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Jet Substructure as a New Higgs-Search Channel at the Large Hadron Collider

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It is widely considered that, for Higgs boson searches at the CERN Large Hadron Colider, WH and ZH production where the Higgs boson decays to $b\bar{b}$ are poor search channels due to large backgrounds. We show that at high transverse momenta, employing state-of-the-art jet reconstruction and decomposition techniques, these processes can be recovered as promising search channels for the standard model Higgs boson around 120 GeV in mass.

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A key aim of the Large Hadron Collider (LHC) at CERN is to discover the Higgs boson, the particle at the heart of the standard-model (SM) electroweak symmetry breaking mechanism. Current electroweak fits, together with the LEP exclusion limit, favor a light Higgs boson, i.e., one around 120 GeV in mass [1]. This mass region is particularly challenging for the LHC experiments, and any SM Higgs-boson discovery is expected to rely on a combination of several search channels, including gluon fusion $\to H \to \gamma\gamma$, vector boson fusion, and associated production with $t\bar{t}$ pairs [2,3].

Two significant channels that have generally been considered less promising are those of Higgs-boson production in association with a vector boson, $pp \to WH$, ZH, followed by the dominant light Higgs-boson decay, to two b-tagged jets. If there were a way to recover the WH and ZH channels, it could have a significant impact on Higgs-boson searches at the LHC. Furthermore, these two channels also provide unique information on the couplings of a light Higgs boson separately to W and Z bosons.

Reconstructing W or Z associated $H \to b\bar{b}$ production would typically involve identifying a leptonically decaying vector boson, plus two jets tagged as containing b-mesons. Two major difficulties arise in a normal search scenario. The first is related to detector acceptance: leptons and b-jets can be effectively tagged only if they are reasonably central and of sufficiently high transverse momentum. The relatively low mass of the VH (i.e., WH or ZH) system means that in practice, it can be produced at rapidities somewhat beyond the acceptance, and it is also not unusual for one or more of the decay products to have too small a transverse momentum. The second issue is the presence of large backgrounds with intrinsic scales close to a light Higgs-boson mass. For example, $t\bar{t}$ events can produce a leptonically decaying W, and in each top-quark rest frame, the b-quark has an energy of ~65 GeV, a value uncomfortably close to the $m_H/2$ that comes from a decaying light Higgs boson. If the second W-boson decays along the beam direction, then such a $t\bar{t}$ event can be hard to distinguish from a WH signal event.

In this Letter, we investigate VH production in a boosted regime, in which both bosons have large transverse momenta and are back-to-back. This region corresponds to only a small fraction of the total VH cross section (about 5% for $p_T > 200$ GeV), but it has several compensating advantages: (i) in terms of acceptance, the larger mass of the VH system causes it to be central, and the transversely boosted kinematics of the V and H ensures that their decay products will have sufficiently large transverse momenta to be tagged; (ii) in terms of backgrounds, it is impossible, for example, for an event with on-shell top-quarks to produce a high-p_T $b\bar{b}$ system *and* a compensating leptonically decaying W, without there also being significant additional jet activity; (iii) the HZ with $Z \to \nu\bar{\nu}$ channel becomes visible because of the large missing transverse energy.

One of the keys to successfully exploiting the boosted VH channels will lie in the use of jet-finding geared to identifying the characteristic structure of a fast-moving Higgs boson that decays to b and $\bar{b}$ in a common neighborhood in angle. We will therefore start by describing the method we adopt for this, which builds on previous work on heavy Higgs decays to boosted W's [4], WW scattering at high energies [5], and the analysis of SUSY decay chains [6]. We shall then proceed to discuss event generation, our precise cuts, and finally show our results.

When a fast-moving Higgs boson decays, it produces a single fat jet containing two b-quarks. A successful identification strategy should flexibly adapt to the fact that the $b\bar{b}$ angular separation will vary significantly with the Higgs p_T and decay orientation, roughly

$$R_{b\bar{b}} \simeq \frac{1}{\sqrt{z(1-z)}} \frac{m_H}{p_T}, \quad (p_T \gg m_H), \tag{1}$$

where z, $1-z$ are the momentum fractions of the two quarks. In particular, one should capture the b, $\bar{b}$ and any gluons they emit, while discarding as much contamination

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as possible from the underlying event (UE), in order to maximize resolution on the jet mass. One should also correlate the momentum structure with the directions of the two b-quarks, and provide a way of placing effective cuts on the z fractions, both of these aspects serving to eliminate backgrounds.

To flexibly resolve different angular scales, we use the inclusive, longitudinally invariant Cambridge or Aachen (CA) algorithm [7,8]: one calculates the angular distance $\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$ between all pairs of objects (particles) i and j, recombines the closest pair, updates the set of distances, and repeats the procedure until all objects are separated by a $\Delta R_{ij} > R$, where R is a parameter of the algorithm. It provides a hierarchical structure for the clustering, like the $K_\perp$ algorithm [9,10], but in angles rather than in relative transverse momenta (both are implemented in FastJet 2.3 [11]).

Given a hard jet j, obtained with some radius R, we then use the following new iterative decomposition procedure to search for a generic boosted heavy-particle decay. It involves two dimensionless parameters, μ and y_{cut}: (1) Break the jet j into two subjets by undoing its last stage of clustering. Label the two subjets j_1, j_2 such that $m_{j_1} > m_{j_2}$. (2) If there was a significant mass drop (MD), $m_{j_1} < \mu m_j$, and the splitting is not too asymmetric, $y = \frac{\min(p_{tj_1}^2, p_{tj_2}^2)}{m_j^2} \Delta R_{j_1,j_2}^2 > y_{\text{cut}}$, then deem j to be the heavy-particle neighborhood and exit the loop. Note that $y \simeq \min(p_{tj_1}, p_{tj_2})/\max(p_{tj_1}, p_{tj_2})$. (Note also that this y_{cut} is related to, but not the same as, that used to calculate the splitting scale in [5,6], which takes the jet p_T as the reference scale rather than the jet mass.) (3) Otherwise, redefine j to be equal to j_1 and go back to step 1. The final jet j is to be considered as the candidate Higgs boson if both j_1 and j_2 have b tags. One can then identify $R_{b\bar{b}}$ with $\Delta R_{j_1 j_2}$. The effective size of jet j will thus be just sufficient to contain the QCD radiation from the Higgs decay, which, because of angular ordering [12–14], will almost entirely be emitted in the two angular cones of size $R_{b\bar{b}}$ around the b-quarks.

The two parameters μ and y_{cut} may be chosen independently of the Higgs mass and p_T. Taking $\mu \gtrsim 1/\sqrt{3}$ ensures that if, in its rest frame, the Higgs decays to a Mercedes $b\bar{b}g$ configuration, then it will still trigger the mass drop condition (we actually take $\mu = 0.67$). The cut on $y \simeq \min(z_{j_1}, z_{j_2})/\max(z_{j_1}, z_{j_2})$ eliminates the asymmetric configurations that most commonly generate significant jet masses in non-b or single-b-jets, due to the soft gluon divergence. It can be shown that the maximum $S/\sqrt{B}$ for a Higgs boson compared to mistagged light jets is to be obtained with $y_{\text{cut}} \simeq 0.15$. Since we have mixed tagged and mistagged backgrounds, we use a slightly smaller value, $y_{\text{cut}} = 0.09$.

In practice, the above procedure is not yet optimal for LHC at the transverse momenta of interest, $p_T \sim$ 200–300 GeV, because from Eq. (1), $R_{b\bar{b}} \gtrsim 2m_H/p_T$ is still quite large and the resulting Higgs mass peak is subject to significant degradation from the underlying event (UE), which scales as $R_{b\bar{b}}^4$ [15]. A second novel element of our analysis is to *filter* the Higgs neighborhood. This involves resolving it on a finer angular scale, $R_{\text{filt}} < R_{b\bar{b}}$, and taking the three hardest objects (subjets) that appear—thus, one captures the dominant $\mathcal{O}(\alpha_s)$ radiation from the Higgs decay, while eliminating much of the UE contamination. We find $R_{\text{filt}} = \min(0.3, R_{b\bar{b}}/2)$ to be rather effective. We also require the two hardest of the subjets to have the b tags.

The overall procedure is sketched in Fig. 1. We illustrate its effectiveness by showing in Table I, (a) the cross section for identified Higgs decays in HZ production, with $m_H = 115$ GeV and a reconstructed mass required to be in a moderately narrow (but experimentally realistic) mass window, and (b) the cross section for background $Zb\bar{b}$ events in the same mass window. Our results (CA MD-F) are compared to those for the $K_\perp$ algorithm with the same y_{cut} and the SISCONE [16] algorithm based just on the jet mass. The $K_\perp$ algorithm does well on background rejection, but suffers in mass resolution, leading to a low signal; SISCONE takes in less UE so gives good resolution on the signal; however, because it ignores the underlying substructure, fares poorly on background rejection. CA MD-F performs well both on mass resolution and background rejection.

The above results were obtained with HERWIG 6.510 [17,18] with JIMMY 4.31 [19] for the underlying event, which has been used throughout the subsequent analysis. The signal reconstruction was also cross checked using PYTHIA 6.403 [20]. In both cases, the underlying event model was chosen in line with the tunes currently used by ATLAS and CMS (see for example [21]). [The non-default parameter setting are: PRSOF = 0, JMRAD(73) = 1.8, PTJIM = 4.9 GeV, JMUEO = 1, with CTEQ6L [22] PDFs.] The leading-logarithmic parton shower approximation used in these programs have been shown to model jet substructure well in a wide variety of processes [23–28]. For this analysis, signal samples of WH, ZH were generated, as well as WW, ZW, ZZ, Z + jet, W + jet, $t\bar{t}$, single top and dijets to study backgrounds. All samples corre-

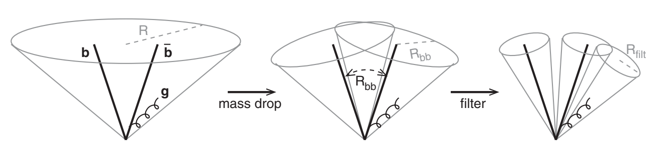

FIG. 1. The three stages of our jet analysis: starting from a hard massive jet on angular scale R, one identifies the Higgs neighborhood within it by undoing the clustering (effectively shrinking the jet radius) until the jet splits into two subjets each with a significantly lower mass; within this region, one then further reduces the radius to R_{filt} and takes the three hardest subjets, so as to filter away UE contamination while retaining hard perturbative radiation from the Higgs decay products.

TABLE I. Cross section for signal and the $Z+$jets background in the leptonic Z channel for $200 < p_{TZ}/\mathrm{GeV} < 600$ and $110 < m_J/\mathrm{GeV} < 125$, with perfect b-tagging; shown for our jet definition, and other standard ones at near optimal R values.

Jet definition	σ_S/fb	σ_B/fb	$S/\sqrt{B \cdot \mathrm{fb}}$
CA, $R = 1.2$, MD-F	0.57	0.51	0.80
$K_\perp$, $R = 1.0$, y_{cut}	0.19	0.74	0.22
SISCONE, $R = 0.8$	0.49	1.33	0.42

spond to a luminosity $\geq 30\ \mathrm{fb}^{-1}$, except for the lowest $\hat{p}_T^{\min}$ dijet sample, where the cross section makes this impractical. In this case, an assumption was made that the selection efficiency of a leptonically-decaying boson factorizes from the hadronic Higgs selection. This assumption was tested and is a good approximation in the signal region of the mass plot, though correlations are significant at lower masses.

The leading order (LO) estimates of the cross section were checked by comparing to next-to-leading order (NLO) results. High-p_T VH and $Vb\bar{b}$ cross sections were obtained with Monte Carlo for FeMtobarn processes (MCFM) [29,30] and found to be about 1.5 times the LO values for the two signal and the $Z^0 b\bar{b}$ channels (confirmed with MC@NLO v3.3 for the signal [31]), while the $W^\pm b\bar{b}$ channel has a K factor closer to 2.5 (as observed also at low-p_T in [30]). (For the $Vb\bar{b}$ backgrounds, these results hold as long as both the vector boson and $b\bar{b}$ jet have a high p_T; relaxing the requirement on p_{TV} leads to enhanced K-factors from electroweak double-logarithms.) The main other background, $t\bar{t}$ production, has a K factor of about 2 (found comparing the HERWIG total cross section to [32]). This suggests that our final LO-based signal/$\sqrt{\text{background}}$ estimates ought not to be too strongly affected by higher order corrections, though further detailed NLO studies would be of value.

Let us now turn to the details of the event selection. The candidate Higgs jet should have a p_T greater than some $\hat{p}_T^{\min}$. The jet R-parameter values commonly used by the experiments are typically in the range 0.4–0.7. Increasing the R-parameter increases the fraction of contained Higgs decays. Scanning the region $0.6 < R < 1.6$ for various values of $\hat{p}_T^{\min}$ indicates an optimum value around $R = 1.2$ with $\hat{p}_T^{\min} = 200$ GeV.

Three subselections are used for vector bosons: (a) An e^+e^- or $\mu^+\mu^-$ pair with an invariant mass $80\ \mathrm{GeV} < m < 100$ GeV and $p_T > \hat{p}_T^{\min}$. (b) Missing transverse momentum $> \hat{p}_T^{\min}$. (c) Missing transverse momentum >30 GeV plus a lepton (e or μ) with $p_T > 30$ GeV, consistent with a W of nominal mass with $p_T > \hat{p}_T^{\min}$. It may also be possible, by using similar techniques to reconstruct hadronically decaying bosons, to recover signal from these events. This is a topic left for future study.

To reject backgrounds, we require that there be no leptons with $|\eta| < 2.5$, $p_T > 30$ GeV apart from those used to reconstruct the leptonic vector boson, and no b-tagged jets in the range $|\eta| < 2.5$, $p_T > 50$ GeV apart from the Higgs candidate. For channel (c), where the $t\bar{t}$ background is particularly severe, we require that there are no additional jets with $|\eta| < 3$, $p_T > 30$ GeV. The rejection might be improved if this cut were replaced by a specific top veto [5]. However, without applying the subjet mass reconstruction to all jets, the mass resolution for $R = 1.2$ is inadequate.

The results for $R = 1.2$, $\hat{p}_T^{\min} = 200$ GeV are shown in Fig. 2, for $m_H = 115$ GeV. The Z peak from ZZ and WZ events is clearly visible in the background, providing a critical calibration tool. Relaxing the b-tagging selection would provide greater statistics for this calibration, and would also make the W peak visible. The major backgrounds are from W or $Z+$jets, and [except for the $HZ(Z \to l^+l^-)$ case], $t\bar{t}$.

Combining the three subchannels in Fig. 2(d), and summing signal and background over the two bins in the range 112–128 GeV, the Higgs signal is seen with a significance of 4.5σ (8.2σ for $100\ \mathrm{fb}^{-1}$). The intrinsic resolution of the jet mass at the particle level would allow finer binning and greater significance. However, studies [33,34] using parameterized simulations of the ATLAS detector indicate that detector resolution would prohibit this.

The b-tagging and mistag probabilities are critical parameters for this analysis, and no detailed study has been published of tagging two high-p_T b subjets. Values used by

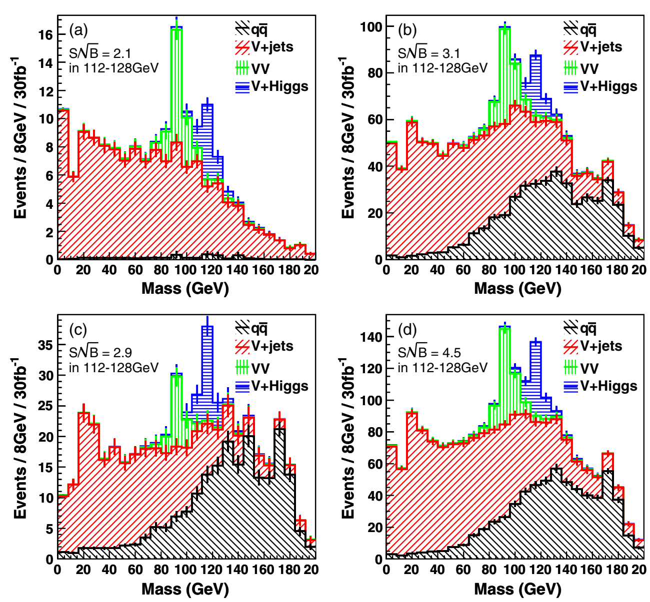

FIG. 2 (color online). Signal and background for a 115 GeV SM Higgs signal simulated using HERWIG, CA MD-F with $R = 1.2$ and $p_T > 200$ GeV, for $30\ \mathrm{fb}^{-1}$. The b tag efficiency is assumed to be 60%, and a mistag probability of 2% is used. The $q\bar{q}$ sample includes dijets and $t\bar{t}$. The vector boson selections for (a), (b), and (c) are described in the text, and (d) shows the sum of all three channels. The errors reflect the statistical uncertainty on the simulated samples and correspond to integrated luminosities $>30\ \mathrm{fb}^{-1}$.

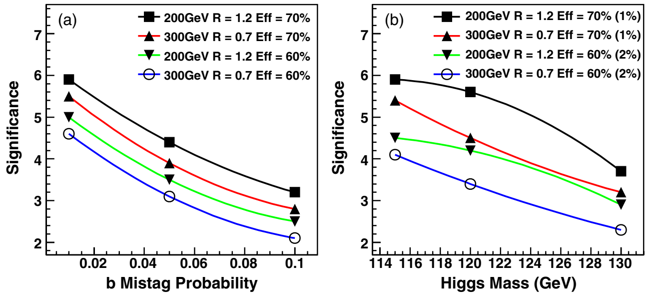

FIG. 3 (color online). Estimated sensitivity for 30 fb^{-1} under various different sets of cuts and assumptions (a) for $m_H = 115$ GeV as a function of the mistag probability for b-subjets and (b) as a function of Higgs mass for the b-tag efficiency (mistag rates) shown in the legend. Significance is estimated as signal$/\sqrt{\text{background}}$ in the peak region.

experiments for single-tag probabilities range up to 70% for the efficiency and down to 1% for mistags. Results for 70% and 60% efficiency are summarized in Fig. 3(a) as a function of the mistag probability.

There is a tradeoff between rising cross section and falling fraction of contained decays (as well as rising backgrounds) as $\hat{p}_T^{\text{min}}$ is reduced. As an example of the dependence on this tradeoff, we show the sensitivity for $\hat{p}_T^{\text{min}} = 300$ GeV, $R = 0.7$ in Fig. 3(a).

The significance falls for higher Higgs masses, as shown in Fig. 3(b), but values of 3σ or above seem achievable up to $m_H = 130$ GeV.

In addition to the b-tagging, the effects of pileup, intrinsic resolution, and granularity of the detector will all have an impact. Several ideas exist to improve some of these, and initial studies with realistic detector simulations indicate that the efficiencies and resolutions assumed here are not unreasonable, though the exact requirements of our analysis have not been studied with such tools.

We conclude that subjet techniques have the potential to transform the high-p_T $WH, ZH(H \to b\bar{b})$ channel into one of the best channels for discovery of a low mass Standard Model Higgs at the LHC. This channel could also provide unique information on the coupling of the Higgs boson separately to W and Z bosons. Realizing this potential is a challenge that merits further experimental study and complementary theoretical investigations.

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