Role of the Z polarization in the $H \rightarrow b\bar{b}$ measurement

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It is widely known that the $ZH$ production channel provides a promising probe to the $H \rightarrow b\bar{b}$ decay at the LHC, when the Higgs and the Z bosons are highly boosted along the transverse direction. Performing a realistic analysis, we show how information on the Z boson polarization can relevantly improve the signal from background discrimination and help us to finally observe the largest Higgs boson branching ratio.

I. Introduction

The decay of the Standard Model Higgs boson to a bottom quark pair ($b\bar{b}$) has the largest branching ratio among all Higgs decay modes, approximately 58%. Measuring this decay is therefore crucial, not only for determining the coupling to bottom quarks, but also for constraining the total Higgs boson decay width under reasonably general assumptions [1, 2].

The largest sensitivity to $H \rightarrow b\bar{b}$ can be gained from the boosted $VH$ production, where $V$ denotes a $W$ or $Z$ boson that is boosted along the transverse direction; their leptonic decays result in clean signatures which can be efficiently triggered on, while vetoing most of the multi-jet backgrounds [3, 4]. Thus far, ATLAS and CMS have reported only evidence for this channel with 3.5$\sigma$ and 3.3$\sigma$ significance [5, 6], respectively. Therefore, possible improvements in the signal extraction are desirable.

When the $Z(\ell^+\ell^-)H(b\bar{b})$ search is performed at the Large Hadron Collider (LHC), the dominant background after signal extraction procedures is $Zbb$ [3, 5]. Although many theoretical efforts to identify the $H \rightarrow b\bar{b}$ decay have thrived since the pioneering work of Ref. [3], the Z polarization has not been exploited to further discriminate the signal from the $Zbb$ background. In general, the Z polarization can intrinsically differ from one process to another and manifests itself in the $Z \rightarrow t^+t^-$ decay angular distributions.

In this letter, we show that the Z boson polarization has relevant information to distinguish the signal from the dominant background, that is currently neglected [3, 6]. We present a procedure to maximally exploit this information and estimate the possible sensitivity gains to the current analyses.

II. Approach

The spin-averaged differential cross section for both $Z(\ell^+\ell^-)H$ and $Z(\ell^+\ell^-)b\bar{b}$ processes can be expanded in general as

$$
\frac{d\sigma}{dq_T^2d\cos\Theta d\cos\theta d\phi} = F_1(1 + \cos^2\theta) + F_2(1 - 3\cos^2\theta) + F_3\sin 2\theta \cos \phi
$$

$$
+ F_4\sin^2\theta \cos 2\phi + F_5 \cos \theta + F_6 \sin \theta \cos \phi
$$

$$
+ F_7 \sin \theta \sin \phi + F_8 \sin 2\theta \sin \phi + F_9 \sin^2 \theta \sin 2\phi, \quad (1)
$$

where $q_T$ is the transverse momentum of the Z boson in the laboratory frame $(q_T \equiv |\vec{q}_T|)$, $\Theta$ is the polar angle of the Z boson from the collision axis in the $Z + H$ (or $b\bar{b}$) center-of-mass frame, $\theta$ and $\phi$ are the polar and azimuthal angles of the lepton ($\ell^-$) in the Z rest frame. We choose the coordinate system of the Z rest frame following Collins and Soper (Collins-Soper frame) [8]. This frame is well recognized and the angular coefficients for the Drell-Yan Z production have been measured by ATLAS [9] and CMS [10]. All of $F_i$ are functions of only $q_T$ and $\Theta$; integrations over other phase space variables are already performed. After integrations over the lepton angles, only $F_1$ remains; $F_1$ is directly related to the total cross section. The eight functions $F_i$ ($i = 2$ to 9) are described by polarization density matrices of the Z boson.

Eq. (1) opportunely simplifies for the signal and background processes under consideration. First, we notice that the signal displays two relevant subprocesses: the quark-initiated Drell-Yan like $q\bar{q} \rightarrow ZH$ and the loop-induced gluon-fusion $gg \rightarrow ZH$. They are denoted by $ZH_{DY}$ and $ZH_{GF}$, respectively. Despite $ZH_{GF}$ being $O(\alpha_s^2)$ suppressed, it results in important contributions at the boosted regime [11, 12]. When CP non-conservation is neglected, the three coefficients $F_{7,8,9}$ are always zero in tree-level calculations of any process [7]. $ZH_{DY}$ can be analytically evaluated without difficulty at the leading-order (LO); we find that the scattering amplitudes for the $J_z = 0$ state of the Z boson are zero.

* We employ the notation of Ref. [7].
therefore $F_{2,3,6}$ are all zero \[15\]. Furthermore, $F_5$ also vanishes in symmetric proton-proton collisions. $ZH_{GF}$ receives constraints from CP conservation and Bose symmetry; as a result, $F_{5,6,8,9}$ are zero at the LO. Although the coefficients $F_{3,7}$ are nonzero in $ZH_{GF}$, these are totally antisymmetric around $\cos \Theta = 0$, thus vanish after the integration over $\cos \Theta$. Estimation of the coefficients apart from $F_{7,8,9}$ in the $Zb\bar{b}$ background process is not easy due to the large number of the scattering amplitudes. This process is part of the $\mathcal{O}(\alpha_s^2)$ correction to the Drell-Yan $Z$ production. Although the angular coefficients in this production have been calculated at $\mathcal{O}(\alpha_s^2, \alpha_s)$ accuracy \[16\], an exclusive calculation of those in the $Zb\bar{b}$ events does not exist in the literature to our knowledge. We have numerically found that $F_{3,5,6}$ are consistent with zero after the integration over $\cos \Theta$, when the signal selections are imposed. Consequently, Eq. (1) simplifies to

\[
\frac{d\sigma}{dq_T^2 \cos \theta d\phi} = \hat{F}_1 [1 + \cos^2 \theta + A_2 (1 - 3 \cos^2 \theta) + A_4 \sin^2 \theta \cos 2\phi], \tag{2}
\]

where $A_2 = \hat{F}_2/\hat{F}_1$ and $A_4 = \hat{F}_4/\hat{F}_1$. The hat above the coefficients implies that the integration over $\cos \Theta$ is performed. This equation suggests that the angles $\theta$ and $\phi$ can be defined in the restricted ranges $0 \leq \theta \leq \pi/2$ and $0 \leq \phi \leq \pi/2$ without losing any information. They can be obtained from

\[
| \cos \theta | = \frac{2 |q^0 p_T^0 - q^3 p_T^3|}{Q \sqrt{Q^2 + |q_T^0|^2}}, \tag{3a}
\]

\[
| \cos \phi | = \frac{2 |q_T^0 \hat{p}_T \cdot \hat{q}_T - |\hat{q}_T|^2 p_T \cdot q|}{Q^2 |\hat{q}_T| \sqrt{Q^2 + |\hat{q}_T|^2}}, \tag{3b}
\]

where $q^\mu = (q^0, \hat{q}_T, q^3)$ and $p_T^\mu = (p_T^0, \hat{p}_T, p_T^3)$ are four-momenta of the $Z$ boson and one of the leptons, respectively, in the laboratory frame and $Q$ is the $Z$ invariant mass. We stress that $p_T^0$ can be the momentum of either $e^-$ or $e^+$ (i.e., either gives the same $\theta$ and $\phi$ values). This feature is particularly important for $Z \rightarrow e^- e^+$ in which case the charge misidentification rate is not negligible \[5\].

To evaluate the two coefficients $A_2$ and $A_4$, we simulate the signal and the background at the LO with MadGraph5_aMC@NLO \[17\] and apply the event selections

\[
75 \text{ GeV} < m_{\ell\ell} < 105 \text{ GeV}, \quad 115 \text{ GeV} < m_{b\bar{b}} < 135 \text{ GeV}, \quad p_T^{Tb} > 25 \text{ GeV}, \quad |y_b| < 2.5, \quad 0.3 < \Delta R_{b\bar{b}} < 1.2. \tag{4}
\]

In Tab. \[1\] we display the results in two $q_T$ regions. We find that both $ZH_{DY}$ and $ZH_{GF}$ present very distinct values $A_{2,4}$ from the $Zb\bar{b}$ background process. These differences clearly appear in the $(\cos \theta, \phi)$ distribution.

In Fig. \[1\] we show the ratio of the normalized $(\cos \theta, \phi)$ profile for the $ZH_{DY}$ process to that for the $Zb\bar{b}$ process, imposing $q_T > 200$ GeV. It is observed in particular that signal events are more distributed at $\phi \sim \pi/2$ and $Zb\bar{b}$ more at $\phi \sim 0$. This is the consequence of the large difference in $A_4$ between the $ZH_{DY}$ and $Zb\bar{b}$ processes. The $Z \rightarrow \ell^+ \ell^-$ decay angular distributions can be, therefore, useful in distinguishing the signal from the background.

| $ZH_{DY}$ | $ZH_{GF}$ | $Zb\bar{b}$ |
|-----------|-----------|-----------|
| $A_2(q_T > 200 \text{ GeV})$ | 0.00 | 0.03 | 0.47 |
| $A_2(q_T > 400 \text{ GeV})$ | 0.00 | 0.05 | 0.50 |
| $A_4(q_T > 200 \text{ GeV})$ | −0.83 | −0.97 | 0.45 |
| $A_4(q_T > 400 \text{ GeV})$ | −0.95 | −0.92 | 0.46 |

Table I. Normalized angular coefficients $A_2$ and $A_4$ in two regions of $q_T$, after the selection in Eq. (4).

Figure 1. Ratio of the normalized $(\cos \theta, \phi)$ distribution for the $ZH_{DY}$ process to that for the $Zb\bar{b}$ background process.

So far, minimum selections in the lepton transverse momentum $p_T^{\ell}$ are not considered. Defining the lepton angles in the Collins-Soper frame has a great advantage: $p_T^{\ell}$ has a simple expression in terms of these angles. In the laboratory frame, in which the $x$-axis is chosen along $\hat{q}_T$, the vectorial transverse momenta of the harder $p_T$ lepton ($\ell_1$) and the softer $p_T$ lepton ($\ell_2$) are given by

\[
\bar{p}_{T\ell 1(2)} = \frac{1}{2} \left( q_T \pm \sqrt{Q^2 + q_T^2 \sin^2 \theta \cos \phi} \pm Q \sin \theta \sin \phi \right). \tag{5a}
\]
Therefore, their absolute values are given by

\[ p_{T1(2)} = \left| \mathbf{p}_{T1(2)} \right| = \frac{1}{2} \sqrt{q_T^2 + Q^2 \sin^2 \theta + q_T^4 \sin^2 \theta \cos^2 \phi \pm 2q_T \sqrt{Q^2 + q_T^2 \sin \theta \cos \phi}, \]  

which are now independent of a choice of the x-axis in the laboratory frame. Representative differences in \( p_{T1} \) between the signal and the background can be revealed as follows. In the phase space where the signal is more concentrated \( \phi \sim \pi/2 \), we find

\[ p_{T1} = p_{T2} = \frac{1}{2} \sqrt{q_T^2 + Q^2 \sin^2 \theta}. \]  

While in the region where the background displays more events \( \phi \sim 0 \), we have

\[ p_{T1(2)} = \frac{1}{2} (q_T \pm \sqrt{Q^2 + q_T^2 \sin \theta}). \]

Eqs. 6 and 7 tell us that the higher (lower) \( p_T \) lepton in the background is predicted to be harder (softer) than that in the signal. To illustrate this feature, we show in Fig. 2 the normalized distributions of \( p_{T1(2)} \) for the \( ZH_{DY} \) (solid curve), \( ZH_{GF} \) (×) and \( Z\bar{b}b \) (dashed curve) processes at the LO. In addition to the cuts in Eq. 4, 200 GeV < \( q_T < 300 \) GeV and a lepton rapidity cut \( |y_l| < 2.5 \) are imposed. The distributions roughly follow Eqs. 6 and 7 which were derived under the extreme conditions (i.e. \( \phi = \pi/2 \) and \( \phi = 0 \)). This observation confirms that the differences in \( p_{T1(2)} \) distributions are consequences of the difference in the Z polarization. It is, therefore, expected that a lepton \( p_T \) selection can partially capture the difference in the Z polarization (\( A_\phi \) in particular) and improve the sensitivity to the signal.

We note in passing that the results in Eqs. 6 and 7 are tailored polarization analysis.

III. Results

We now estimate the potential sensitive gains from the polarization information to a realistic \( pp \rightarrow Z(\ell \ell)H(b\bar{b}) \) LHC study. Our signal is characterized by two charged leptons, \( \ell = e \) or \( \mu \), which reconstruct a boosted Z boson recoiling against two b-jets. The major backgrounds are \( Z\bar{b}b \), \( t\bar{t} \)+jets, and \( ZZ \).

We simulate our samples with Sherpa+OpenLoops [19–21]. The \( ZH_{DY} \) and \( ZH_{GF} \) signal and \( Z\bar{b}b \) and \( ZZ \) background samples are merged at LO up to one extra jet emission via the CKKW algorithm [22]. Higher order effects to \( ZH_{DY}, Z\bar{b}b \) and \( ZZ \) samples are accounted for by a flat NLO K-factor [11]. Finally, the \( t\bar{t} \) is generated at NLO with the MC@NLO algorithm [24]. Hadronization and underlying event effects are taken into account in our simulation.

We follow the BDRS [8] analysis as a well understood benchmark. We require two leptons, which have the same flavor and opposite-sign charges, with \( |\eta| < 2.5 \) in the invariant mass range 75 GeV < \( m_{\ell\ell} < 105 \) GeV. The Z boson is required to have a large boost \( q_T > 200 \) GeV. The hadronic activity is reclustered with the Cambridge-Aachen jet algorithm [25] with \( R = 1.2 \), requiring at least one boosted \( (p_{T,j} > 200 \) GeV) and central \( (|\eta| < 2.5 \) fat-jet. This must be Higgs-tagged via the BDRS algorithm, demanding three sub-jets with the hardest two being b-tagged. Our study assumes a flat 70% \( b \)-tagging efficiency and 1% miss-tag rate. To further enhance the signal to background ratio, we demand the filtered Higgs mass to be in the range \( |m_{WHD} - m_H| < 10 \) GeV. The resulting event rate is presented in Tab. 1 for which \( p_{T\ell} > 30 \) GeV is imposed.

| BDRS reconstruction \( m_{WHD} - m_H \) < 10 GeV | \( ZH_{DY} \) | \( ZH_{GF} \) | \( Z\bar{b}b \) | \( t\bar{t} \) | ZZ |
|---|---|---|---|---|---|
| 0.16 | 0.03 | 0.35 | 0.02 | 0.02 |

Table II. Signal \( ZH_{DY} \) and \( ZH_{GF} \) and background \( Z\bar{b}b \), \( t\bar{t} \), and \( ZZ \) event rate after the BDRS analysis. Hadronization and underlying event effects are taken into account. The rates are given in unit of fb and take account of 70% \( b \)-tagging efficiency and 1% mis-tag rate.

To quantify the importance of the Z polarization, we perform a two dimensional binned log-likelihood analysis based on the \( (\cos \theta, \phi) \) distribution, invoking the CLs.
On the other hand, the solid curve shows that the required luminosity for a $5\sigma$ observation monotonically increases with the $\cos(\theta, \phi)$ threshold. The solid curve takes the $\cos(\theta, \phi)$ distribution, while the dashed curve accounts only for the rate. This is precisely what we have expected as a consequence of the difference in the polarization; see the discussion below Eq. (4). It does not improve anymore above 35 GeV, because the statistics of the signal is also much depleted. On the other hand, the solid curve shows that the required luminosity monotonically increases with the $p_{T\ell\ell}$ threshold. This is because the polarization information (more practically the $\cos(\theta, \phi)$ distribution) is disturbed by the $p_{T\ell\ell}$ lower cut. This selection can capture the difference in polarization only partially, therefore it is never better than the explicit use of the polarization information. It is, therefore, suggested to define $p_{T\ell\ell}$ threshold as small as possible and to exploit the difference in the $\cos(\theta, \phi)$ distribution between the signal and the background.

We stress that, because our proposal relies only on lepton reconstruction, it can be readily included in the current ATLAS and CMS studies. The current ATLAS (CMS) study [5, 6] uses the $p_{T\ell\ell}$ threshold 7 GeV (20 GeV), in which case the benefit of exploiting the $Z$ polarization is estimated to be $\sim 15\%$ ($\sim 10\%$) in the required luminosity for $5\sigma$ observation.

**IV. Summary**

We have studied the potential of the $Z$ polarization to improve the sensitivity to the signal $pp \to Z(\ell\ell)H(bb)$. At first, we have shown that the signal and the $Zb\bar{b}$ dominant background exhibit different states of $Z$ polarization, which appear as the large difference in the lepton angles ($\theta, \phi$) distribution. This difference can be partially captured by a suitable value for the $p_{T\ell\ell}$ lower threshold, and fully taken into account by explicitly analyzing the $\cos(\theta, \phi)$ distribution. We have estimated the impact of these two approaches for the $5\sigma Z(\ell\ell)H(bb)$ observation, and found relevant improvements. Since this proposal relies only on lepton reconstruction, displaying small experimental uncertainties, it can be promptly included in the current ATLAS and CMS studies.

With our encouraging results, our approach could be applicable to other important channels, e.g., $i)$ $Z(\ell\ell)H(\text{invisible})$ and $ii)$ $W(\nu)H(bb)$. We conclude with several comments on these two channels. $i)$ Needless to say, the $Z$ polarization is independent of how the Higgs boson decays; the $Z$ polarization in the $ZH(\text{invisible})$ is the same as that in the $ZH(bb)$. The dominant background in this channel is $Z(\ell\ell)Z(\nu\nu)$. We have confirmed that the $ZZ$ process shows almost the same $A_{2\Delta, 4}$ values as the $Zb\bar{b}$ process. $ii)$ Despite of the neutrino in the final state, by assuming that the charged lepton and the neutrino construct a $W$ boson nominal mass, $|\cos\theta|$ and $|\cos\phi|$ in Eq. (3) are still uniquely determined [7]. Since the $W^+$ and $W^−$ are always in the same state of polarization [7], we can simply add $W^−H$ events and $W^+H$ events. We have confirmed that the $WH$ and the irreducible background $Wb\bar{b}$ show the similar $A_{2\Delta, 4}$ values as the $ZH_{DY}$ and the $Zb\bar{b}$, respectively. Details will be published elsewhere [13].

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