Inclusive production of $H \rightarrow b\bar{b}$ plus a recoil for the LHC Run-II

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Abstract – This letter presents a study of the inclusive production of $H \rightarrow b\bar{b}$ plus a recoil, using simulated samples of $pp$ collisions at $\sqrt{s} = 14$ TeV for an integrated luminosity in the range between 30 fb$^{-1}$ and 3 ab$^{-1}$. The case for experiments to include un-prescaled $b$-tag multijet triggers for this topology is made and the ideal jet thresholds are discussed. The sensitivity to the Standard Model Higgs boson with a transverse momentum of at least 200 GeV is evaluated with respect to a continuous background, dominated by multijet processes. The mass of $b$-jet-pairs is analysed, quoting sensitivity to cross-sections in the range from 1 to 2 pb, for 100 fb$^{-1}$, covering the total Higgs-boson production cross-section of 1.8 pb. The trigger strategy presented in this letter is compared to triggers already in use, showing an increase on the signal efficiency for masses below 200 GeV and a performance comparable to a logical OR of all the currently available akin triggers for higher masses. The robustness of the expected sensitivity against systematic uncertainties is estimated by considering various typical sources, such as those on the fitting parameters of the continuous background, shape uncertainties affecting the signal acceptance and the background modelling. The accuracy of the Higgs-boson production cross-section measurements is also discussed, quoting sensitivity to deviations of 50% for 100 fb$^{-1}$ and 10% for 3 ab$^{-1}$.

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Introduction. – Although the Higgs boson has been discovered at the LHC [1,2], a 5$\sigma$ observation for its largest decay mode $H \rightarrow b\bar{b}$ has not been achieved so far. The combination of huge backgrounds with large modelling uncertainties transforms the observation of this hadronic decay mode into a non-trivial task. The usual production channels, Higgs Strahlung ($VH$), associated top-pair Higgs boson ($ttH$) and vector boson fusion (VBF), provide upper limits on the event rate of, respectively, 1.4, 1.5 and 2.8 times the Standard Model (SM) expectation [3–5]. Measuring the Higgs-bottom coupling is of crucial importance at the LHC. Not many channels to measure this coupling exist. So far only $HZ$, $ttH$ and VBF have been studied [6–10]. In this letter, a new channel in gluon fusion is explored.

The early observation of $H \rightarrow \gamma\gamma$ at the LHC demonstrates that despite a small signal-to-background ratio, a data-driven background approach, high statistics and control over systematic uncertainties can yield a discovery. This letter explores the possibility of pursuing this strategy for the SM $H \rightarrow b\bar{b}$ channel, as well as for the search for SM $Z$-bosons and beyond the SM $CP$-odd bosons ($A$) decaying into $bb$ predicted by the two-Higgs-doublet model (2HDM) [11,12].

The study presented here explores the boosted $X \rightarrow bb$ kinematic regime such that the combinatorics are reduced, yet each heavy resonance $X$ decay can still be resolved via standard jet-clustering algorithms with typical jet radius. Requiring high-$p_T$ jets is further motivated by the limited capability of trigger systems of detectors to record events with a high rate. This, however, can be compensated by triggering on events with multiple $b$-jets, which is the strategy explored in the following. The dominant multi-jet background comes from the pure QCD $bb$+jets production. Additional $b$-jets from $g \rightarrow bb$ may be present in both signal and background — all such candidates are included in the analysis. Interestingly, the $Z \rightarrow bb$ channel has already been measured using the 8 TeV data with a similar analysis strategy [13].

This letter is organised as follows: First, the analysis strategy is presented, devoting special emphasis to the background fitting approach. Second, the LHC Run-II bounds to the SM Higgs boson and $Z$-boson via the strategy proposed here are derived.
Event generation and analysis. – Signal Monte Carlo (MC) samples are generated for scalar and pseudoscalar production with MCFM+PYTHIA8 [14,15] accounting for the full top and bottom mass effects in the production vertex. The higher-order QCD effects are included with a flat correction factor of 1.6 [16,17]. For the Z-boson signal and dijets and t+jets backgrounds, the SHERPA event generator in the four-flavour scheme [18] is used. All spin correlation effects in the Z event generator in the four-flavour scheme [18] is used. All spin correlation effects in the Z event generator in the four-flavour scheme [18] is used. All spin correlation effects in the Z event generator in the four-flavour scheme [18] is used. All spin correlation effects in the Z event generator in the four-flavour scheme [18] is used. All spin correlation effects in the Z event generator in the four-flavour scheme [18] is used. 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The cut flow is implemented in RIVET [21], which makes extensive use of FASTJET [22] for the jet finding. Jets are defined with the anti-$k_t$ [23] algorithm with a radius parameter $R = 0.4$ satisfying $p_T > 30$ GeV and $|\eta| < 3.0$. A jet is labelled as b-tagged if it can be geometrically matched\(^1\) to a b-hadron, using $\Delta R(b$-hadron, jet) < 0.3. A b-tagging efficiency of 70% and 1% of mistagging rate [24] are assumed. A lepton is isolated if the hadronic transverse energy within a cone of $R = 0.2$ surrounding the lepton tautamounts to less than 20% of the lepton transverse energy deposited.

\(^1\)The distance between two objects in the $\eta$-$\phi$ space is measured in terms of $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$. \(p_1 (1 - x)^{p_2} x^{p_3}\),

where $p_1$ is a normalisation factor, $p_2$ and $p_3$ are dimensionless shape parameters. An equivalent function is used in similar searches for resonances against a steeply falling background in hadronic final states [25,26]. Also in this figure, all the signal cross-sections are set to 2 pb. A reference integrated luminosity of 100 fb\(^{-1}\) is used. The bottom panel illustrates the expected sensitivity, by computing a bin-by-bin ratio of the number of expected signal events ($S$) to the statistical uncertainty on the background prediction ($\sqrt{B}$). The grey-shaded area illustrates the lower bound of the fitting range. This boundary is caused by the $R = 0.4$ jets no longer being able to resolve each b-hadron as an individual jet. This can be illustrated by running the event selection with a smaller jet radius parameter $R = 0.2$, see fig. 1(b). Here, the reach of the fitted form for low masses increases by 15 GeV. The usage of a smaller $R$-parameter, however, also increases the out-of-cone radiation, therefore degrading the signal mass resolution. Techniques to better resolve the collimated $bb$ system usually rely on jet substructure techniques [27–29]. However, this is outside of the scope of this paper as most of the signal events are in the resolved regime for our considered mass points.

Figure 2 shows the difference between signal-injected background and the background fit using the generator cross-section predictions for the SM Higgs boson and Z-boson, and a fixed 2 pb cross-section for $CP$-odd bosons.
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Fig. 2: (Colour online) Difference between the signal-injected background and the background fit for the SM Higgs boson, the $Z$-boson and the pseudo-scalar $A$ with $m(A) = 150, 175, 200$ GeV signal samples. The signal injection is performed and shown for each signal sample separately.

Fig. 3: Efficiency of various triggers and for the combination of all these triggers.

for a reference integrated luminosity of $100 \text{ fb}^{-1}$. This illustrates the size of the expected signal bump with respect to the statistical uncertainty on the background prediction.

**Trigger effects.** It is natural to expect that for a very large integrated luminosity the $H \rightarrow bb$ process would eventually become significant over the statistical uncertainty of a continuous background. This strategy, however, has not been pursued by experimental collaborations in part due to the limited rate of triggered events that can be recorded. Figure 3 shows the efficiency of some of the most akin triggers currently included in active trigger menus\(^2\). Individually, none of these triggers goes above a 50% efficiency, for the SM Higgs boson. This efficiency increases for larger masses. When combining events collected via all trigger strategies, an 80% of efficiency for the SM Higgs boson and nearly a 100% for very large masses is achieved. Notice that each trigger yields a different background shape and acceptance boundary. In the combination of all triggers, the acceptance boundary is still shifted to 80 GeV therefore limiting the accessibility to the $Z \rightarrow bb$ channel. This is shown in fig. 4.

In this letter, a trigger with two $b$-tagged jets recoiling against one or more jets is proposed, requiring in addition one large-$R$ jet with $p_T > 400$ GeV. For $Z$-bosons, with only 1 fb\(^{-1}\), sensitivity to cross-sections around 20 pb is observed. For the SM Higgs boson and 100 fb\(^{-1}\), two-sigma sensitivity to a cross-section of around

\[ 2 \pm 1 \text{ pb}, \text{ SM Higgs-boson}\]

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\[ m_2 \rightarrow X + 2 \text{ jets}, \ p_T > 400 \text{ GeV}\]

is presented against the integrated luminosity. For comparison, the SM cross-section prediction for these processes is also shown.

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Fig. 6: Comparison between the expected sensitivity to the signal cross-section times $\text{BR}(X \to b\bar{b})$ for the statistical uncertainty only and the limit after the addition of individual sources of uncertainties. This is shown for SM Higgs-boson (left) and pseudo-scalar $A$ sources of uncertainties. This is shown for SM Higgs-boson production cross-section measurement. The system boost is parametrised in terms of the scalar sum of all jets passing the event selection $H_T$. The global observable $H_T$ is chosen instead of the more intuitive $b\bar{b}$ pair $p_T$, as it does not require to uniquely identify a candidate, in line with the inclusive approach presented in this paper.

Table 1 summarises the changes on the signal and background acceptance in terms of the overall boost of the system. Here, the total background cross-section drops by one (two) orders of magnitude for the 3rd (4th) $H_T$ bin, regardless of $R$. This drop is accompanied by a reduction of 2 pb observed. This is in agreement with the simple $S/\sqrt{B}$ shown in fig. 1(a). Notice that the early $Z$-boson observation becomes ideal for an in situ uncertainty constraint to be used in the later $H \to b\bar{b}$ measurement.

Robustness against systematic uncertainties. The impact of various potential sources of systematic uncertainties is studied by varying the signal and background rates and shapes. The aim is to access the impact of potential extra sources of uncertainties that were not accounted for in the MC generation, such as, for instance, detector effects. In HistFit, each systematic variation is associated to a nuisance parameter that is fitted simultaneously with the signal strength. Nuisance parameters can be constrained by the data, corresponding in this case to the MC background prediction. Large uncertainties, as those testing the background MC modelling, are over-constrained minimising their impact. This undesired feature can be avoided by separating uncertainties in two classes: those likely to be encountered in a real data-driven background scenario and those that are only relevant when considering the potentially inaccurate description of the background by the MC. The former are assigned nuisance parameters while to test the impact of the latter the nominal background prediction is substituted by the systematic variation.

Figure 6 compares the nominal sensitivity to that obtained after including a given uncertainty, for an integrated luminosity of 100 fb$^{-1}$. The top entry shows the nominal value. The error bars correspond to ±2σ. The central panel shows the impact of uncertainties considered as nuisance parameters, such as those affecting the signal acceptance and the statistical uncertainty on the parameters of eq. (1). From this class, the uncertainty on the signal mass resolution is shown to have the largest effect, particularly on the ±2σ band. The bottom panel shows the impact of uncertainties due to the MC modelling of the background. Apart from a 50% drop on the MC background cross-section, which, as expected, improves the sensitivity, these uncertainties have a minor impact on the overall result.

**SM Higgs-boson production cross-section measurement.** The sensitivity to deviations from the SM Higgs-boson production cross-section prediction is tested by assuming the signal hypothesis

$$N_{\text{obs}} = N_{\text{SM} \ H \to b\bar{b}} + N_{\text{signal}},$$

where $N_{\text{signal}}$ is proportional to the signal strength parameter in the maximum-likelihood fit. Here $N_{\text{obs}}$ is given by the number of expected events from multi-jet, $tt$ and SM $H \to b\bar{b}$, Figure 7 shows the expected sensitivity relative to the SM prediction. Here, for an integrated luminosity of 100 fb$^{-1}$, a sensitivity to 50% deviations is achieved. At the high-luminosity LHC with a total integrated luminosity of $L = 3 \text{ ab}^{-1}$ a sensitivity of 10% deviations can be obtained.

Booster the $b\bar{b}$ system. To further decrease the event rate, the jet $p_T$ threshold could be raised, therefore boosting the $b\bar{b}$ system. The system boost is parametrised in terms of the scalar sum of all jets passing the event selection $H_T$. The global observable $H_T$ is chosen instead of the more intuitive $b\bar{b}$ pair $p_T$, as it does not require to uniquely identify a candidate, in line with the inclusive approach presented in this paper.
of the fitting range and of the signal efficiency for SM Z-bosons and hence, from the 2nd $H_T$ bin onward, sensitivity to this process is not expected. For the lowest mass points, $m(A) = 70\text{ GeV}$ and to a lesser extent for SM Z-bosons, at very large $H_T$, a considerable loss in signal acceptance and mass resolution is observed. This loss could be recovered by using $R = 0.2$, however, this change is observed to bring little improvement to the other mass points, in all but the final $H_T$ bin, showing that the bulk of the events is in the resolved regime, except for very low-mass signals at very large $H_T$.

Summary. – This is the first study to demonstrate a simple and feasible strategy for discovering $X \rightarrow b\bar{b}$ exploring the continuous and steeply falling background via a suitable fit. In this letter it is shown that the 14 TeV LHC can observe the $X \rightarrow b\bar{b}$ decay very early for the Z-boson and the SM Higgs-boson. Moreover, the SM Higgs-boson production uncertainties for this decay can achieve 10% for the high-luminosity LHC, therefore they are competitive to the other production channels.

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