Jet substructure as a new Higgs search channel at the LHC

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We show that WH and ZH production where the Higgs boson decays to $b\bar{b}$ can be recovered as good search channels for the Standard Model Higgs at the Large Hadron Collider. This is done by requiring the Higgs to have high transverse momentum, and employing state-of-the-art jet reconstruction and decomposition techniques.

1. INTRODUCTION

A key aim of the Large Hadron Collider (LHC) is to discover the Higgs boson, or to prove its non-existence, and hence elucidate the mechanism of mass generation and electroweak symmetry breaking. Current electroweak fits, together with the LEP exclusion limit, favour 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 $\rightarrow H \rightarrow \gamma \gamma$, 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, $pp \rightarrow WH$, ZH, followed by the dominant light Higgs boson decay, to two b-tagged jets. In this contribution we summarise the work of [4], which presented a way to recover the WH and ZH channels.

2. KINEMATIC SELECTION

Reconstructing W or Z associated $H \rightarrow b\bar{b}$ production would typically involve identifying a leptonically decaying vector boson, plus two jets tagged as containing b-mesons. However, 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. In addition, there are large backgrounds with intrinsic scales close to a light Higgs 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.

If one applies kinematic cuts to select VH production in a boosted regime, in which both bosons have large transverse momenta and are back-to-back, the visible cross-section is reduced by a large factor (about 20 for $p_T >$ 200 GeV). However, the remaining events are those for which the acceptance of the rest of analysis selection is high. 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. In addition, the backgrounds are reduced by a larger factor than the signal. Finally, the HZ with $Z \to \nu \bar{\nu}$ channel becomes visible because of the large missing transverse energy.

In this configuration, the Higgs decay products will be highly collimated, and typically found inside a single jet. In the main analysis it was required that this Higgs candidate jet should have a $p_T > 200$ GeV.

Three subselections were used for vector bosons: (a) An e^+e^- or $\mu^+\mu^-$ pair with an invariant mass 80 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 $p_T > \hat{p}_T^{\min}$.

To reject backgrounds we required 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.

3. HIGGS RECONSTRUCTION

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. In particular one should capture the b, \bar{b} and any gluons they emit, while discarding as much contamination as possible from the underlying event (UE), in order to maximise 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. Our method is new, but builds upon prevous work on identifying boosted Ws [5, 6].

To flexibly resolve different angular scales we use the inclusive, longitudinally invariant Cambridge/Aachen (C/A) 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, $y = \frac{\min(p_{ij_1}^2, p_{ij_2}^2)}{m_i^2} \Delta R_{j_1, j_2}^2 > y_{\text{cut}}$, then deem j to be the heavy-particle neighbourhood and exit the loop.
- 3. Otherwise redefine j to be equal to j_1 and go back to step 1.

The final jet j is the candidate Higgs boson if both j_1 and j_2 have b tags. One can then identify $R_{b\bar{b}}$ with $\Delta R_{j_1j_2}$. 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, 13, 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, $y_{\text{cut}} = 0.09$.

A second novel element of our analysis is to *filter* the Higgs neighbourhood. This involves rerunning the C/A algorithm with a smaller radius, $R_{\text{filt}} = \min(0.3, R_{b\bar{b}}/2)$, and taking the three hardest objects (subjets) that appear — thus one captures the dominant $\mathcal{O}(\alpha_s)$ radiation from the Higgs decay, while contamination from the underlying event. We also require the two hardest of the subjets to have the *b* tags.

The results were obtained with HERWIG 6.510[15, 16] with JIMMY 4.31 [17] for the underyling event, which has been used throughout the subsequent analysis. The underlying event model was chosen in line with the tunes currently used by ATLAS and CMS (see for example [18]). The leading-logarithmic parton shower approximation



Figure 1: (Left) Signal and background for a 115 GeV SM Higgs simulated using HERWIG, C/A MD-F with R = 1.2 and $p_T > 200$ GeV, for 30 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 fb⁻¹. (Right) 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.

used in HERWIG has been shown to model jet substructure well in a wide variety of processes [19, 20, 21, 22, 23, 24]. For this analysis, signal samples of WH, ZH were generated, as well as $WW, ZW, ZZ, Z + \text{jet}, W + \text{jet}, t\bar{t}$, single top and dijets to study backgrounds.

The leading order (LO) estimates of the cross-section were checked by comparing to next-to-leading order (NLO) results. The K-factors were such that we do not expect a large effect of the significance.

4. RESULTS

The results for R = 1.2, $\hat{p}_T^{\min} = 200$ GeV are shown in Fig. 1(left), for $m_H = 115$ GeV. The Z peak from ZZ and WZ events is clearly visible in the background, providing a critical calibration tool. 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 sub-channels in Fig. 1d, and summing signal and background over the two bins in the range 112-128 GeV, the Higgs is seen with a significance of 4.5 σ (8.2 σ for 100 fb⁻¹). The signal region summed over is consistent with the single jet mass resolution for K_{\perp} -jets found using detailed simulations of the ATLAS detector [2].

The *b*-tagging and mistag probabilities are critical parameters for this analysis. Values used by 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 summarised in Fig. 1a(right) as a function of the mistag probability.

There is a trade-off between rising cross-section and falling fraction of contained decays (as well as rising backgrounds) as \hat{p}_T^{\min} is reduced. As an example of the dependence on this trade-off, we show the sensitivity for $\hat{p}_T^{\min} = 300 \text{ GeV}, R = 0.7 \text{ in Fig.1a(right)}.$

The significance falls for higher Higgs masses, as shown in Fig. 1b(right), but values of 3σ or above seem achievable

5. Outlook

Sub-jet techniques have the potential to transform the high- $p_T WH, ZH(H \rightarrow b\bar{b})$ channel into one of the best channels for discovery of a low mass Standard Model Higgs at the LHC. Realising this potential is a challenge that merits further experimental study and complementary theoretical investigations.

Jet finding, jet mass and sub-jet technology has come a long way since the previous round of colliders, and has many applications at the LHC, where we will have interesting physics at O(100 GeV), and phase space open at O(1 TeV). This means that a single jet often contains interesting physics, and it becomes essential to study sub-jet structure. This has already been shown for example in applications such as hadronic vector-boson decays from vector-boson scattering [6] and SUSY decay chains [25], and boosted tops [26], including those from from exotic resonances [27]. We emphasise that this is a qualitatively new collider signature technique at the LHC and has a lot of potential still to be explored.

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