, and it provides an in situ control sample.

![Graph](image1)

**FIG. 8:** Transverse energy distribution of the next-to-leading lepton after isolation at ATLAS.

![Graph](image2)

**FIG. 9:** Opposite-sign dilepton transverse mass for individual heavy-flavor backgrounds (HFB) at ATLAS after the cut on $\not{p}_T$ is raised from 10 GeV to 20 GeV. The $b\bar{b}$ background is a lower limit; the $c\bar{c}$ contribution could be as large as $b\bar{b}$ production.
FIG. 10: Opposite-sign dilepton transverse mass for a 160 GeV Higgs boson, the continuum $WW$ background, and the additional heavy-flavor background (HFB) at ATLAS after the cut on $p_T l_2$ is raised from 10 GeV to 20 GeV.

While an increase in the lepton transverse-energy cut is effective at reducing the background, it is important to note that every level of cuts is significant. In particular, some of the proposed cuts are potentially quite sensitive to actual detector performance, noise, and the underlying event — none of which will be known until data are accumulated. We point out the effect on these backgrounds if some of the cuts have to change.

Since isolation criteria are not finalized, this seems a logical place to start. The complete prescriptions for isolation are described in Refs. [6, 17]. Electron isolation hinges on the energy $E_{12}$ being less than 3 GeV in 12 calorimeter cells surrounding a central $2\times2$ core. Muons are required to have less than 4 GeV of additional charged tracks in a cone of size $\Delta R = 0.2$, and less than 10 GeV of calorimeter energy in a cone of size $\Delta R = 0.4$.

The size of the underlying event and measured shower shapes may require raising or lowering of thresholds for allowed radiation. Lowering the thresholds by a factor of two has little effect on electron isolation, and only a factor of 2 reduction in the background for muons. Raising the isolation thresholds by 50% (a typical high-luminosity scenario [6]) still has little effect on the electrons, but increases the muon background by a factor of 2 per muon (so

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4 The tracking and calorimeter cuts for muons are highly correlated. Investigations into the efficacy of dropping one cut are ongoing [17].
the contributions from $b\bar{b}$ and $c\bar{c}$ increase by a factor of 4).

A change of the missing energy cut by $\pm 10$ GeV has little effect on the overall significance. However, the signal begins to decrease significantly once the $E_T$ increases above 50 GeV. The jet veto threshold is expected to be raised to 40 GeV for high luminosity operation. At a higher threshold, the Higgs boson signal increases by about 25%, while the background increases by no more than 50%. It may be advisable to relax the jet veto threshold to 40 GeV to reduce sensitivity to the underlying event, and improve the significance during low luminosity operation. Finally, it is notable that the tight $\Delta \phi$ cut reduces the signal by almost a factor of 2. It may be desirable to relax this cut to the DØ choice $\Delta \phi < 2.0$ to improve the event rate. None of these other cuts has nearly the impact of an increase in the $E_T$ threshold of the next-to-leading lepton.

IV. CONCLUSIONS

In this paper we perform a full Monte Carlo simulation of the background for Higgs boson decay to dilepton plus missing energy that arises from leptonic decays of heavy flavors. The processes that produce these backgrounds typically begin $10^5$–$10^{12}$ times as large as the signals of interest. Contrary to popular lore, these backgrounds are only mildly suppressed by isolation cuts. Instead, it is the detailed sequence of cuts on the phase space of the events that suppresses their size.

Throughout this paper we compare the heavy-flavor background (HFB) to the largest previously calculated background, continuum $W^+W^-$ production. For events with one heavy-flavor lepton ($Wc, Wb\bar{b}, \ldots$), the analysis cuts tend to chip away at the heavy-flavor backgrounds. The net result is an additional background that is half as large as continuum $WW$ at the Tevatron, but potentially 25 times larger than $WW$ at the LHC. For events with two heavy-flavor leptons ($b\bar{b}, c\bar{c}$), the additional background estimate is less certain, but it is potentially even larger.

Spin correlations in the $H \rightarrow W^+W^-$ signal tend to cause the leptons to be fairly soft, hence the $E_T$ cut on the next-to-leading lepton is pushed as low as possible — 10 GeV in the cases of both DØ and ATLAS. We demonstrate that simply raising the cut on this additional lepton to $E_T > 20$ GeV preserves roughly 2/3 of the signal, but it reduces these background by factors of 10–30.
Raising the $E_T$ cut is very effective for removing the HFB, but we emphasize that extrapolations of the magnitude and shape of this background using Monte Carlo techniques have large inherent uncertainties. In particular, there is a strong correlation between the cut on missing transverse energy $E_T$ and isolation. We recommend that the HF background be measured \textit{in situ}, with cuts as close as possible to the final sample. We describe a preliminary technique that could be used at the Tevatron. At the LHC the HFB is large enough that it can be studied in the final transverse mass $M_{T}^{ll}$ distribution and fully controlled.

While this paper focuses in detail on analyses of $H \rightarrow W^+W^-$, our intention is to raise a broader awareness of the potential danger of heavy-flavor leptons to multilepton analyses. Vector-boson fusion into a Higgs boson is similar to the process studied here, with the added requirement of two hard jets at large and opposite rapidities. The jet requirement may \textit{increase} the backgrounds from $b\bar{b}$ and $c\bar{c}$, because these processes naturally come with additional radiation. Other Higgs boson decay modes may also be effected, e.g., $H \rightarrow ZZ \rightarrow 4$ leptons has a background from $Zb\bar{b}$. Even trilepton searches for supersymmetry typically have very soft additional leptons. If lepton transverse momentum cuts must be raised to remove the heavy-flavor leptons, there could be a far-ranging impact on analyses of these types of signals. Complete correlated studies should be performed to determine whether heavy flavor leptons are a problem and contingencies made to measure them.

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\textit{Note added}— As this paper was being completed, the CDF Collaboration released a preprint \cite{CDF} describing a new analysis based on the D$\phi$ method studied here. In that paper, the $b\bar{b}/c\bar{c}$ resonances are suppressed by the cut on the minimum dilepton invariant mass $M_{ll} > 16$ GeV. According to our investigation, the minimum $E_T$ cuts and weighting of the $\Delta \phi$ distribution force $M_{ll} > 16$ GeV for most heavy flavor events (all events with $\Delta \phi > 1.2$). This dilepton mass cut is looser than the D$\phi$ choice of 20 GeV and will yield less suppression.
against $Wc$. The $W+\text{heavy-flavor}$ events and $b\bar{b}/c\bar{c}$ events may well make up the systematic difference between the background estimate and the small excess observed in the CDF data.

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