On the possibility to detect the Higgs decay $H \rightarrow b\bar{b}$ in the associated $Z + b\bar{b}$ production at the LHC

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January 22, 2015

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Abstract

We investigate the possibility to detect the scalar Higgs boson decay $H \rightarrow b\bar{b}$ in the associated $Z$ and $b\bar{b}$ production at the LHC using the $k_T$-factorization QCD approach. Our consideration is based on the off-shell (i.e. depending on the transverse momenta of initial quarks and gluons) production amplitudes of $q^*\bar{q}^* \rightarrow ZH \rightarrow Zq'\bar{q}'$, $q^*\bar{q}^* \rightarrow Zq'\bar{q}'$ and $g^*g^* \rightarrow Zq'\bar{q}'$ partonic subprocesses supplemented with the Catani-Ciafaloni-Fiorani-Marchesini (CCFM) dynamics of parton densities in a proton. We argue that the $H \rightarrow b\bar{b}$ signal could be observed at large transverse momenta near Higgs boson peak despite the overwhelming QCD background, and point out an important role of angular correlations between the produced $Z$ boson and $b$-quarks.

PACS number(s): 12.38.Bx, 14.65.Fy, 14.70.Hp, 14.80.Bn
In 2012, during the search performed by the CMS and ATLAS Collaborations at the LHC, the scalar Higgs boson $H$ with a mass $m_H$ near 125 GeV has been discovered [1,2], giving us the confidence in the physical picture of fundamental interactions which follows from the Standard Model Lagrangian. Some time later, the ATLAS Collaboration has reported first measurements of the Higgs boson differential cross sections in the $\gamma\gamma$ decay mode [3]. The measured cross sections were found a bit higher than the central next-to-next-to-leading order (NNLO) expectations [4–9] and those matched with soft-gluon resummation carried out up to next-to-next-to-leading logarithmic accuracy (NNLL) [10, 11], although no significant deviations from theoretical predictions are observed within the uncertainties [3]. The significant signal was detected also in channels where the Higgs boson decays into the $ZZ$ or $WW$ pairs [12, 13]. The interaction of the Higgs particle with the massive $Z$ and $W$ bosons indicates that, as it was expected, it plays a role in electroweak symmetry breaking. However, the interaction with the fermions and whether the Higgs field serves as the source of mass generation in the fermion sector still remains to be established. Since Higgs boson with mass $m_H \sim 125$ GeV decays mainly into a beauty quark-antiquark pair [14], the observation and study of the $H \to b\bar{b}$ decay (which involves the direct coupling of the Higgs boson to beauty quarks) is therefore essential in determining the nature of the newly discovered boson.

The most sensitive channel for the $H \to b\bar{b}$ events at the LHC is the production of Higgs particle in association with the $Z$ boson [15]. Despite the largest branching fraction ($\sim 58\%$), the $H \to b\bar{b}$ final state is a more difficult for the experimental observation compared to the signatures provided by the diphoton or diboson decay modes due to small signal over background ratio. One of main backgrounds for the associated Higgs and $Z$ boson production is the associated production of $Z$ boson and two $b$-quark jets. The corresponding cross sections, calculated at the NNLO level (see [14]), are several orders of magnitude larger than the Higgs boson signal. However, recently CMS Collaboration reported [16] an excess of events above the expected background with a local significance of 2.1 standard deviations, which is compatible with a Higgs boson mass of 125 GeV. Earlier, the CDF and D0 Collaborations at the Tevatron also reported [15] evidence for an excess of events in the 115 – 140 GeV mass range, consistent with the mass of the Higgs boson observed at the LHC.

The experimental searches [15,16] are stimulated us to investigate the associated Higgs (decaying into a $b\bar{b}$ pair) and $Z$ boson production as well as corresponding main background process, associated production of $Z$ boson and two $b$-quark jet[1], using the $k_T$-factorization approach of QCD [17,18]. A detailed description of this formalism can be found, for example, in reviews [19]. We only mention that the main part of higher-order QCD corrections (namely, NLO + NNLO + N$^3$LO + ... contributions which correspond to the log $1/x$ enhanced terms in perturbative series) is effectively taken into account in the $k_T$-factorization approach already at leading order, and it provides solid theoretical ground for the effects of initial parton radiation and transverse momenta of initial quarks and gluons. Recently, the $k_T$-factorization QCD approach was successfully applied [20,21] to describe the ATLAS data [3] on the inclusive Higgs production in the diphoton decay mode.

Let us start from a short review of calculation steps. Our consideration is based on the

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1 Other background processes, like as $t\bar{t}$ pair, diboson or QCD multijet production are out of our present consideration.

2 In our opinion, the results [21] suffer from the problem of double counting and contain the wrong numerical factor.
off-shell (depending on the transverse momenta of initial partons) partonic subprocesses:

\[
q^*(k_1) + q^*(k_2) \rightarrow Z + H \rightarrow Z(p) + q'(p_1) + \bar{q}'(p_2),
\]

\[
q^*(k_1) + \bar{q}^*(k_2) \rightarrow Z(p) + q'(p_1) + \bar{q}'(p_2),
\]

\[
g^*(k_1) + g^*(k_2) \rightarrow Z(p) + q'(p_1) + \bar{q}'(p_2),
\]

where the four-momenta of all corresponding particles are given in the parentheses (see Fig. 1). The subprocesses (2) and (3) correspond to the main QCD background to the associated Higgs and Z boson production. Note, to calculate the production amplitudes, we apply the reggeized parton approach [22][23], which is based on the effective action formalism [24], currently explored at next-to-leading order [25], and take into account the virtualities of both initial quarks and gluons. In this point our consideration differs from the one based on the collinear QCD factorization, where these virtualities are not taken into account. The use of effective vertices [22][23] ensures the exact gauge invariance of calculated amplitudes despite the off-shell initial partons.

The off-shell amplitude of subprocess (1) reads:

\[
\mathcal{M}_1 = ee_q e^\mu(p) \bar{v}_{s_1}(p_2) \Gamma_{Hq\bar{q}}u_{s_2}(p_1) \frac{1}{(p_1 + p_2)^2 - m_H^2 - im_H \Gamma_H} \times
\]

\[
\times \Gamma_{ZZH}^{\mu\nu} \left[ g^{\mu\lambda} - \frac{(k_1 + k_2)^{\nu}(k_1 + k_2)^\lambda}{m_Z^2} \right] \frac{1}{\hat{s} - m_Z^2 - im_Z \Gamma_Z} \bar{v}_{r_1}(k_2) \Gamma_{q\bar{q}Z}^{\lambda\nu} u_{r_2}(k_1),
\]

where \( e \) and \( e_q \) are the electron and incoming quark (fractional) electric charges, \( e^\mu \) is the polarization 4-vector of produced Z boson, \( \hat{s} = (k_1 + k_2)^2 \), \( \Gamma_H \) is the full decay width of Higgs boson, \( m_Z \) and \( \Gamma_Z \) are the mass and full decay width of Z boson. We will take the propagators of intermediate Z and Higgs bosons in the Breit-Wigner form to avoid any artificial singularities in the numerical calculations. The fermion and gauge boson to Higgs vertices are usual:

\[
\Gamma_{Hq\bar{q}} = -\frac{e}{\sin 2\theta_W} \frac{m_q}{m_Z},
\]

\[
\Gamma_{ZZH}^{\mu\nu} = \frac{e}{\sin 2\theta_W} g^{\mu\nu} m_Z,
\]

where \( m_q \) is the mass of produced quark or antiquark, \( \theta_W \) is the Weinberg mixing angle. We will neglect the masses of initial quarks compared to the masses of final state particles but keep their non-zero transverse momenta: \( k_{1T}^2 = -k_{1T}^2 \neq 0, k_{2T}^2 = -k_{2T}^2 \neq 0 \). The effective vertex \( \Gamma_{q\bar{q}Z}^{\mu\nu} \) which describes the effective coupling of off-shell quark and antiquark to Z boson reads [22][23] (see also [26]):

\[
\Gamma_{q\bar{q}Z}^{\mu\nu} = \left[ \gamma^\mu - \hat{k}_1 \frac{P_1^\mu}{(l_1 \cdot k_2)} - \hat{k}_2 \frac{P_2^\mu}{(l_2 \cdot k_1)} \right] (C_V^q - C_A^g \gamma^5),
\]

where \( l_1 \) and \( l_2 \) are the 4-momenta of colliding protons, \( C_V^q \) and \( C_A^g \) are the corresponding vector and axial coupling constants. The effective vertex \( \Gamma_{q\bar{q}Z}^{\mu\nu} \) satisfy the Ward identity \( \Gamma_{q\bar{q}Z}^{\mu}(k_1 + k_2)_\mu = 0 \). The off-shell amplitude of subprocess (2) reads:

\[
\mathcal{M}_2 = ee_q g^2 t^a \delta^{ab} t^b e^\mu(p) \bar{v}_{s_1}(p_2) F_{1}^{\mu\nu} u_{s_2}(p_1) \frac{g^{\nu\lambda}}{(k_1 + k_2)^2} \bar{v}_{r_1}(k_2) \Gamma_{q\bar{q}g}^{\lambda\nu} u_{r_2}(k_1) +
\]

\[
+ ee_q g^2 t^a \delta^{ab} t^b e^\mu(p) \bar{v}_{s_1}(p_2) F_{2}^{\mu\lambda} u_{s_2}(p_1) \frac{g^{\nu\lambda}}{(p_1 + p_2)^2} \bar{v}_{r_1}(k_2) \gamma^\nu u_{r_2}(k_1),
\]
where $e_q$ is the produced quark (fractional) electric charge, $g$ is the strong charge, $a$ and $b$ are the eight-fold color indexes, and
\[ F_1^{\mu\nu} = \Gamma_{qqZ}^{\mu\nu} \left( \hat{p} + \hat{p}_1 + \frac{m_q}{F_Z} \gamma^\nu + \gamma^\nu \frac{-\hat{p} - \hat{p}_2 + \frac{m_q}{F_Z}}{(-p - p_2)^2 - m_q^2} \right) \gamma^\mu, \]  
(9)
\[ F_2^{\mu\lambda} = \Gamma_{q'qZ}^{(+)\lambda}(k_1 + p_1, p_2, p_2) + \frac{\hat{k}_1 - \hat{p}}{(k_1 - p)^2} \Gamma_{q'qZ}^{(-)\mu}(k_1, p) + \frac{\hat{k}_2 - \hat{p}}{(-k_2 - p)^2} \Gamma_{q'qZ}^{(-)\lambda}(k_1, p) + \Delta^{\mu\lambda}(k_1, -k_2, p, p_1 + p_2). \]  
(10)

The on-shell quark coupling to the $Z$ boson is taken in a standard form:
\[ \Gamma_{qqZ}^{\mu} = \gamma^\mu (C_V^q - C_A^q \gamma^5). \]  
(11)

The effective vertices can be written as \[22\,23]:
\[ \Gamma_{q'qg}^{\mu\nu\sigma} = \gamma^{\mu - \hat{k}_1 (l_1 \cdot k_2) - \hat{k}_2 (l_2 \cdot k_1)} \]  
(12)
\[ \Gamma_{q'qg}^{(+)}(k, q) = \gamma^{\mu - \hat{k}_1 (l_1 \cdot q)} \]  
(13)
\[ \Gamma_{q'qg}^{(-)}(k, q) = \gamma^{\mu - \hat{k}_2 (l_2 \cdot q)}. \]  
(14)

The corresponding couplings of the off-shell quark or antiquark to usual on-shell quark and $Z$ boson are constructed as it was done earlier \[26]:
\[ \Gamma_{q'qZ}^{(+)}(k, q) = \Gamma_{q'qZ}^{(+)}(k, q) (C_V^q - C_A^q \gamma^5). \]  
(15)

The induced term $\Delta^{\mu\nu}(k_1, k_2, q_1, q_2)$ has the form \[27]:
\[ \Delta^{\mu\nu}(k_1, k_2, q_1, q_2) = \hat{k}_1 \frac{l_1^{\mu} l_1^{\nu}}{(q_1 \cdot l_1)(q_2 \cdot l_1)} + \hat{k}_2 \frac{l_2^{\mu} l_2^{\nu}}{(q_1 \cdot l_2)(q_2 \cdot l_2)}. \]  
(16)

The summation on the produced $Z$ boson polarizations is carried out with the usual covariant formula:
\[ \sum \epsilon^\mu(p) \epsilon^\nu(p) = -g^{\mu\nu} + \frac{p^\mu p^\nu}{m_Z^2}. \]  
(17)

Further calculations are straightforward and in other respects follow the standard QCD Feynman rules. The evaluation of traces was performed using the algebraic manipulation system FORM \[28]. We do not list here the obtained lengthy expressions because of lack of space. The off-shell amplitude of gluon-gluon fusion subprocess (3) was derived in our previous paper \[29\] (see also \[30\]).

The cross section of any process in the $k_T$-factorization approach is calculated as a convolution of the off-shell partonic cross section and the unintegrated, or transverse momentum dependent (TMD), parton densities in a proton. The cross sections of subprocesses (1) and (2) read:
\[ \sigma = \sum_q \int \frac{1}{256\pi^3(x_1x_2s)^2} |\mathcal{M}_{1,2}|^2 \times \]
\[ \times f_q(x_1, k_{1T}^2, \mu^2) f_{\bar{q}}(x_2, k_{2T}^2, \mu^2) d k_{1T}^2 d k_{2T}^2 d p_{1T}^2 d p_{2T}^2 d y dy_1 dy_2 \frac{d\phi_1}{2\pi} \frac{d\phi_2}{2\pi} \frac{d\psi_1}{2\pi} \frac{d\psi_2}{2\pi}. \]  
(18)
where \( f_q(x, k_T^2, \mu^2) \) is the TMD quark density in a proton, \( y \) is the rapidity of produced \( Z \) boson, \( s \) is the total energy, \( p_{1T}, p_{2T}, y_1, y_2, \psi_1 \) and \( \psi_2 \) are the transverse momenta, rapidities and azimuthal angles of final state quarks, respectively. The incoming quarks have fractions \( x_1 \) and \( x_2 \) of initial protons longitudinal momenta and azimuthal angles \( \phi_1 \) and \( \phi_2 \). The cross sections of subprocess (3) can be written as:

\[
\sigma = \int \frac{1}{256\pi^3(x_1x_2s)^2} |\mathcal{M}_3|^2 \times \]

\[
\times f_g(x_1, k_{1T}^2, \mu^2) f_g(x_2, k_{2T}^2, \mu^2) dk_{1T}^2 dk_{2T}^2 dp_{1T}^2 dp_{2T}^2 dy_1 dy_2 \frac{d\phi_1}{2\pi} \frac{d\phi_2}{2\pi} \frac{dv_{\psi_1}}{2\pi} \frac{dv_{\psi_2}}{2\pi},
\]

where \( f_g(x_1, k_{1T}^2, \mu^2) \) is the TMD gluon density in a proton, and \( \mathcal{M}_3 \) is the off-shell amplitude of subprocess (3).

Concerning the TMD parton densities in a proton, we concentrate on the approach based on the CCFM evolution equation [31]. The CCFM parton shower, based on the principle of color coherence, describes only the emission of gluons, while real quark emissions are left aside. It implies that the CCFM equation describes only the distinct evolution of TMD gluon and valence quarks, while the non-diagonal transitions between quarks and gluons are absent. Below we use the TMD gluon and valence quark distributions which were obtained [32,33] from the numerical solutions of the CCFM equation. Following to [34], we calculate the TMD sea quark density with the approximation, where the sea quarks occur in the last gluon-to-quark splitting. At the next-to-leading logarithmic accuracy \( \alpha_s/\alpha_s \ln x \), the TMD sea quark distribution can be written as follows [34]:

\[
f_{q}(x, k_{T}^2, \mu^2) = \int \frac{dz}{z} \int dq_{T}^2 \frac{1}{\Delta^2} \frac{\alpha_s}{2\pi} P_{qq}(z, q_{T}^2, \Delta^2) f_{q}(x/z, q_{T}^2, \mu^2),
\]

where \( z \) is the fraction of the gluon light cone momentum carried out by the quark, and \( \Delta = k_T - zq_T \). The sea quark evolution is driven by the off-shell gluon-to-quark splitting function \( P_{qq}(z, q_{T}^2, \Delta^2) \) [35]:

\[
P_{qq}(z, q_{T}^2, \Delta^2) = T_R \left( \frac{\Delta^2}{\Delta^2 + z(1-z)q_{T}^2} \right)^2 \left[ (1-z)^2 + z^2 + 4z(1-z)q_{T}^2/\Delta^2 \right],
\]

where \( T_R = 1/2 \). The splitting function \( P_{qq}(z, q_{T}^2, \Delta^2) \) has been obtained by generalizing to finite transverse momenta, in the high-energy region, the two-particle irreducible kernel expansion [35]. It takes into account the small-\( x \) enhanced transverse momentum dependence up to all orders in the strong coupling constant, and reduces to the conventional splitting function at lowest order for \( |q_T| \to 0 \). The scale \( \mu^2 \) is defined [34] from the angular ordering condition which is natural from the point of view of the CCFM evolution:

\[
\mu^2 = \Delta^2/(1-z)^2 + q_{T}^2/(1-z).
\]

Other essential parameters were taken as follows: renormalization scale \( \mu_R^2 = m_Z^2 + p_T^2 \), factorization scale \( \mu_F^2 = \hat{s} + Q_T^2 \) (with \( Q_T \) being the transverse momentum of initial parton pair), beauty quark mass \( m_b = 4.75 \, \text{GeV} \), \( m_Z = 91.1876 \, \text{GeV} \), \( m_H = 125 \, \text{GeV} \), \( \Gamma_Z = 2.4952 \, \text{GeV} \), \( \Gamma_H = 4.3 \, \text{MeV} \), \( \sin^2\theta_W = 0.23122 \) and we use the LO formula for the strong coupling constant \( \alpha_s(\mu^2) \) with \( n_f = 4 \) active quark flavors at \( \Lambda_{QCD} = 200 \, \text{MeV} \), so that \( \alpha_s(m_Z^2) = 0.1232 \). To take into account the non-logarithmic loop corrections to the production cross sections, we apply the effective \( K \)-factor, as it was done in [37,35]:

\[
K = \exp \left[ C_F \frac{\alpha_s(\mu^2)}{2\pi} \right],
\]
where color factor $C_F = 4/3$. A particular scale choice $\mu^2 = p_T^{4/3} m_Z^{2/3}$ was proposed to eliminate sub-leading logarithmic terms. Note we choose this scale to evaluate the strong coupling constant in (22) only. Everywhere the multidimensional integration have been performed by the means of Monte Carlo technique, using the routine vegas. The corresponding C++ code is available from the authors on request.

We now are in a position to present our numerical predictions. The differential cross sections of associated $Zb\bar{b}$ production in $pp$ collisions as a function of $M$, the invariant mass of final beauty quarks, and $Z$ boson transverse momentum at $\sqrt{s} = 8$ and 14 TeV are shown in Figs. 2 and 3. The solid, dashed and dash-dotted histograms correspond to the contributions from the subprocesses (1), (2) and (3), respectively. There is no any cuts applied. One can see that the associated Higgs (decaying into the $b\bar{b}$ pair) and $Z$ boson production cross section lies below the QCD backgrounds by several orders of magnitude in a whole $p_T$ range, but peaks near Higgs mass. To increase the relative contribution from Higgs signal, we repeated the calculations in the restricted region of $M$, namely $120 < M < 130$ GeV (see Fig. 4). We found that here the associated Higgs and $Z$ boson production gives a sizeble contribution to the $Zb\bar{b}$ cross section at high $Z$ boson transverse momenta. So, at $\sqrt{s} = 8$ TeV it practically coincides with the leading contribution from the gluon-gluon fusion subprocess at $p_T > 200$ GeV. At $\sqrt{s} = 14$ TeV, it lies below the latter. However, these contributions are almost comparable at $p_T > 300$ GeV. With the expected LHC luminosity of about 40 fb$^{-1}$, our estimation gives 400 $-$ 500 events (with beauty quarks originating from the Higgs boson decays) for both energies, 8 and 14 TeV. Therefore, the possibility for the experimental detection of Higgs signal appears in the kinematical region defined above.

A special opportunity to detect the decays of scalar Higgs bosons can be provided by the investigations of different angular correlations between the final state particles. As an example, we calculated the distributions on the angle $\theta$ between the produced $Z$ boson and $b$-quark in the Collins-Soper frame (where $z$ axis is defined with respect to the bisector of colliding protons in the $b\bar{b}$ rest frame), and on the azimuthal angle difference $\Delta \phi$ between the final beauty quarks in the $pp$ center-of-mass frame. The results of our calculations performed near Higgs boson peak (with $120 < M < 130$ GeV) are shown in Figs. 5 and 6, where an additional cut $p_T > 200(300)$ GeV is applied at $\sqrt{s} = 8(14)$ TeV. As it was expected, the isotropic decay of scalar Higgs particle $H \rightarrow b\bar{b}$ greatly differs from the angular distributions predicted by the off-shell amplitudes of subprocesses (2) and (3). Moreover, the beauty quarks, originating from the Higgs boson decay, populate mostly at low $\Delta \phi$ (see Fig. 6), whereas the leading QCD background, as given by the gluon-gluon fusion subprocess (3), has more flat $\Delta \phi$ distribution. So, the different angular correlations between the final state particles in the associated $Zb\bar{b}$ production are very sensitive to the source of $b\bar{b}$ pairs, and therefore future experimental investigations of such observables at the LHC with increased luminosity can give a clear information about Higgs signal.

To conclude, in the present note we applied the $k_T$-factorization approach of QCD to study the possibility to detect the scalar Higgs boson decay $H \rightarrow b\bar{b}$ in the associated $Z$ and $b\bar{b}$ production at the LHC. Our consideration was based on the off-shell production amplitudes of $q^*\bar{q}^* \rightarrow ZH \rightarrow Zq^*\bar{q}'$, $q^*\bar{q}' \rightarrow Zq^*\bar{q}'$ and $g^*g^* \rightarrow Zq^*\bar{q}'$ partonic subprocesses supplemented with the CCFM dynamics of parton densities in a proton. The main part of higher-order QCD corrections (corresponding to the log $1/x$ enhanced terms in perturbative series) is effectively taken into account in our consideration. We demonstrated that the $H \rightarrow b\bar{b}$ signal can be observed at large transverse momenta near Higgs boson peak despite the overwhelming QCD background, and pointed out an important role of angular correlations between the produced $Z$ boson and $b$-quarks. The gauge invariant off-shell
amplitudes of $q^*\bar{q}^* \rightarrow ZH \rightarrow Zq'\bar{q}'$ and $q^*\bar{q}^* \rightarrow Zq'\bar{q}'$ partonic subprocesses, calculated for the first time, can be implemented in a different Monte Carlo event generators, like as, for example, CASCADE [40].

Acknowledgements. The authors are grateful to H. Jung for very useful discussions which give us the idea of present study. We thank also S. Baranov for helpful discussion concerning the role of angular distributions and M. Malyshev for additional check of the off-shell amplitude of $q^*\bar{q}^* \rightarrow ZH \rightarrow Zq'\bar{q}'$ subprocess. This research was supported by the FASI of Russian Federation (grant NS-3042.2014.2). We are also grateful to DESY Directorate for the support in the framework of Moscow—DESY project on Monte-Carlo implementation for HERA—LHC.

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Figure 1: Examples of Feynman diagrams corresponding to $q^*\bar{q}^* \rightarrow ZH \rightarrow Zb\bar{b}$ (a), $g^*g^* \rightarrow Zb\bar{b}$ (b) and $q^*\bar{q}^* \rightarrow Zb\bar{b}$ (c, d) subprocesses. Full set of diagrams can be obtained by permutations of quark, gluon, Higgs and Z boson lines.

Figure 2: The associated $Z + b\bar{b}$ cross sections in $pp$ collisions calculated as a function of invariant mass of $b\bar{b}$ quarks at $\sqrt{s} = 8$ TeV (left panel) and $\sqrt{s} = 14$ TeV (right panel). The solid, dashed and dash-dotted histograms correspond to the contributions from the $q^*\bar{q}^* \rightarrow ZH \rightarrow Zb\bar{b}$, $q^*\bar{q}^* \rightarrow Zb\bar{b}$ and $g^*g^* \rightarrow Zb\bar{b}$ subprocesses, respectively. No cuts is applied.
Figure 3: The associated $Z + b\bar{b}$ cross sections in $pp$ collisions calculated as a function of $Z$ boson transverse momentum at $\sqrt{s} = 8$ TeV (left panel) and $\sqrt{s} = 14$ TeV (right panel). Notation of all histograms is the same as in Fig. 2. No cuts is applied.

Figure 4: The associated $Z + b\bar{b}$ cross sections in $pp$ collisions calculated as a function of $Z$ boson transverse momentum at $\sqrt{s} = 8$ TeV (left panel) and $\sqrt{s} = 14$ TeV (right panel) at $120 < M < 130$ GeV. Notation of all histograms is the same as in Fig. 2.

Figure 5: The associated $Z + b\bar{b}$ cross sections in $pp$ collisions calculated as a function of angle $\theta$ between the produced $Z$ boson and beauty quark in the Collins-Soper frame at $\sqrt{s} = 8$ TeV (left panel) and $\sqrt{s} = 14$ TeV (right panel) at $120 < M < 130$ GeV. An additional cut $p_T > 200(300)$ GeV is applied for $\sqrt{s} = 8(14)$ TeV. Notation of all histograms is the same as in Fig. 2.
Figure 6: The associated $Z + b\bar{b}$ cross sections in $pp$ collisions calculated as a function of azimuthal angle difference $\Delta \phi$ between the produced beauty quarks in the $pp$ center-of-mass frame at $\sqrt{s} = 8$ TeV (left panel) and $\sqrt{s} = 14$ TeV (right panel) at $120 < M < 130$ GeV. An additional cut $p_T > 200(300)$ GeV is applied for $\sqrt{s} = 8(14)$ TeV. Notation of all histograms is the same as in Fig. 2.