

A new analysis of $PP \rightarrow b\bar{b}\ell\nu jj$ at the LHC: Higgs and W boson associated production with two tag jets.

Alessandro Ballestrero,^a Giuseppe Bevilacqua^{ab} and Ezio Maina^{ab}

^aSezione di Torino, INFN,

Via Giuria 1, Torino, Italy

^bDipartimento di Fisica Teorica, Università di Torino,

Via Giuria 1, Torino, Italy

E-mail: ballestr@to.infn.it, bevilacq@to.infn.it, maina@to.infn.it

ABSTRACT: Higgs production in association with a W boson and two energetic tag jets at the LHC is studied for $M_H = 120$ GeV, with the Higgs decaying to $b\bar{b}$ and the W to $\ell\nu$ ($\ell = e, \mu$), guaranteeing high trigger efficiency. All parton level backgrounds are analyzed, including the effect of fake b -tagging. We discuss two detection strategies: in the first, more traditional, one, two jets are required to be b -tagged while in the second, which has not been previously examined in detail, only one tag is required. After all selection cuts about 80 and 200 events are foreseen in the two cases for a standard luminosity of 100 fb⁻¹ with a S/B ratio of 1/25 and 1/60 respectively. The corresponding statistical significancies, S/\sqrt{B} are 1.81 and 1.82.

KEYWORDS: Higgs Physics, QCD, Hadronic Colliders, Standard Model.

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1. Introduction

Higgs couplings to fermions are predicted unambiguously in all chiral theories in which Electroweak Symmetry Breaking is realized through the Higgs mechanism. A fundamental consequence of this general scheme is the proportionality of the Yukawa couplings to the corresponding fermion masses. A check of this proportionality is a fundamental test of EWSB.

The coefficient of proportionality between the Yukawa couplings and the fermion masses depend on the structure of the Higgs sector. For instance they are different in the Standard Model and in the MSSM. Therefore a measurement of these couplings would be extremely useful in distinguishing among competing theories

The $H \rightarrow b\bar{b}$ channel is of crucial relevance. It is by far the largest Higgs boson decay channel for a light Higgs, $M_H < 140$ GeV. It suffers from huge QCD backgrounds and it is necessary to consider production mechanisms which enhance Higgs production in comparison with QCD $b\bar{b}$ production in order to have a fighting chance to its detection. This typically involves additional particles or energetic jets in the final state.

A detailed discussion of the extraction of the Higgs couplings to gauge bosons and fermions and extensive references to previous literature can be found in [1, 2].

A number of channels have been studied in the past:

- $t\bar{t}b\bar{b}$ [3–6]: this channel provides spectacular events with four b 's, one high p_T lepton and two additional jets with a cross section of about 200 fb for $M_H = 200$ GeV. It suffers however from a large combinatorial background due to the very presence

of four b 's in the final state which makes it difficult to reconstruct the Higgs peak. Earlier analysis [3–5] were rather optimistic claiming a statistical significance of about $3 \div 4$ for an integrated luminosity of 30 fb^{-1} . A more recent analysis [6], using full detector simulation, is more cautious, obtaining a statistical significance of order 1.5 for a luminosity of 60 fb^{-1} , which should strike a cautionary note concerning the conclusions of all papers, including the present one, which do not incorporate the full reconstruction chain.

- $b\bar{b}Wjj$ [7]: this channel was studied in a Vector Boson Fusion like regime, characterized by large separation and large mass of the two tag jets, and compared to the background due to $Wb\bar{b}jj$ non resonant QCD production, and $t\bar{t}+2jets$ 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. The presence of an isolated, high p_T lepton guarantees high triggering efficiency. Very interesting signal to background ratios were reported.
- $b\bar{b}jj$ [8]: Vector Boson Fusion like cuts allow the extraction of the signal, but the required luminosity is in the range of about 600 fb^{-1} .
- $b\bar{b}\gamma jj$ [9]: the requirement of an additional high- p_T photon increases substantially the signal to background ratio. This channel was analyzed and compared with the one in [8] using the same selection criteria, obtaining significancies in the range between one and three for a standard high luminosity of 100 fb^{-1} and Higgs masses between 120 and 140 GeV.

In the following we reanalyze the reaction $PP \rightarrow b\bar{b}W(\ell\nu)jj$ as a mean to detect the Higgs decay to $b\bar{b}$ for $M_H = 120 \text{ GeV}$. In the next section we discuss the analysis performed in [7] and propose a number of possible improvements, while in section 3 the main features of the calculation are shown. Then we present our results: in section 4 employing the traditional approach which requires both b 's from the Higgs decay to be tagged and in section 5 requiring only a single b -tag. Finally we summarize the main points of our discussion.

2. $PP \rightarrow H(b\bar{b})W(\ell\nu)jj$ and its backgrounds

For convenience we recall here the main features of the study performed in [7]. The $WHjj$ events considered were pure EW processes. The QCD contribution to $WHjj$ was conservatively neglected. The main background processes were taken to be nonresonant QCD $Wb\bar{b}jj$ production, and $t\bar{t}+2jets$ events, where both W 's from the top quarks decay leptonically (e or μ) and one of the leptons is soft and undetected, the limit being set at $p_T(l, min) < 10 \text{ GeV}$.

The following set of cuts were used:

$$\begin{aligned}
 p_{T_j} &\geq 30 \text{ GeV}, & |\eta_j| &\leq 5.0, & \Delta R_{jj} &\geq 0.6, \\
 p_{T_b} &\geq 15 \text{ GeV}, & |\eta_b| &\leq 2.5, & \Delta R_{jb} &\geq 0.6, \\
 p_{T_\ell} &\geq 20 \text{ GeV}, & |\eta_\ell| &\leq 2.5, & \Delta R_{j\ell, b\ell} &\geq 0.6,
 \end{aligned}
 \tag{2.1}$$

$$\eta_{j,min} + 0.7 < \eta_{b,\ell} < \eta_{j,max} - 0.7,$$

$$\begin{aligned} \eta_{j_1} \cdot \eta_{j_2} &< 0, & \Delta\eta_{\text{tags}} = |\eta_{j_1} - \eta_{j_2}| &\geq 4.4. \\ M_{j_1 j_2} &> 600 \text{ GeV}, & p_T(b_1, b_2) &> 50, 20 \text{ GeV}. \end{aligned} \quad (2.2)$$

$$p_T < 100 \text{ GeV}, \quad M_T(\ell, \not{p}_T) < 100 \text{ GeV}. \quad (2.3)$$

where $j = d, u, s, c, g$ while j_1 and j_2 are the tag jets and $b_{1(2)}$ refers to the b -quark with highest (lowest) p_T . For the cuts described in eqs. (2.1)–(2.3) and $\ell = e, \mu$ the cross sections for $WHjj$, $Wb\bar{b}jj$, $t\bar{t}jj$ were found to be 1.1, 4.3 and 1.2 fb respectively, including the decays of the two bosons, with a signal over background ratio of 1/5. With an estimated overall efficiency of about 25% and an educated guess concerning the effect of a central mini-jet veto $p_T^{\text{veto}}(j) \geq 20 \text{ GeV}$ of an efficiency of 75% for the signal and of 30% for the background a statistical significance of about 4.4 was foreseen, taking into account 100 fb^{-1} of data for each of the two experiments.

We propose that a number of issues should receive further attention:

1. The $\mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$ contribution is potentially large. In fact, a simulation of $jj\ell\nu H$, with the Higgs on shell and $M_H = 120 \text{ GeV}$, yields a cross section of 65 fb with the following selection cuts:

$$\begin{aligned} p_{T_j} &\geq 20 \text{ GeV}, & |\eta_j| &\leq 5.0, \\ p_{T_b} &\geq 20 \text{ GeV}, & |\eta_b| &\leq 5.0, \\ p_{T_\ell} &\geq 20 \text{ GeV}, & |\eta_\ell| &\leq 3.0, \\ M_{jj} &\geq 60 \text{ GeV}, & M_{bb} &\geq 60 \text{ GeV}. \end{aligned} \quad (2.4)$$

With such a relatively large cross section, the impact of this production channel should be assessed.

2. The analysis has only been performed with cuts optimized for WW scattering studies. The Higgs can be produced through boson scattering but also in Higgs-strahlung which can have quite different kinematic distributions. It remains to be explored whether other selection procedures are equally or more effective in extracting a signal. We are interested in $H \rightarrow b\bar{b}$ regardless of the details of the production mechanism.
3. The important background due to $t\bar{t}$ production has not been studied. The semileptonic decay of a $t\bar{t}$ pair gives exactly the final state we are interested in, $b\bar{b}\ell\nu jj$, at a prodigious rate compared to the signal. The top-related background considered in [7], $t\bar{t}jj$ production with one charged lepton lost in the beampipe turns out to be much smaller than $t\bar{t}$ production even after all selection cuts, as discussed in section 4. The additional jet activity and the particular kinematic signatures expected in top production, will be effective in reducing both backgrounds (and should be taken into account for $\mathcal{O}(\alpha_{EM}^4 \alpha_S^2) bbWjj$ production).
4. b -tagging is based on several physical observables which discriminate between jets initiated by b 's and jets originating from other kind of partons. There is however a

non negligible probability that c -quarks and even light quarks or gluons produce jets which satisfy the b -tagging criteria. The impact of these fake b -taggings has not been taken into account. Typical values for the probabilities to pass the b -tagging test are: $\epsilon_b = 0.5$ for a b -quark, $\epsilon_c = 0.1$ for a c -quark and $\epsilon_{q/g} = 0.01$ for a light quark or a gluon, $q = d, u, s$. In the presence of very large backgrounds as $t\bar{t}$ and $W + 4j$ production, fake hits can have a huge effect even after severe cuts.

5. The double b -tag requirement sharply decreases the expected yield. The overall detection efficiency is proportional to $\epsilon_b^2 = 0.25$ for $\epsilon_b = 0.5$ with double b -tagging, while it becomes $2\epsilon_b(1 - \epsilon_b) + \epsilon_b^2 = 0.75$ if at least one b -tagging is required. In addition the central jet which is supposed to originate from the Higgs decay, and which is not required to pass the b -tagging test, can be detected in a much larger angular range than the b -tagging coverage, with a further efficiency increase. It is therefore worthwhile to explore whether strategies based on single b -tagging or no b -tagging at all are viable.

Therefore, in view of the high relevance of measuring the properties of the Higgs boson as accurately as possible, in the following we update and extend the analysis of $PP \rightarrow b\bar{b}W(\ell\nu)jj$ including all the features mentioned above.

3. Calculation

Three perturbative orders contribute to $4j + \ell\nu$ at the LHC. In figure 1 some representative Feynman diagrams are presented. The diagrams in the first row are purely electroweak: they correspond to boson-boson scattering and to boson-boson fusion to Higgs with an additional W emission. Contributions similar to diagrams (f)–(g), with a neutral electroweak boson in place of the gluon, are also present at $\mathcal{O}(\alpha_{EM}^6)$. In the second row, diagrams (e)–(h), a number of processes at $\mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$ are illustrated. Diagram (e) refers to one of the main backgrounds, namely $t\bar{t}$ production, while diagrams (g)–(h) presents some of the possibilities for producing a Higgs particle in association with a W boson at $\mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$. The last row, diagrams (i)–(l), exemplifies the $W + 4j$ QCD background at $\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)$ where no Higgs boson can be present. These processes provide the continuum in the mass of the two central jet distribution above which the Higgs signal has to be extracted.

The $\mathcal{O}(\alpha_{EM}^6)$ and $\mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$ samples have been generated with PHANTOM [11–13], while the $\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)$ sample has been produced with MADEVENT [15]. Both programs generate events in the Les Houches Accord File Format [14]. In all samples full $2 \rightarrow 6$ matrix elements, without any production times decay approximation, have been used.

The $\mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$ contribution is particularly challenging because it is dominated by $t\bar{t}$ production. It has been necessary to generate two event samples. The first one has been produced considering only final states with at least two b 's and imposing antitop selection requirements, in order to obtain a sample in which the $H \rightarrow b\bar{b}$ peak could be seen. For this purpose, we have required that no jet triplet satisfies

$$|M_{jjj} - M_t| < 15 \text{ GeV} \tag{3.1}$$

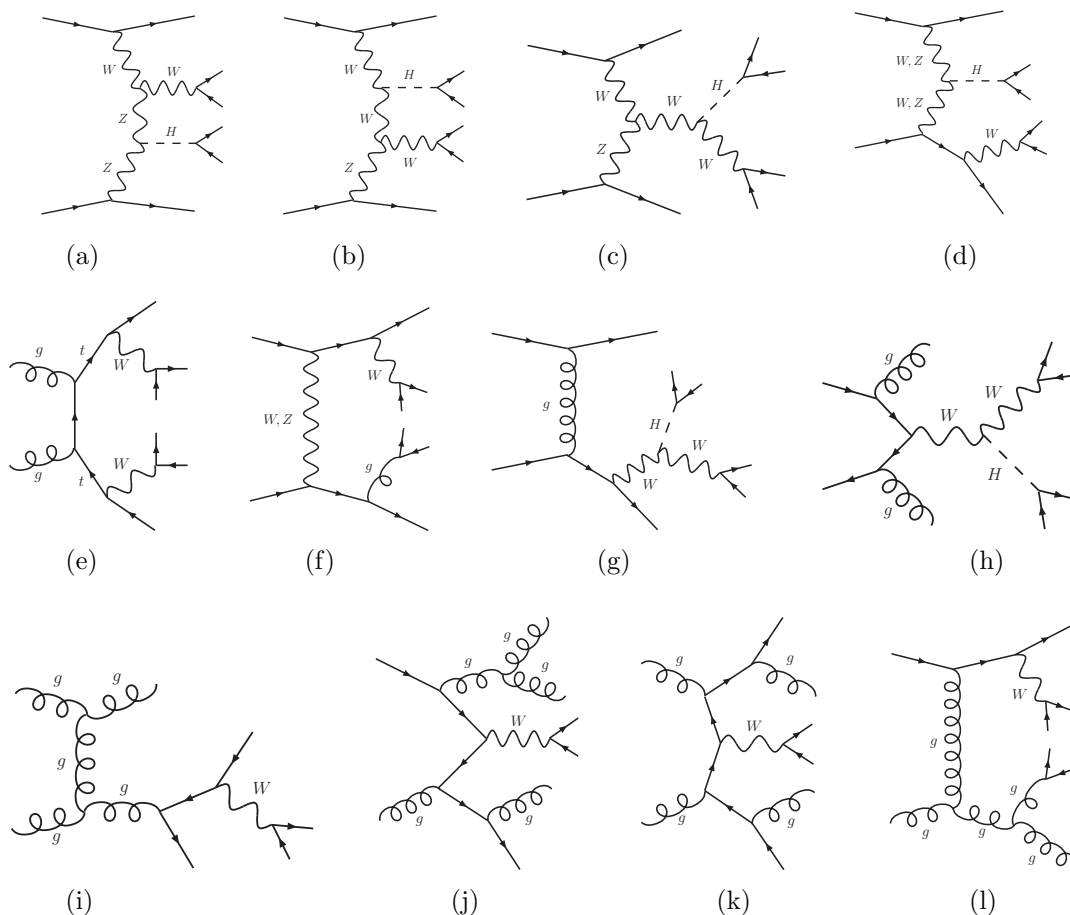


Figure 1: Representative Feynman diagrams for the various perturbative orders contributing to $4j + l\nu$ production at the LHC. The diagrams in the first row are purely electroweak, at $\mathcal{O}(\alpha_{EM}^6)$. In the second row a number of processes at $\mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$ are illustrated. Diagram (e) refers to one of the main backgrounds, namely $t\bar{t}$ production, while diagrams (g)–(h) contribute to the $HWjj$ signal at $\mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$. The last row exemplifies the $W + 4j$ QCD background at $\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)$.

and no jet satisfies

$$|M_{j\nu} - M_t| < 15 \text{ GeV}. \tag{3.2}$$

We have taken $M_t = 175 \text{ GeV}$. The second sample is the complementary one in which less than two b 's are present in the final state or at least one of the conditions in eqs. (3.1)–(3.2) is met. It includes all contributions from $t\bar{t}$ and single top production as well as all reactions which cannot lead to a final state compatible with the production of a Higgs particle decaying to $b\bar{b}$. These samples will be referred in the following as $2b - \text{notop}$ and rest respectively. The second one is dominated by top production even though it includes a much larger set of reactions.

The $\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)$ sample, which correspond to $W + 4j$, includes all possible reactions with b 's in the final state as well as all reactions without any final b , which can only contribute through fake hits.

We work at parton level with no showering and hadronization. The two jets with the largest and smallest rapidity are identified as forward and backward tag jet respectively. The two intermediate jets are considered as candidate Higgs decay products.

The neutrino momentum is reconstructed according to the usual prescription, requiring the invariant mass of the $\ell\nu$ pair to be equal to the W boson nominal mass,

$$(p^\ell + p^\nu)^2 = M_W^2, \tag{3.3}$$

in order to determine the longitudinal component of the neutrino momentum. This equation has two solutions,

$$p_z^\nu = \frac{\alpha p_z^\ell \pm \sqrt{\alpha^2 p_z^{\ell 2} - (E^{\ell 2} - p_z^{\ell 2})(E^{\ell 2} p_T^{\nu 2} - \alpha^2)}}{E^{\ell 2} - p_z^{\ell 2}}, \tag{3.4}$$

where

$$\alpha = \frac{M_W^2}{2} + p_x^\ell p_x^\nu + p_y^\ell p_y^\nu. \tag{3.5}$$

If the discriminant of eq. (3.4) is negative, which happens only if the actual momenta satisfy $(p^\ell + p^\nu)^2 > M_W^2$, it is reset to zero. The corresponding value of p_z^ν is adopted. This value of p_z^ν results in the smallest possible value for the mass of the $\ell\nu$ pair which is compatible with the known components of p^ℓ and p^ν . The corresponding mass is always larger than M_W . If the determinant is positive and the two solutions for p_z^ν have opposite sign we choose the solution whose sign coincides with that of p_z^ℓ . If they have the same sign we choose the solution with the smallest ΔR with the charged lepton. The reconstructed value is used for computing all physical observables.

Our basic selection cuts, which have been applied already in generation are:

$$p_{T_j} \geq 30 \text{ GeV}, \quad |\eta_j| \leq 5.0, \quad p_{T_\ell} \geq 20 \text{ GeV}, \quad |\eta_\ell| \leq 3.0, \\ M_{jj} \geq 60 \text{ GeV} \tag{3.6}$$

where $j = d, u, s, c, b, g$. b -tagging is active for $|\eta| \leq 2.4$ [10] with efficiencies $\epsilon_b = 0.5$ for a b -quark, $\epsilon_c = 0.1$ for a c -quark, $\epsilon_{q/g} = 0.01$ for a light quark or a gluon. It should however be noted that these efficiencies are up to a point tunable, modifying the identification thresholds, and adapted to the analysis at hand. This necessarily involves a tradeoff between efficiency and purity and is expected to improve in parallel with the understanding of the detector response.

All samples have been generated using CTEQ5L [16] parton distribution functions. For the $\mathcal{O}(\alpha_{EM}^6)$ and $\mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$ samples, generated with PHANTOM, the QCD scale has been taken as:

$$Q^2 = M_W^2 + \frac{1}{6} \sum_{i=1}^6 p_{Ti}^2. \tag{3.7}$$

while for the $\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)$ sample the scale has been set to $Q^2 = M_Z^2$. This difference in the scales leads to a definite relative enhancement of the $4j + W$ background. Tests in comparable reactions have shown an increase of about a factor of 1.5 for the processes computed at $Q^2 = M_Z^2$ with respect to the same processes computed with the larger scale eq. (3.7).

In our estimates below we have only taken into account the muon and electron decays of the W boson. The possibility of detecting high p_T taus has been extensively studied in connection with the discovery of a light Higgs in Vector Boson Fusion in the $\tau^+\tau^-$ channel [17] with extremely encouraging results. Efficiencies of order 50% have been obtained for the hadronic decays of the τ 's. The expected number of events in the $H \rightarrow \tau\tau \rightarrow e\mu + X$ is within a factor of two of the yield from $H \rightarrow WW^* \rightarrow e\mu + X$ for $M_H = 120$ GeV where the $\tau\tau$ and WW^* branching ratios of the Higgs boson are very close, suggesting that also in the leptonic decay channels of the taus the efficiency is quite high. Therefore we expect the $W \rightarrow \tau\nu$ channel to increase the detectability of the $b\bar{b}Wjj$ final state.

A minijet veto has been broadly discussed as a tool to separate electroweak dominated processes from QCD dominated backgrounds. For the class of processes we study in this paper, this issue has been raised in refs. [7, 9]. Both groups foresee large gains in statistical significance with modest losses in signal rate.

4. Double b-tagging analysis

The two central jets are required to be b tagged within the active region $|\eta| \leq 2.4$.

As a check, using cuts similar (but not exactly equal because of the lower p_T threshold used in [7] compared to eq. (3) where b 's are treated on the same footing as all other jets) to eq. (2.1) + eq. (2.2) and perfect b -jet efficiency ($\epsilon_b = 1.0$, $\epsilon_c = \epsilon_{q/g} = 0.0$) we obtain results which are in reasonable agreement with those in the second column of table II of [7]. In the following we will use a different selection procedure.

In addition to the basic selection cuts eq. (3) the following cuts are imposed:

$$M_{j_c j_c j_1(2)} \geq 185 \text{ GeV} \tag{4.1}$$

$$\Delta\eta_{\text{tags}} = |\eta_{j_1} - \eta_{j_2}| \geq 1.8 \tag{4.2}$$

$$M_{j_1 j_2} \geq 400 \text{ GeV} \tag{4.3}$$

$$\Delta\eta_{VV} \geq 0.7 \tag{4.4}$$

where $j_c j_c$ refers to the two central jets and $\Delta\eta_{VV}$ is the pseudorapidity separation between the reconstructed vector bosons.

The initial sample of $\mathcal{O}(\alpha_{EM}^6)$ events contains a non negligible contribution from $t\bar{t}$ purely EW production which is eliminated by the requirement $M_{j_c j_c j_1(2)} \geq 185$ GeV.

More stringent cuts on $|\eta_{j_1} - \eta_{j_2}|$ or on $M_{j_1 j_2}$, as employed for instance in WW scattering studies, do not improve the statistical significance. Figure 2 shows that the $Wb\bar{b}jj$ $\mathcal{O}(\alpha_{EM}^4 \alpha_S^2)_{2b\text{-notop}}$ contribution to the signal turns out to be small, while adding a few events to the background count.

The $\mathcal{O}(\alpha_{EM}^6)$ cross section is dominated by the Higgs and Z peaks, with a small background contribution due to misidentification of the Higgs decay products, jet mistagging and the irreducible background from diagrams which do not include Higgs production as a subdiagram. It is therefore appropriate to consider the integral of the mass distribution in the ± 10 GeV mass window around the Higgs mass as the signal, as we do in table 4 and

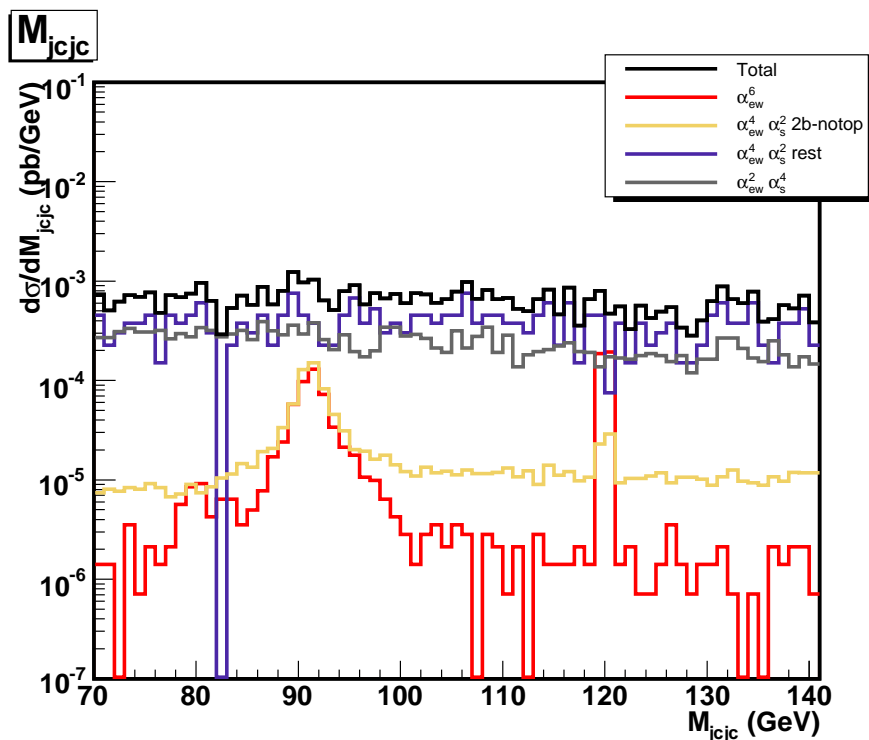


Figure 2: M_{jj} distribution for double b-tagging. Cuts as in eq. (3) and eqs. (4.1)–(4.4).

$W + 4j$	(3)	+ (4.1)	+ (4.2)	+ (4.3)	+ (4.4)
$\mathcal{O}(\alpha_{EM}^6)$ signal	90	64	59	50	41
$\mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$ $2b\text{-notop}$	54	53	48	37	25
$\mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$ rest	9168	3332	1606	1108	641
$\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)$	770	705	625	425	365
S/\sqrt{B}	0.90	1.00	1.24	1.26	1.28

Table 1: Number of events for an integrated luminosity $L = 100 \text{ fb}^{-1}$ for each leptonic decay channel of the W for the $WHjj$ signal with $M_H = 120 \text{ GeV}$, and the principal backgrounds. The two central jets are required to be b -tagged. The selection cuts are given in eq. (3) and eqs. (4.1)–(4.4). A mass bin $110 < M_{b\bar{b}} < 130 \text{ GeV}$ is assumed. The statistical significancies are obtained considering only the $\mathcal{O}(\alpha_{EM}^6)$ events in the $M_H \pm 10 \text{ GeV}$ mass window as the signal and everything else as background.

in the following. The $\mathcal{O}(\alpha_{EM}^6)$ background discussed above amounts to about 10% in the selected mass window.

The total background is essentially flat in the mass region of interest. It can be measured from the sidebands of the known Higgs mass, drastically decreasing the measurement uncertainty. Even though we have not explicitly required a minimum ΔR among jets, they turn out to be well separated. Only about 5% of the events which pass all selection cuts

have $\Delta R < 0.5$ in each sample.

The contribution of the $t\bar{t}jj$ background is estimated in [7] to be at most of a few hundredths of a femtobarn per GeV. Therefore, being much smaller than the $t\bar{t}$ one, has been neglected.

Considering only the $\mathcal{O}(\alpha_{EM}^6)$ events in the $M_H \pm 10 \text{ GeV}$ mass window as the signal the significance S/\sqrt{B} is about 1.28. A factor of two can be gained by considering the W decay to both e and μ and summing the statistics of the two experiments. Obtaining the standard 5σ significance requires a further factor of about 3.8 in statistics.

Our estimate is considerably more pessimistic than the one presented in [7], with a signal over background ratio of about 1/25 instead of about 1/7, with a similar number of expected signal events in the two analysis. This is due to the inclusion of the $t\bar{t}$ channel which represent about two thirds of the background and also to a larger predicted background from $Wjjjj$ due to the effect of c -quarks and light partons being tagged as b 's.

This unsatisfactory result depends quite strongly on the assumed tagging and fake probabilities. Any improvement in this area could make this channel much more attractive.

Since the background is dominated by QCD processes a minijet veto could be useful.

A more sophisticated selection based on a multivariate data analysis is likely to yield more optimistic results.

The $\mathcal{O}(\alpha_{EM}^6)$ cross section for $Z(\rightarrow b\bar{b})Wjj$ is of the same order of magnitude as the cross section for $H(\rightarrow b\bar{b})Wjj$. Therefore it might be possible to observe $ZWjj$ production through the Z decay to $b\bar{b}$. This can be exploited as a calibration/control point and as a window to ZW scattering which is difficult to separate from WW scattering in the semileptonic channel.

We can compare our result with those presented in table 8 of ref. [9] where both irreducible and reducible backgrounds are taken into account. In [9] the b -tagging efficiency is taken as $\epsilon_b = 0.6$, while a reduction of the signal events by 70% is assumed as a consequence of finite $b\bar{b}$ mass resolution. The combined effect of a larger ϵ_b and of including the $b\bar{b}$ mass resolution nicely corresponds to taking $\epsilon_b = 0.5$ and the two set of results are directly comparable. The expected significance in the $b\bar{b}\gamma jj$ channel is 2.2(1.8) for $p_T^\gamma > 20(30) \text{ GeV}$ which is to be compared with a significance of 1.81 in the $b\bar{b}\ell\nu jj$ channel, when two lepton species $\ell = e, \mu$ are considered. The number of expected signal events is similar in all cases.

5. Single b-tagging analysis

At least one of the two central jets is required to be b -tagged within the active region $|\eta| \leq 2.4$. The second central jet can fall anywhere in the region $|\eta| \leq 5.0$.

In addition to the basic selection cuts eq. (3) the following cuts are imposed:

$$M_{j_c j_{c(2)}} \geq 185 \text{ GeV} \tag{5.1}$$

$$M_{j_1 j_2} \geq 600 \text{ GeV} \tag{5.2}$$

$$\Delta\eta_{\text{tags}} = |\eta_{j_1} - \eta_{j_2}| \geq 4.0 \tag{5.3}$$

$$M_{\text{vis}} \geq 1200 \text{ GeV} \tag{5.4}$$

$W + 4j$	(3)	+ (5.1)	+ (5.2)	+ (5.3)	+ (5.4)
$\mathcal{O}(\alpha_{EM}^6)$ signal	1037	285	146	122	99
$\mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$ $2b$ -notop	335	322	126	96	69
$\mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$ rest	177490	24036	4328	3611	2352
$\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)$	19584	17408	7354	4636	3487
S/\sqrt{B}	2.33	1.39	1.34	1.34	1.29

Table 2: Number of events for an integrated luminosity $L = 100 \text{ fb}^{-1}$ for each leptonic decay channel of the W for the $WHjj$ signal with $M_H = 120 \text{ GeV}$, and the principal backgrounds. At least one of the two central jets is required to be b -tagged. The selection cuts are given in eq. (3) and eqs. (5.1)–(5.4). A mass bin $110 < M_{bb} < 130 \text{ GeV}$ is assumed. The statistical significancies are obtained considering only the $\mathcal{O}(\alpha_{EM}^6)$ events in the $M_H \pm 10 \text{ GeV}$ mass window as the signal and everything else as background.

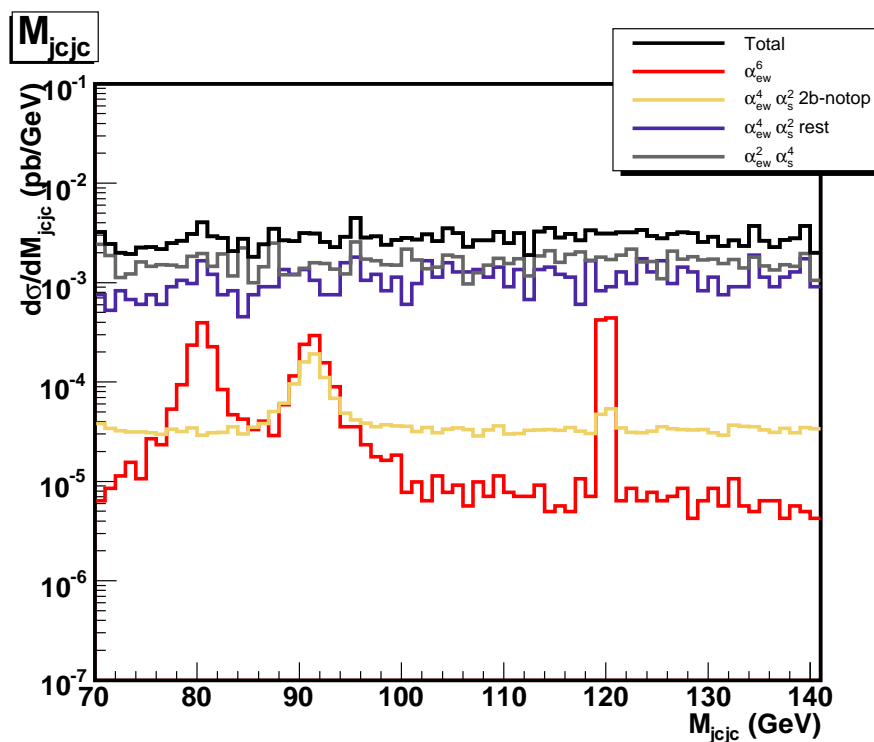


Figure 3: M_{jj} distribution for single b -tagging. Cuts as in eq. (3) and eqs. (5.1)–(5.4).

Here M_{vis} is the total visible mass, which at parton level coincides with the mass of the $4j + \ell$ system.

Both a Z and a W peak appear in the invariant mass distribution in figure 3. Their cross section is of the same order of magnitude as the Higgs one and might therefore be observable.

Also in this case, the background is essentially flat and a direct measurement from the

sidebands is possible. As mentioned before, the $Wjjjj$ background, which is the largest one in the present case, has been generated with a smaller QCD scale compared to the other samples. Therefore our estimate of this background is quite conservative. In the following we will only take into account events in a ± 10 GeV mass window around the Higgs mass. Considering only the $\mathcal{O}(\alpha_{EM}^6)$ events as the signal the significance S/\sqrt{B} is about 1.29 which becomes 1.58 if we assume that the $W + 4j$ background is overestimated to about 1.5 times its actual value. A factor of two can be gained by considering the W decay to both e and μ and summing the statistics of the two experiments. Obtaining the standard 5σ significance requires a further factor of about 3.8 in statistics.

The significancies reported in the last line of table 5, and in particular their decrease as the cuts are tightened, should be taken with great care. In fact, there is in general a significant contamination of what we define as signal from the $\mathcal{O}(\alpha_{EM}^6)$ continuum which decreases as further cuts are imposed. As can be readily seen from figure 3 this contamination is about 15% for the rightmost column. For the first column on the left the continuum contribution is actually about three times the area of the Higgs peak. Therefore while the significancies are coherent with our definition of signal, they do not actually correspond, at least for the columns on the left side, to the ratio of the pure Higgs signal to the square root of the total background.

To our knowledge, a single b -tagging approach to the detection of the Higgs decay to $b\bar{b}$ has only been briefly discussed in [9] but no detailed analysis has been reported. Our study suggests that such an approach is perfectly viable even when all backgrounds are included and that indeed it results in the same statistical significance as the selection procedure that requires two jets to be tagged. We expect this technique to be useful in other production channels as the $b\bar{b}\gamma jj$ one.

Again a minijet veto could be useful.

It is obviously feasible to combine the double tag and single tag measurements. It is possible, requiring for instance exactly one tag in the single tag analysis, to produce event samples which are mutually exclusive. Nonetheless they would be correlated because of common systematic uncertainties, as a consequence, for example, of using the same procedure for tagging b 's. Therefore it is non trivial to give an estimate of the statistical significance of the combined measurements in the double tag and single tag channels.

6. No b -tagging analysis

As in the previous analysis the background due to the top appears to be manageable. However in this case the $\mathcal{O}(\alpha_{EM}^2\alpha_S^4)$ contribution, $W + 4j$ is overwhelming. We have been unable to find physical observables which provide sufficient discrimination. This channel therefore looks hopeless.

7. $WHjj$ production at the SLHC

Since the number of expected events for the projected LHC total luminosity of about 300 fb^{-1} is rather small, the reaction we have discussed in this paper could benefit from

$W + b\bar{b} + 2j$	2 tags	1 tag
signal	41	99
background	1031	5908
S/\sqrt{B}	1.28	1.29
S/\sqrt{B}	3.13	3.15

Table 3: Number of events and statistical significancies for the $WHjj$ signal with $M_H = 120$ GeV and the total background in the two tag and single tag approach. The first three lines refer to an integrated luminosity $L = 100 \text{ fb}^{-1}$ for each leptonic decay channel of the W . The fourth line gives the corresponding statistical significancies for an integrated luminosity $L = 300 \text{ fb}^{-1}$ and summing over both leptonic channels. In addition to the basic selection cuts eq. (3) the cuts in eqs. (4.1)–(4.4) and eqs. (5.1)–(5.4) respectively are applied to the two tag and single tag case. A mass bin $110 < M_{b\bar{b}} < 130$ GeV is assumed. The statistical significancies are obtained considering only the $\mathcal{O}(\alpha_{EM}^6)$ events in the $M_H \pm 10$ GeV mass window as the signal and everything else as background.

the larger luminosity which would be provided by the Super LHC which is expected to be ten times higher. According to the preliminary studies reported in [18], it can be assumed that at the SLHC b -tagging and reconstruction of isolated high p_T particles will be possible with efficiencies comparable to those presently foreseen at CMS and ATLAS. The most serious challenge for all vector boson fusion like channels, which rely on tag jets in order to discriminate between signal and QCD dominated background, is represented by pile-up: multiple scattering events during the same bunch crossing which could produce spurious jets unrelated to the main interaction. These jets could mimic forward and backward tag jets as well as spoil the possibility of a central jet veto to increase the signal to background ratio. The probability of extra jets from pile-up depends strongly on the energy or p_T threshold, therefore it is generally expected that a good efficiency can be recovered using more stringent requirement on jet recognition. Quite interestingly, another route to the same goal is to adopt a smaller cone size. This approach would benefit the whole field of vector boson fusion processes in which high p_T bosons decay to two jets which often merge into one when cones of size $\Delta R = 0.5 \div 0.7$ are used.

While a detailed study of pile-up effects is beyond the scope of this paper, in figure 4 we present the distribution of the smallest p_T of the two tag jets in the double b -tagging case. The distribution is similar for all set of processes, with the maximum at about 50 GeV and then a rather mild decrease at larger values. For instance, setting the threshold at 100 GeV would lead to 120 signal event and about 3500 events for the background, for an integrated luminosity $L = 3000 \text{ fb}^{-1}$ and summing over both leptonic channels, with a significance of about two. Clearly, the p_T threshold and the full selection procedure can be optimized however, taking into account that a large additional background from pile-up is expected, the prospect of studying $WHjj$ production at the SLHC looks quite difficult.

8. Conclusions

In this paper we have studied Higgs production in association with a W boson and two energetic tag jets at the LHC for $M_H = 120$ GeV, with the Higgs decaying to $b\bar{b}$ and the

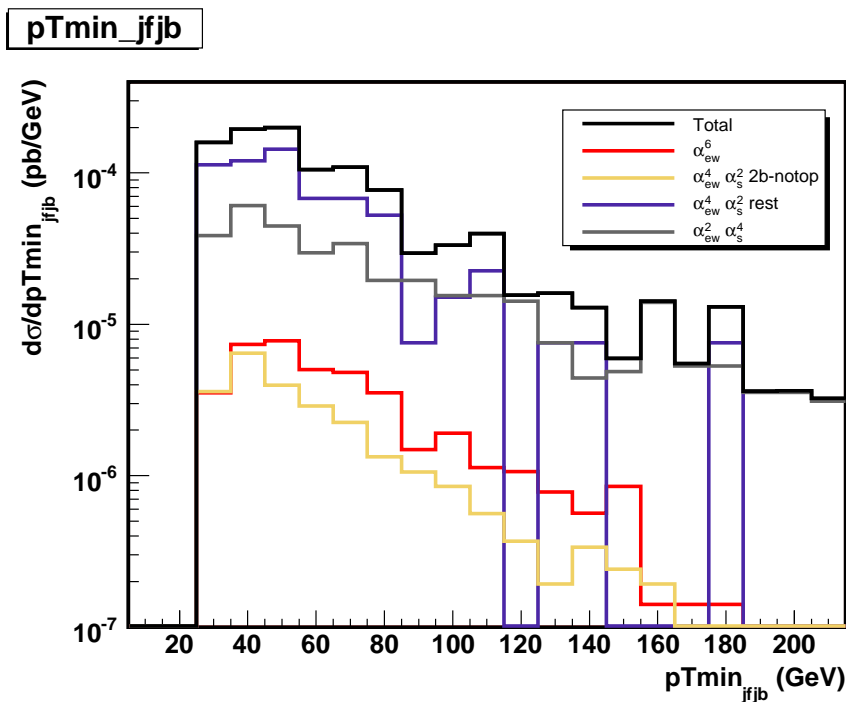


Figure 4: Distribution of the smallest p_T of the two tag jets in the double b -tagging case. Cuts as in eq. (3) and eqs. (4.1)–(4.4).

W to leptons. All parton level backgrounds have been analyzed, including the effect of fake b -tagging which, with realistic efficiencies, turns out to be large. We have discussed two detection strategies, whose results are summarized in table 6: the first one requires two jets to be b -tagged. In the second one, which has not been examined in detail before, at least one tag is required. After all selection cuts about 80 and 200 events are predicted in the two cases, summing the electron and muon channels, for a standard luminosity of 100 fb^{-1} with a S/B ratio of $1/25$ and $1/60$ respectively. The corresponding statistical significance, S/\sqrt{B} , are of the order of 1.3 for each leptonic decay channel of the W boson with a luminosity of 100 fb^{-1} , which becomes of order three for $L = 300 \text{ fb}^{-1}$ and summing over both leptonic channels, comparable to the significancies found in other channels. For the double b -tagging case looser cuts than those used in previous studies appear to be viable. The single b -tagging analysis provides the same statistical significance than the double b -tagging one with almost three times the number of signal events. It appears unlikely that $WHjj$ production could be studied at the SLHC exploiting the higher luminosity.

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