the bottom quark Yukawa coupling at the CERN Large Hadron Collider

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We propose a new method for measuring the bottom quark Yukawa coupling at the LHC. Higgs boson production in purely electroweak $WHjj$ events is calculated. The Standard Model signal rate including decays $W \to \ell\nu$ and $H \to b\bar{b}$ is 11 fb for $M_H = 120$ GeV. It is possible to suppress the principal background, $t\bar{t} + jets$, to below the level of the signal. As the top quark Yukawa coupling does not appear in this process, it promises a reliable extraction of g_{Hbb} in the context of extensions to the Standard Model, especially the MSSM.

The observation of electroweak symmetry breaking (ESB) in nature with the discovery of massive weak bosons is both a triumph and a tribulation of the Standard Model (SM) of particle interactions. While the SM has been incredibly successful in both explaining the data from various experiments, it has also made very powerful predictions for other behavior that was later observed. To date there are no glaring contradictions with the SM, nor even any moderately uncomfortable ones. Despite this success, direct observation of the mechanism believed to be responsible for ESB, the Higgs boson, has not been made.

All quantum numbers of the SM Higgs boson are known from theory except for its mass, which is a free parameter. While fits to electroweak (EW) data suggest that the Higgs boson is considerably lighter than its theoretical upper limit of 1 TeV, probably on the order of 100 GeV [1], the current direct search exclusion limit of $M_H > 107$ GeV [2] has pushed the SM Higgs boson mass above the EW fits central value. One may interpret this as a statement that we are on the verge of discovering the Higgs boson in present or near-future experiments.

If a new Higgs–like resonance is discovered at either the CERN Large Electron Positron collider, Fermilab's Tevatron machine or the soon to be built CERN Large Hadron Collider (LHC), it will be up to the LHC to determine the quantum numbers of the resonance and state with conviction whether it is the SM Higgs boson, a Higgs boson of an extension to the SM, or something else entirely. Of primary importance are the spin and couplings, which must be $SU(2)$ gauge couplings to the weak bosons and Yukawa couplings to fermions, proportional to the mass of the fermion. At the LHC, it will be fairly straightforward to determine the spin [3] as well as to extract the gauge couplings [4]. Measuring the Yukawa couplings is more difficult. Higgs boson decays to fermions are substantial only for $M_H \lesssim 150$ GeV (except for $H \to t\bar{t}$, which is significant for $M_H \gtrsim 350$ GeV); heavier Higgs bosons decay dominantly to W, Z. However, the LHC will be able to measure the τ Yukawa coupling quite easily [4].

Measurement of other Yukawa couplings may not be possible, however. For example, in the MSSM there are five physical Higgs bosons, two of which have the same quantum numbers as the SM Higgs bosons, but can vary in mass, subject to the constraint that the lighter of the two states must have a mass $M_h \lesssim 135$ GeV. As such, this state will typically have substantial rate for decays to fermions. In the MSSM however, Yukawa couplings of up-type and down-type fermions can be altered relative to each other already at tree level. This characteristic of the MSSM affects also the rare decay modes (e.g. $H \to \gamma\gamma$). In addition, large radiative corrections to the Yukawa couplings can modify the tree level decay rates considerably [5], e.g. causing "misalignment" of the couplings to b and to τ. Thus, direct observation of more than one decay mode can provide a constraint on the model. Observation of $H \to c\bar{c}$ is not likely to be possible at the LHC. $H \to b\bar{b}$ will be extremely difficult, but possible in $t\bar{t}H$ associated production for Higgs boson masses below ~ 120 GeV [3]. However, this process suffers from the complication that both an up-type and down-type Yukawa coupling are convoluted. Thus, another measurement of $H \to b\bar{b}$ would be highly desirable.

The utility of weak boson fusion (WBF) production of a Higgs boson, $pp \to qqVV + X \to qqH + X$, where the final state quarks appear as high-pT tagging jets at far forward and backward rapidities in the detector, has been shown to allow for excellent signal to background (S/B) ratio, typically much better than 1/1 [7]. WBF is, in fact, what would make observation of $H \to \tau^+\tau^-$ possible at the LHC, if the Higgs boson lies in the appropriate mass range. The rate for $qqVV \to qqH \to b\bar{b}jj$ would be almost an order of magnitude higher than for the decay to tau pairs, but would suffer from large backgrounds so we would expect such a search to be very difficult. Aside from the background issue is that of triggering on $b\bar{b}jj$ events, as they do not contain a high-p_T lepton, and may not pass a $\sum E_T$ trigger with great efficiency.

TABLE I. Cross sections (fb) for the $WHjj$ signal as a function of Higgs boson mass. Shown on successive lines are the inclusive rate without W or H decays, the Higgs boson branching ratio to $b\bar{b}$, and the inclusive rate multiplied by the $h \to b\bar{b}$ and $W \to e\nu, \mu\nu$ branching ratios.

M_H	110	120	130	140	150
inclusive	84	80	76	72	70
$B_H(b\bar{b})$	0.77	0.67	0.52	0.33	0.17
$B_W \cdot B_H \cdot \sigma$	13.9	11.2	8.6	5.1	2.5

Thus, we seek a process that provides a high-p_T lepton in addition to the far forward/backward tagging jets and the Higgs boson. The ideal choice is $WHjj$ production. Four classes of Feynman diagrams contribute to $pp \to WHjj + X$: WBF H production with W bremsstrahlung off a quark leg; WBF H production with additional W emission off the t-channel weak boson pair; and WBF W production and W bremsstrahlung where Higgs boson is radiated off the W. Note that the $WHjj$ events we consider are *not* QCD corrections to WH associated production, but are pure EW processes; QCD corrections to WH events will ultimately constitute an enhancement of the signal, but will typically not survive the tagging jet cuts and so are neglected here, a conservative approximation.

We calculate the cross section for $pp \to WHjj + X$ at the LHC, $\sqrt{s} = 14$ TeV, using full tree level matrix elements for all EW subprocesses, including finite width and off-shell effects for $W \to \ell\nu$ ($\ell = e, \mu$), and finite width effects for $H \to b\bar{b}$. The matrix elements were generated by MADGRAPH [8]. The Higgs boson NLO decay and total widths are corrected via input from HDECAY [9], with a further correction to the $H \to W^+W^-$ width including finite width effects from an explicit matrix element calculation, as a function of M_H. CTEQ4L structure functions [10] are employed with a choice of factorization scale $\mu_{f_i} = p_{T_i}$ of the outgoing tagging jets. Gaussian smearing of final state particle four-momenta is employed according to ATLAS expectations [3]. As some Feynman diagrams with a t-channel photon contribute, the total cross section, shown as a function of M_H in line 1 of Table I, is calculated with an explicit initial-final state quark pair $Q_{ij}^2 > 100$ GeV^2 to avoid the singularity from the photon propagator. This cut introduces a small uncertainty for the total rate without cuts, $\approx \pm 15\%$ for varying the Q^2 cut by a factor of 2 (1/2). It does not, however, affect the cross sections with cuts.

The total signal rate appears to be large enough to obtain a significant data sample. However, to determine whether this measurement is realistic, we calculate the cross section for the main background which can mimic the signal. The largest resonant backgrounds are QCD and EW $WZjj; Z \to b\bar{b}$ production, but in these cases the Z pole is well-separated from the Higgs boson resonance so the overlap should be minimal. Instead, the largest background to this signal is expected to be $t\bar{t} + jets$ events, where both W's from the top quarks decay leptonically (e or μ) and one of the leptons is too low in p_T to be observed; we take this cut to be $p_T(l, min) < 10$ GeV. These events consist of QCD corrections to $t\bar{t}$ production, but are completely perturbative in the phase space region of interest, as the QCD radiation can appear in the detector as far forward/backward tagging jets. In addition, there are tree level processes that do not correspond to initial or final state gluon radiation.

We calculate the $t\bar{t}jj$ rate using exact tree-level matrix elements [11] including top quark and W leptonic decays to e, μ. CTEQ4L structure functions [10] are employed with $\mu_f = min(E_T)$ of the jets/top quarks, and $\alpha_s(M_Z) = 0.118$ with 1-loop running and renormalization scale $\mu_r = E_T(jet/top)$. One factor of α_s is taken from each of the outgoing jets/top quarks, to take into account appropriately the relevant scale of each outgoing parton.

The basic WBF signature requires the two tagging jets to be at high rapidity and in opposite hemispheres of the detector, and the H, W decay products to be central and in between the tagging jets. The kinematic requirements for the "rapidity gap" level of cuts are as follows:

$$
\begin{gathered}
p_{T_j} \geq 30 \text{ GeV}\,, \quad |\eta_j| \leq 5.0\,, \quad \triangle R_{jj} \geq 0.6\,, \\
p_{T_b} \geq 15 \text{ GeV}\,, \quad |\eta_b| \leq 2.5\,, \quad \triangle R_{jb} \geq 0.6\,, \\
p_{T_\ell} \geq 20 \text{ GeV}\,, \quad |\eta_\ell| \leq 2.5\,, \quad \triangle R_{j\ell,b\ell} \geq 0.6\,, \\
\eta_{j,min} + 0.7 < \eta_{b,\ell} < \eta_{j,max} - 0.7\,, \\
\eta_{j_1} \cdot \eta_{j_2} < 0, \quad \triangle\eta_{tags} = |\eta_{j_1} - \eta_{j_2}| \geq 4.4\,. \qquad (1)
\end{gathered}
$$

The results for $M_H = 120$ GeV are shown in the first column of Table II. At this level the background is already quite manageable, but we observe two strikingly different characteristics of the signal v. the background: $t\bar{t}jj$ events have significantly higher $\not{p}_T$ on average; and they do no exhibit a Jacobian peak in the $m_T(\ell, \not{p}_T)$ distribution, a characteristic of W decays. Both features are due to the fact that by suppressing observation of the second charged lepton, the neutrino from that W's decay has significantly enhanced transverse momentum, which is unobserved, and greatly distorts the $m_T(\ell, \not{p}_T)$ distribution. We choose maximum cutoff values for both observables such that a S/B ratio of better than 1/1 can be obtained with reasonable signal rate intact (as shown in Table II):

$$
\not{p}_T < 100\,\text{GeV}\,, \quad m_T(\ell, \not{p}_T) < 100\,\text{GeV}\,. \qquad (2)
$$

A final cut that may be utilized is to reject any candidate event if it contains additional central QCD

TABLE II. Cross sections (fb) for the $WHjj$ signal with $M_H = 120$ GeV, and $t\bar{t}jj$ principal background, at various levels of cuts. Also shown are the progression of S/B and Poisson statistical significance in equivalent Gaussian sigma for 100 fb^{-1} of data for one experiment. A mass bin $100 < m_{b\bar{b}} < 130$ GeV is implicit for all levels of cuts, which captures about 80% of the signal.

cuts level	rap. gap	$+\not{p}_T < 100$ GeV	$+m_T(\ell, \not{p}_T) < 100$ GeV	+ veto	$\times\epsilon_{\rm ID} = 0.25$
$WHjj$ signal	1.4	1.3	1.22	0.92	0.23
$t\bar{t}jj$ bkg	4.9	2.3	1.54	0.46	0.12
S/B	1/3.5	1/1.8	1/1.3	2.0/1	2.0/1
σ_{Gauss} (100 fb^{-1})	6.3	8.3	9.8	10.9	5.3

(jet) activity of moderate p_T: a minijet [12]. Studies of the minijet rate for WBF, EW and QCD events can be found in Refs. [13,7] and references therein. Here, we simply apply the results from those studies. The probability of a signal event surviving a minijet veto, $p_T^{vet}(j) > 20$ GeV, is estimated to be 75%, slightly lower than that typical of WBF Higgs boson events, because the W bremsstrahlung components of $WHjj$ events can slightly enhance the minijet activity. The probability of a $t\bar{t}jj$ background event surviving a minijet veto is much lower, only about 30%; previous studies have indicated it may be even better than this for $t\bar{t} + jets$ events, but we choose to remain conservative for our proof of concept estimates here. This allows us to achieve a S/B rate of better than 1/1, which holds for Higgs boson masses up to 140 GeV. Thus, systematic uncertainties will not play as large a role as statistics in this measurement, at least for the first LHC run.

At this stage, shown in the fourth column of Table II, the statistical significance appears quite good. However, in reality only about 25% of these events will be captured in the data sample due to detector efficiencies. We take the expected values for ATLAS and CMS to be 86% for each tagging jet, 95% for the charged lepton, and 60% for each b quark tag. With 100 fb^{-1} of data, the expected output of the first LHC run, this yields a better than 5σ observation of $H \to b\bar{b}$. In comparison, for $M_H = 120$ GeV, ATLAS expects the significance of a $t\bar{t}H; H \to b\bar{b}$ observation to be only 3.6σ, with S/B $\sim 1/3$ and thus greater vulnerability to systematic uncertainties.

To illustrate that this would not be simply a counting experiment, but rather a distinct resonance could be observed, Fig. 1 shows the invariant mass spectrum for the tagged b quark pair. The $t\bar{t}jj$ background distribution is nearly flat in the mass region about $M_H = 120$ GeV, and is clearly below the level of the signal.

We have demonstrated the feasibility of a measurement of $H \to b\bar{b}$ decays at the LHC in a potentially low background environment with reasonable luminosity. The technique shows promise for Higgs boson masses up to about 140 GeV, safely above the mass limit of the MSSM. More importantly, it does this in a production mode independent of any other Yukawa couplings (e.g. top quark), thus reducing the model dependence in extraction of g_{Hbb}. The only reliance is on g_{HWW}, which will be the best-measured Higgs coupling at the LHC for Higgs boson masses above ~ 120 GeV [4]. To be sure, a more detailed study of this process including other significant backgrounds such as QCD $Wjjb\bar{b}$ production must be performed and is already underway [14]. The complete study will also examine the impact this measurement will have on MSSM scenarios – its ability to help distinguish the location in parameter space.

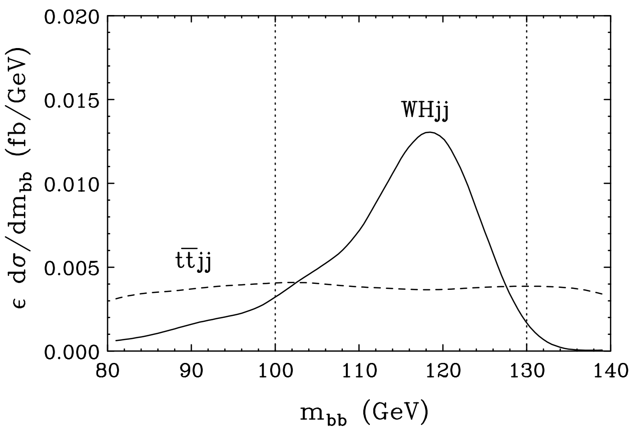

FIG. 1. $b\bar{b}$ invariant mass distribution of the $WHjj$ signal (solid) for $M_H = 120$ GeV and $t\bar{t}jj$ background (dashed) after the cuts of Eqs. (1),(2), a minijet veto and application of expected detector ID efficiencies as discussed in the text; $\epsilon = 0.25$. Vertical dotted lines denote the mass bin used for calculating statistical significance of the signal.

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