Measurement of the cross section and angular correlations for associated production of a Z boson with b hadrons in pp collisions at s√ = 7 TeV

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Abstract: A study of proton-proton collisions in which two b hadrons are produced in association with a Z boson is reported. The collisions were recorded at a centre-of-mass energy of 7 TeVwith the CMS detector at the LHC, for an integrated luminosity of 5.2 fb−1. The b hadrons are identified by means of displaced secondary vertices, without the use of reconstructed jets, permitting the study of b-hadron pair production at small angular separation. Differential cross sections are presented as a function of the angular separation of the b hadrons and the Z boson. In addition, inclusive measurements are presented. For both the inclusive and differential studies, different ranges of Z boson momentum are considered, and each measurement is compared to the predictions from different event generators at leading-order and next-to-leading-order accuracy.

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Contents

1 Introduction 1

2 CMS detector and simulated samples 5

3 Event reconstruction and selection 5

4 Cross section measurement 8

5 Systematic uncertainties 9

6 Theoretical predictions and uncertainties 11

7 Results 13

8 Conclusions 13

The CMS collaboration 20

1 Introduction

The measurement of Z/γ^* (henceforth denoted by "Z") production in association with b quarks at the Large Hadron Collider (LHC) is relevant for various experimental searches. In particular, the process constitutes one of the dominant backgrounds to standard model (SM) Higgs boson production associated with a Z boson, where the Higgs boson decays subsequently to a $b\bar{b}$ pair. The discovery by the ATLAS and Compact Muon Solenoid (CMS) experiments of a neutral boson with a mass of about 125 GeV [1, 2] motivates further studies to establish its nature and determine the coupling of the new boson to b quarks. Furthermore, for models featuring an extended Higgs sector, such as two-Higgs-doublet models [3–6], an interesting discovery channel is $\phi_1 \to Z\phi_2$ with the subsequent decay $\phi_2 \to b\bar{b}$, where $\phi_{1,2}$ are neutral Higgs bosons. Since the mass difference $m_{\phi_1} - m_{\phi_2}$ may be large, the Higgs decay would consist of a pair of collinear b quarks produced in association with a Z boson.

Of particular interest is the measurement of angular correlations of b hadrons, especially at small opening angles, where significant theoretical uncertainties in the description of the collinear production of b quarks remain. Several theoretical predictions, obtained with different techniques and approximations, can be tested. Tree-level calculations allowing for large numbers of extra partons in the matrix elements (as initial- and final-state radiation) are available. These are provided by MadGraph [7, 8], alpgen [9], and sherpa [10], in both the five- and four-flavour approaches, i.e. by considering the five or four lightest

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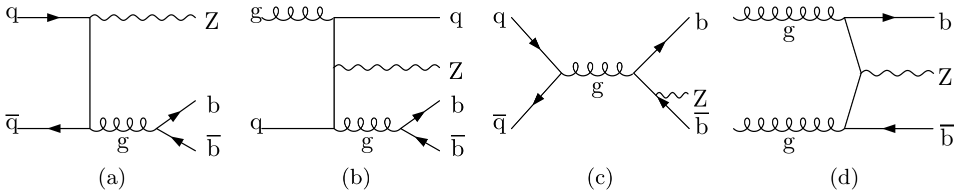

Figure 1. Tree-level Feynman diagrams for (a,b) qi $\to$ Zb$\overline{\text{b}}$X subprocesses (where i = q, g) involving g $\to$ b$\overline{\text{b}}$ splitting; (c) q$\overline{\text{q}}$ $\to$ Zb$\overline{\text{b}}$ with the emission of a Z boson from a b quark; and (d) gg $\to$ Zb$\overline{\text{b}}$.

quark flavours in the proton parton distribution function (PDF) sets. Next-to-leading-order (NLO) calculations have been performed in both the five-flavour (MCFM) [11] and four-flavour [12, 13] approaches. A fully automated NLO computation matched to a parton shower simulation is implemented by the aMC@NLO event generator [14, 15]. A detailed discussion of b-quark production in the different calculation schemes is available in ref. [16].

From the experimental point of view, the study of b-hadron pair production using the standard jet-based b-tagging methods [17] suffers from geometrical limitations due to the jet cone size. Hadronic cascades from b-quark pairs at small angular separation can merge into a single jet, making this region of phase space difficult to access using jet-based b-tagging techniques. To overcome this obstacle, an alternative method is used, consisting of the identification of b hadrons from displaced secondary vertices, which are reconstructed from their charged decay products. This approach is implemented in the inclusive secondary vertex finder (IVF) [18]. The IVF exploits the excellent tracking capabilities of the CMS detector and, being independent of the jet reconstruction, extends the sensitivity to small angular separations and softer b-hadron transverse momenta (p_{T}).

Four variables are used to parametrise the angular correlations in the Zb$\overline{\text{b}}$ final state: ΔR_{BB}, $\Delta\phi_{\mathrm{BB}}$, minΔR_{ZB}, and A_{ZBB}. The angular correlation between the b hadrons is described by two variables, ΔR_{BB} and $\Delta\phi_{\mathrm{BB}}$, the angular separation between the flight directions of the two particles in (η, ϕ) and in the transverse plane, respectively. The variable ΔR_{BB} is defined as $\Delta R_{\mathrm{BB}} = \sqrt{(\Delta\phi_{\mathrm{BB}})^2 + (\Delta\eta_{\mathrm{BB}})^2}$, where $\Delta\phi_{\mathrm{BB}}$ and $\Delta\eta_{\mathrm{BB}}$ are the azimuthal (in radians) and pseudorapidity separations. The pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle relative to the anticlockwise beam direction. The ΔR_{BB} distribution constitutes a direct test of the modelling of the different pp $\to$ Zb$\overline{\text{b}}$X production modes. This quantity allows the identification of the contribution from the qi $\to$ Zb$\overline{\text{b}}$X subprocesses (where i = q, g) for which the scattering amplitude modelling is based on Feynman diagrams with g $\to$ b$\overline{\text{b}}$ splitting. Leading order diagrams for these subprocesses are shown in figures 1 (a) and (b), together with diagrams representative of other pp $\to$ Zb$\overline{\text{b}}$ production modes: emission of a Z boson from a b-quark line (c), and b-quark fusion gg $\to$ Zb$\overline{\text{b}}$ (d).

A second variable, the angular separation between the b hadrons in the transverse plane, $\Delta\phi_{\mathrm{BB}}$, is also considered because it is a better observable for the back-to-back configuration. Since the relative fraction of quark- and gluon-initiated subprocesses is

JHEP12(2013)039

correlated with the Z-boson momentum p_T^Z, the differential ΔR_{BB} and $\Delta\phi_{BB}$ distributions are measured in different intervals of p_T^Z.

Two additional angular variables are considered: the angular separation between the Z boson and the closest b hadron in the (η, ϕ) plane, $\min\Delta R_{ZB}$, and the asymmetry between the b-hadron emission directions and the Z production direction, A_{ZBB}, defined as

$$A_{ZBB} = \frac{\max\Delta R_{ZB} - \min\Delta R_{ZB}}{\max\Delta R_{ZB} + \min\Delta R_{ZB}}, \tag{1.1}$$

where $\max\Delta R_{ZB}$ is the distance between the Z boson and the further b hadron. Configurations in which the two b hadrons are emitted symmetrically with respect to the Z direction yield a value of A_{ZBB} close to zero. Emission of additional gluon radiation in the final state results in a nonzero value of A_{ZBB}. Hence, the A_{ZBB} variable helps to indirectly test the validity of quantum chromodynamics (QCD) at higher orders of the perturbative series. The $\min\Delta R_{ZB}$ variable identifies events with the Z boson in the vicinity of one of the two b hadrons, and is therefore useful for testing NLO corrections involving Z radiation from a quark [19].

The contribution of the $\mathrm{q}i \to \mathrm{Zb\bar{b}X}$ subprocesses to the total production is illustrated in figure 2 as a function of each of the four variables described above. The distributions are shown for both the nonboosted (all p_T^Z) and the boosted ($p_T^Z > 50\,\mathrm{GeV}$) regions of the Z transverse momentum. For all the variables, the contribution of the $\mathrm{q}i \to \mathrm{Zb\bar{b}X}$ subprocesses differs from the contribution of $\mathrm{gg} \to \mathrm{Zb\bar{b}X}$. The $\mathrm{q}i \to \mathrm{Zb\bar{b}X}$ subprocesses are dominant in the following regions: $\Delta R_{BB} < 1$, $\Delta\phi_{BB} < 0.75$, $\min\Delta R_{ZB} > 3.2$, and $A_{ZBB} < 0.05$.

In this analysis, the differential production cross sections for the process $\mathrm{pp} \to \mathrm{Zb\bar{b}X}$ (henceforth the processes are denoted by their final state, here "$\mathrm{Zb\bar{b}}$") as functions of the four kinematic variables listed above are evaluated from CMS data. These cross sections are given at the hadron level and compared to the predictions provided by several of the Monte Carlo (MC) generators mentioned above. The total cross section is also measured. The results are given for different regions of p_T^Z. Because of the limited size of the available data sample, the differential measurements are calculated in the nonboosted and boosted regions. The total cross section is evaluated for p_T^Z larger than 0, 40, 80, and 120 GeV. Z bosons are reconstructed in the $\mathrm{e^+e^-}$ and $\mu^+\mu^-$ decay modes. The analysis exploits the full 2011 data set recorded at $\sqrt{s} = 7\,\mathrm{TeV}$, corresponding to an integrated luminosity of $(5.2 \pm 0.1)\,\mathrm{fb}^{-1}$. Measurements of the Z-boson production cross section in association with one or two b-tagged jets at the LHC have been reported previously by the ATLAS and CMS Collaborations [20, 21].

The paper is organised as follows: the description of the CMS experiment and simulated samples are given in section 2; the event reconstruction and selection are presented in section 3; the measurement technique is explained in section 4; the systematic uncertainties are discussed in section 5; the theoretical uncertainties associated with different models of $\mathrm{Zb\bar{b}}$ production are summarized in section 6; the results and conclusions are presented in sections 7 and 8, respectively.

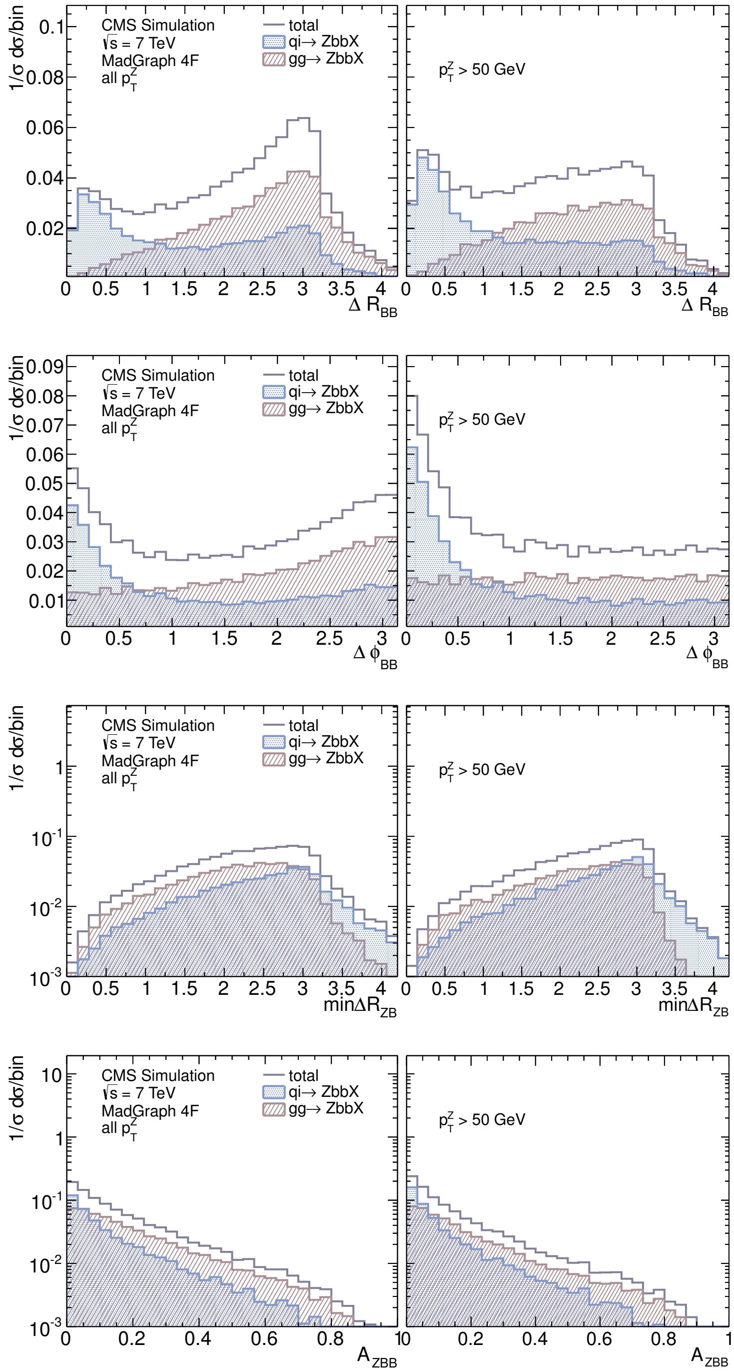

Figure 2. Distribution of ΔR_{BB} (first row), $\Delta\phi_{\mathrm{BB}}$ (second row), $\min\Delta R_{\mathrm{ZB}}$ (third row), and A_{ZBB} (fourth row) as predicted by MadGraph in the four-flavour scheme, in the nonboosted (left) and boosted (right) regions of the Z transverse momentum. The component from $\mathrm{gg} \to \mathrm{Zb\bar{b}X}$ is represented by the hatched histogram, while the contribution from $\mathrm{q}i \to \mathrm{Zb\bar{b}X}$ subprocesses (where $i = \mathrm{q, g}$) is represented by the shaded histogram. The unshaded histogram corresponds to the sum of the two components.

2 CMS detector and simulated samples

A detailed description of the CMS experiment can be found in ref. [22]. The main subdetectors used in this analysis are the silicon tracker, the electromagnetic calorimeter (ECAL), and the muon system. The tracker consists of silicon pixel and strip detector modules and is immersed in a 3.8 T magnetic field, which enables the measurement of charged particle momenta over the pseudorapidity range $|\eta| < 2.5$. The electromagnetic calorimeter consists of nearly 76 000 lead tungstate crystals, which provide coverage for $|\eta| \lesssim 1.48$ in a cylindrical barrel region and $1.48 \lesssim |\eta| \lesssim 3.0$ in two endcap regions, except for a insensitive gap in the region $1.442 < |\eta| < 1.566$ between the ECAL barrel and endcap. Muons are identified in the range $|\eta| < 2.4$ by gas-ionisation detectors embedded in the steel return yoke. The first level of the CMS trigger system consists of custom hardware processors and uses information from the calorimeters and muon system to select the most interesting events in less than 1 μs. The high level trigger processor farm further decreases the event rate to less than 300 Hz before data storage.

Samples of signal and background events are produced using various event generators to estimate the signal purity, efficiency, and detector acceptance, with the CMS detector response modelled in extensive detail with GEANT4 [23].

The $\mathrm{Zb\bar{b}}$ signal sample is produced with the MADGRAPH 1.4.8 generator in the four-flavour approach. No b quarks are present in the initial state, while up to two additional light partons are produced in association with the Z boson and the two b quarks. The PDF set is CTEQ6L1 and the simulation of parton shower, hadronisation, and multiparton interactions is done with PYTHIA 6.4.2.4 [24]. The background samples are Z plus jets, where the additional jets are from light quarks or gluons (u, d, c, s, g), top pair production ($\mathrm{t\bar{t}}$), and Z pair production. The Z + jets sample is extracted from a Drell-Yan inclusive sample produced with MADGRAPH in the five-flavour approach and interfaced with PYTHIA. The $\mathrm{t\bar{t}}$ sample is also produced with the MADGRAPH generator interfaced with PYTHIA, while the diboson ZZ sample is generated with PYTHIA. The tune considered in PYTHIA is Z2*, which is the Z1 tune [25] with the PDF set changed to CTEQ6L1 and minor modifications of the underlying event modelling, namely `PARP(90)` = 0.227 and `PARP(82)` = 1.921.

Additional interactions per bunch crossing (pileup) are included in the simulation with the distribution of pileup interactions matching that observed in data.

3 Event reconstruction and selection

The first step of the analysis is the online event selection with the loosest available dimuon and dielectron triggers in order to enrich the sample with $\mathrm{Z} \to \mu^+\mu^-$ and $\mathrm{e^+e^-}$ decays. The dielectron trigger line requires loose electron identification and isolation and imposes 17 and 8 GeV transverse momentum thresholds on the two electron candidates, respectively. The transverse momentum thresholds of the muon trigger line, which changed with time to cope with increasing instantaneous luminosity, were initially 7 GeV on both muon candidates, then 13 or 17 GeV on one candidate and 8 GeV on the other.

Muon candidates are then required to pass tight selection requirements to ensure high purity [26]. Electron candidates are reconstructed from energy deposits in the ECAL, and must satisfy the standard CMS electron identification criteria [27]. Leptons are required to have $p_{\mathrm{T}} > 20\,\mathrm{GeV}$, and to be within the pseudorapidity range $|\eta| < 2.4$. Prompt leptons are selected by requiring a distance of closest approach between the track and the primary pp interaction (identified as the vertex with the largest quadratic sum of its constituent tracks' p_{T}) smaller than $200\,\mu$m. A requirement is applied on the lepton isolation, computed using the particle-flow technique [28], which exploits the information from all subdetectors to individually identify the particles produced in the collisions. The isolation, defined as the ratio between the scalar sum of the transverse momentum or transverse energy (E_T) of the particles within a $\Delta R < 0.4$ (0.3) cone around the muon (electron) and its transverse momentum, $(\sum_{\text{charged had.}} p_{\mathrm{T}} + \sum_{\text{neutral had.}} E_T + \sum_{\text{photon}} E_T)/p_{\mathrm{T}}$, must be at most 0.15. In order to ensure that the selection is stable regarding the large and varying number of primary interactions, the charged particle-flow candidates are required to be associated with the selected primary vertex (PV). In addition, a correction is applied to subtract the energy contribution of neutral hadrons and photons produced in pileup interactions. This correction is estimated event by event from the median of the energy density distribution and applied within the isolation cone [29].

Only events with two oppositely charged same-flavour lepton candidates with invariant mass between 60 and 150 GeV are selected. The signal region is then defined as the $81 < M_{\ell\ell} < 101\,\mathrm{GeV}$ interval to reduce the contamination from $\mathrm{t\bar{t}}$ events.

Events containing b hadrons are selected by applying the inclusive vertex finder technique. The secondary vertex (SV) reconstruction on which the IVF is based is initiated by the identification of a set of "seed" tracks that are significantly displaced with respect to the primary vertex. Such tracks are selected by requiring their three-dimensional impact parameter to be larger than $50\,\mu$m, and their impact parameter (IP) significance $S_{\mathrm{IP}} = \mathrm{IP}/\sigma_{\mathrm{IP}}$ larger than 1.2, where σ_{IP} is defined from the uncertainties on both the PV position and the point of closest approach between the track and the PV. Additional tracks are clustered together with the seed tracks if they fulfil several requirements. First, the distance of closest approach of a track to the seed must not exceed $500\,\mu$m, and its significance must be smaller than 4.5. Second, the angle between the vector defined by the PV and the point of closest approach on the seed track and the seed track direction at the vertex has to be smaller than 45° so only forward tracks from b-hadron decays are retained. Secondary vertices are built from the seeds and clustered tracks [30].

The SV four-momentum is calculated as $p_{\mathrm{SV}} = \sum p_i$ where the sum is over all tracks associated with that vertex. The pion mass hypothesis is used for every track to obtain its energy E_i. The vertex mass m_{SV} is given by $m^2_{\mathrm{SV}} = E^2_{\mathrm{SV}} - p^2_{\mathrm{SV}}$.

The IVF technique establishes a list of b-hadron (B) candidates from the reconstructed SVs. If two SVs are present, they can potentially be the signature of a $\mathrm{b} \to \mathrm{cX}$ decay chain and are merged into a single B candidate if the following conditions are fulfilled: i) $\Delta R(\mathrm{SV}_1, \mathrm{SV}_2) < 0.4$, ii) the sum of the invariant masses of track candidates associated with the vertices is smaller than 5.5 GeV, and iii) $\cos\delta > 0.99$, where δ is the angle between the vector from the position of the SV that is closer to the PV to the position of the other SV

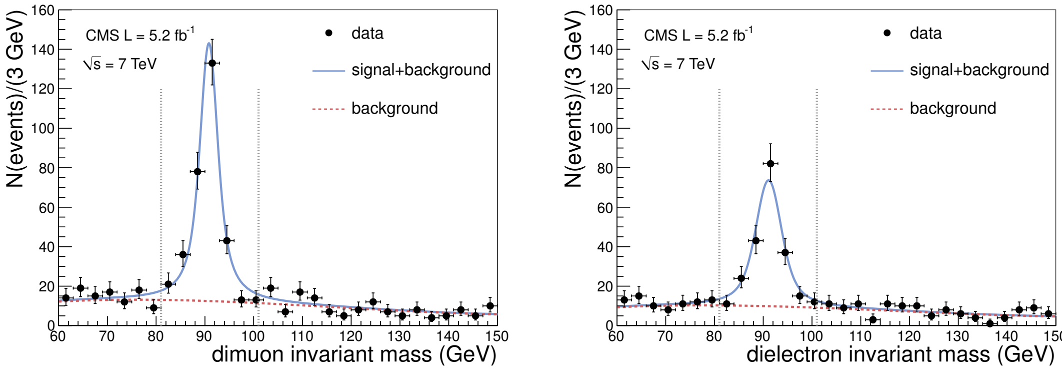

Figure 3. Fit results for the dimuon (left) and dielectron (right) invariant mass distributions for events with two leptons and two B candidates selected as described in section 3. The dashed line shows the fitted background component and the solid line the sum of the fitted signal and background components, which are described in the text. The vertical dashed lines indicate the boundaries of the signal region. The points with errors represent the data.

and the three-momentum of the vertex with larger decay length. The flight distance significance of a B candidate is calculated from the distance between the PV and SV divided by its uncertainty. More details of the SV and B candidate reconstruction can be found in ref. [18].

The flight distance L is defined as the length of the three-dimensional vector connecting the primary and secondary vertices. Its significance S_L is obtained by dividing L by its uncertainty, calculated as quadratic sum of the PV and SV position uncertainties. A b hadron candidate is retained if $S_L > 5$, $|\eta| < 2$, $p_{\mathrm{T}} > 8\,\mathrm{GeV}$, and invariant mass $m > 1.4\,\mathrm{GeV}$. The B candidate mass and flight distance significance cuts, along with the requirement of at least three tracks associated with the secondary vertex, are the most effective requirements for rejecting background events from $\mathrm{Zc\bar{c}}$ production.

Events that have exactly two B candidates are retained. The resulting dimuon and dielectron invariant masses are shown between 60 and 150 GeV in figure 3. In total, 330 (223) events pass all the selection requirements in the muon (electron) channel in the $81 < M_{\ell\ell} < 101\,\mathrm{GeV}$ signal mass region. Thanks to the excellent performance of the CMS tracking system, the IVF angular resolution is approximately 0.02 for ΔR_{BB} and $\Delta\phi_{\mathrm{BB}}$ and 0.03 for $\min\Delta R_{\mathrm{ZB}}$ and A_{ZBB}.

The main source of background contamination in the final sample is top-quark pair production. The $\mathrm{t\bar{t}}$ fraction is assessed from an unbinned maximum-likelihood fit to the measured dilepton invariant mass distribution as described in section 4. The fit yields a $\mathrm{t\bar{t}}$ contamination of approximately 30% in the inclusive event sample, and of about 23% for $p_{\mathrm{T}}^{\mathrm{Z}} > 50\,\mathrm{GeV}$.

The measured and simulated distributions of the most significant event properties are compared at the detector level, as shown in figure 4. The measured distributions of mass and transverse momentum of the leading B candidate, i.e. that with the largest p_{T}, as well as $p_{\mathrm{T}}^{\mathrm{Z}}$, agree with MC predictions within uncertainties.

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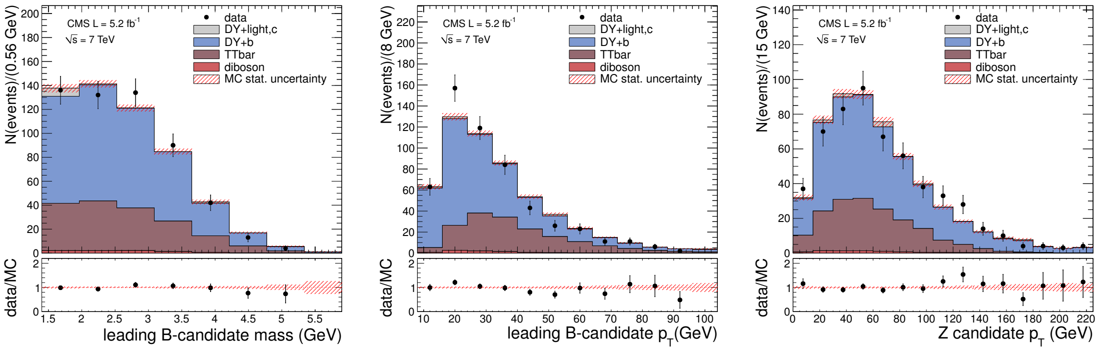

Figure 4. Distribution of the leading B candidate invariant mass (left), transverse momentum (centre), and p_T^Z (right) for the muon and electron channels combined, in the signal region ($81 < M_{\ell\ell} < 101$ GeV). The CMS data are represented by solid points and the MC simulation by stacked histograms. The shaded region represents the statistical uncertainty in the MC prediction. The fraction of signal and top background in the simulation is extracted by mean a fit (figure 3) and the sum is normalised to the number of entries in the data. The bottom plots show the ratio of measured and simulated numbers of entries in each bin with the MC uncertainty represented by the dotted area.

4 Cross section measurement

The differential and total cross sections are obtained by subtracting the background and correcting for detector acceptance, signal efficiency, and purity. The correction factors refer to the kinematic phase space for events with exactly two b hadrons and a lepton pair from a Z decay. The b hadrons have $p_T > 15$ GeV and pseudorapidity $|\eta| < 2$. Each lepton has $p_T > 20$ GeV, $|\eta| < 2.4$, and the dilepton invariant mass is $81 < M_{\ell\ell} < 101$ GeV. The differential cross sections are measured for $p_T^Z > 0$ GeV and $p_T^Z > 50$ GeV. In the former case, the bin sizes are 0.7, 0.53, 0.84, and 0.2 for ΔR_{BB}, $\Delta\phi_{BB}$, minΔR_{ZB}, and A_{ZBB}, respectively. In the latter, the corresponding values are 0.84, 0.63, 1.0, and 0.25. Since the IVF angular resolution is significantly smaller than the bin size for all the measured distributions, no unfolding procedure is applied to measure the hadron-level differential cross sections.

The hadron-level differential cross section is calculated from

$$\sigma_{\alpha,j} = \mathcal{F}(\mathrm{n}^{\mu}_{\alpha,j}, \mathrm{n}^{\mathrm{e}}_{\alpha,j}) \cdot \frac{\mathcal{S}^{\mathrm{B}}_{\alpha,j}}{\epsilon^{2\mathrm{B}}_{\alpha,j}} \cdot \mathcal{P}_{\alpha,j} \cdot \frac{1}{\mathcal{L}}, \tag{4.1}$$

where

$$\mathrm{n}^{\ell}_{\alpha,j} = \frac{N^{\ell}_{\alpha,j}}{\epsilon^{\ell}_{\alpha,j} \cdot A^{\ell}_{\alpha,j}}, \tag{4.2}$$

with $\ell = \mathrm{e}, \mu$. For each bin j of the angular variable α, indicating one of the four variables defined in section 1, the number of signal events $N^{\ell}_{\alpha,j}$ is extracted from an extended unbinned maximum-likelihood fit to the lepton pair invariant mass distribution. A Breit-Wigner distribution convolved with a Gaussian resolution function is used for the signal and a third-degree Chebychev polynomial distribution for the background, as shown in figure 3. The signal shape parameters are evaluated from data while the background parameters are obtained from simulation. $N^{\ell}_{\alpha,j}$ is corrected for the dilepton reconstruction and selection efficiency $\epsilon^{\ell}_{\alpha,j}$ and acceptance $\mathcal{A}^{\ell}_{\alpha,j}$. The corrected yields $\mathrm{n}^{\ell}_{\alpha,j}$ in the muon and electron channels are found to be in agreement, within statistical uncertainties.

The two channels are combined into a single measurement $\mathcal{F}(\mathrm{n}^{\mu}_{\alpha,j}, \mathrm{n}^{\mathrm{e}}_{\alpha,j})$ using the BLUE algorithm [31, 32], which performs a weighted average of the input values taking into account the respective uncertainties and their correlations.

The resulting yield is corrected for the b-hadron pair identification efficiency $\epsilon^{\mathrm{2B}}_{\alpha,j}$, the b-hadron purity $\mathcal{P}_{\alpha,j}$, and the integrated luminosity $\mathcal{L}$. The factor $\mathcal{S}^{\mathrm{B}}_{\alpha,j}$ corrects for events with b hadrons with $p_{\mathrm{T}} < 15\,\mathrm{GeV}$.

The dilepton trigger efficiency is estimated from data with a tag-and-probe method, as a function of the lepton kinematics. It is approximately 93% for the dimuon and 98% for the dielectron trigger selections. The lepton offline reconstruction and selection efficiencies, around 80% for muon and 50% for electron pairs, are obtained from simulation and are rescaled to match the values measured in data with a tag-and-probe procedure, as a function of the lepton pseudorapidity.

The total b-hadron identification efficiency is estimated using multijet events containing semileptonic decays of b-hadrons and from events enriched with top quarks. In addition, a dedicated study is performed to verify that the efficiency measurements are valid for the inclusive vertex finding algorithm as well.

The efficiency for identifying b-hadron pairs, which ranges between 8% and 10%, is corrected by applying a factor of 0.88 to account for the discrepancy observed between the measured and simulated efficiency. This scale factor is measured from data, in the same way as it is done for the Simple Secondary Vertex method that identifies b hadrons inside jets [17]. This study requires the association of the vertices reconstructed with the IVF with jets and exploits the features of muons produced in semileptonic decays of the b hadrons, namely their high transverse momenta with respect to the jet axis. The purity $\mathcal{P}_{\alpha,j}$ and correction factor $S^{B}_{\alpha,j}$ are evaluated to be about 85% and 97%, respectively, based on MC simulation.

The same method is used to derive the total cross section for different ranges of $p^{\mathrm{Z}}_{\mathrm{T}}$. The extended maximum-likelihood fit and the procedure to extract the correction factors are applied to the corresponding event sample.

5 Systematic uncertainties

The following uncertainties on the differential cross sections are considered:

- *Uncertainty in combined dilepton signal*

  The procedure to combine the muon and electron channels takes into account the systematic uncertainties on the $N^{\ell}_{\alpha,j}$ yields and on the dilepton efficiency correction factors. The systematic uncertainty affecting the resulting combination is estimated by the BLUE algorithm, and is approximately ±2%. More details are given below.

- *Uncertainty in the signal yield*

  The systematic uncertainty associated with the extraction of $N^{\ell}_{\alpha,j}$ from the extended unbinned maximum-likelihood fit is estimated by varying the shape parameters within their uncertainties. For the signal, the shape parameters are the Breit-Wigner mean and width, as well as the Gaussian standard deviation. For the background, the parameters of the Chebychev polynomial distribution are considered. A variation of these factors leads to a signal yield uncertainty below ±2%.

- *Uncertainty in the trigger efficiency and the lepton efficiency scale factors*

  The lepton reconstruction and selection efficiency corrections are computed with the MC simulation, and rescaled to match the efficiency values measured from data with the tag-and-probe method. The corresponding systematic uncertainty is estimated by varying the scale factors and the trigger efficiency extracted from data within their systematic uncertainties, mostly due to the background shape parametrisation. The resulting variation is ±0.5% for the muon channel and ±1% for the electron channel.

- *Uncertainty in the efficiency scale factor*

  The scale factors between the b-hadron pair identification efficiency in data and simulation are determined as a function of the jet transverse momentum. The maximal deviation of the measured values from a constant leads to a ±12% systematic uncertainty assigned to the cross section.

- *Uncertainty in the purity correction factor*

  The purity correction factor accounts for the contamination from events with at least one reconstructed B candidate produced by a charm hadron decay or, more rarely, by a light jet. Three categories contribute to such impurity: $\mathrm{Zb\bar{b}}$ events with a charm hadron from a sequential c decay reconstructed as b hadron, $\mathrm{Zc\bar{c}}$ events, and $\mathrm{Zb\bar{b}c}$ events. The uncertainty in the purity originates essentially from the $\mathrm{Zb\bar{b}c}$ and $\mathrm{Zc\bar{c}}$ processes, where there is no measurement related to the production of one or two charm quarks produced in association with a Z boson. We therefore provide a conservative estimate of such uncertainty by varying the $\mathrm{Zb\bar{b}c}$ and $\mathrm{Zc\bar{c}}$ fractions by 50% in the simulation. The resulting uncertainty in $\mathcal{P}_{\alpha,j}$ is ±2.1%.

- *Bin-to-bin migrations*

  Possible migrations of events from one bin to the adjacent ones are accounted for as a source of systematic uncertainty. The effect varies between ±1–2% for ΔR_{BB} and $\min\Delta R_{\mathrm{ZB}}$, and ±3–4% for the $\Delta\phi_{\mathrm{BB}}$ and A_{ZBB} variables. Such uncertainty does not affect the total cross section measurement.

- *Uncertainty in the luminosity*

  The luminosity $\mathcal{L}$ is known with a systematic uncertainty of ±2.2% [33].

Source	Uncertainty (%)
Dilepton channel combination	2
IVF efficiency scale factors	12
B purity	2.1
Bin-to-bin migrations (ΔR_{BB}, minΔR_{ZB})	1–2
Bin-to-bin migrations ($\Delta\phi_{\mathrm{BB}}$, A_{ZBB})	3–4
MC statistics — Differential	2.0–3.7
MC statistics — Total	1.0–3.5
Integrated luminosity	2.2

Table 1. Summary of systematic uncertainties assigned to the differential and total cross section measurements. The systematic uncertainties in $N_{\alpha,j}$ and in the dilepton efficiency are used in the combination of the muon and electron channels, and are reported in the text.

- *MC statistical uncertainty*

  The uncertainties on the efficiency and purity corrections are dominated by the limited size of the four-flavour $\mathrm{Zb\bar{b}}$ MadGraph sample. The effect is evaluated in each bin for the differential measurements, and globally for the total cross section determination, and is taken as an additional source of uncertainty that varies between ±2% and ±3.7%.

The systematic uncertainties are summarised in table 1, for the differential cross sections and the total cross section measurements.

6 Theoretical predictions and uncertainties

The measured cross sections are compared at hadron level to the predictions by the MadGraph MC, in both the five- (MG5F) and four-flavour (MG4F) approaches, and by the alpgen generator in the four-flavour approach.

The MG5F prediction is based on a matrix-element calculation where up to four partons are produced in association with the Z boson, the b quarks are assumed massless, the proton PDF set is CTEQ6L1, and the jet matching is performed using the standard k_{T}-MLM scheme at a matching scale $\mathcal{Q}_{\mathrm{match}} = 20\,\mathrm{GeV}$ [34]. Events with b-hadron pairs from a second partonic scattering are included.

The MG4F prediction considers massive b quarks in the matrix-element calculation with the mass set to $m_{\mathrm{b}} = 4.7\,\mathrm{GeV}$. In the matrix element two additional light partons are produced in association with the $\mathrm{Zb\bar{b}}$ final state. The jet matching scheme is also the k_{T}-MLM with $\mathcal{Q}_{\mathrm{match}} = 30\,\mathrm{GeV}$.

The alpgen prediction adopts the four-flavour calculation scheme, with the MLM jet matching and CTEQ5L PDF set. The matching parameters are $\Delta R^{\mathrm{match}}$(parton-jet) = 0.7 and $p_{\mathrm{T}}^{\mathrm{match}} = 20\,\mathrm{GeV}$. In addition to the tree-level predictions mentioned above, the measurements are compared to the NLO expectations by aMC@NLO, which implements the four-flavour scheme with the MSTW2008 NLO PDF set.

JHEP12(2013)039

	μ_F^2	μ_R^2
MG5F	$m_{\mathrm{Z}}^2 + p_{\mathrm{T}}^2(\text{jets})$	k_{T}^2 at each vertex splitting
MG4F	$m_{\mathrm{T,Z}} \cdot m_{\mathrm{T}}(\mathrm{b}, \mathrm{b})$	k_{T}^2 at each vertex splitting (excl. b)
ALPGEN	$m_Z^2 + \sum_{\text{jets}}(m_{\text{jets}}^2 + p_{T,\text{jets}}^2)$	k_{T}^2 at each vertex splitting (excl. b)
aMC@NLO	$m_{\ell\ell'}^2 + p_{\mathrm{T}}^2(\ell\ell') + \frac{m_{\mathrm{b}}^2 + p_{\mathrm{T}}^2(\mathrm{b})}{2} + \frac{m_{\mathrm{b}}'^2 + p_{\mathrm{T}}^2(\mathrm{b}')}{2}$	$= \mu_F^2$

Table 2. Summary of the central scale functional forms used in the different theoretical predictions for the factorisation (μ_F^2) and renormalisation (μ_R^2) scales. The label *jets* can be (u, d, s, c, b, g) for the MG5F production, while it is (u, d, c, s, g) for the MG4F one, for which the label b is mentioned explicitly to denote the b quark. m_{T} denotes the transverse mass.

The parton shower and hadronisation of all tree-level samples is obtained with PYTHIA, with p_{T}-ordered showers, while aMC@NLO is interfaced with HERWIG. The choices of QCD factorisation and renormalisation scales are summarised in table 2.

The MG5F prediction is rescaled by a k-factor of 1.23, corresponding to the ratio between the next-to-next-to-leading-order (NNLO) prediction of the inclusive Z production cross section, and the tree-level cross section from MadGraph. The tree-level cross section prediction for MG4F (ALPGEN) is rescaled by a k-factor obtained from the aMC@NLO cross section of 16 pb obtained for $M_{\ell\ell} > 30\,\mathrm{GeV}$ divided by the corresponding MG4F (ALPGEN) prediction.

The following uncertainties on the theoretical predictions are considered and combined quadratically:

- The shape uncertainties associated with the b-quark mass, m_{b}, for the MadGraph 4F prediction are assessed by varying m_{b} between 4.4 and 5.0 GeV. Each distribution is rescaled so that the normalisation matches the NLO cross section provided by aMC@NLO and the envelope is considered as the uncertainty band.

- The shape uncertainties due to the factorisation and renormalisation scales are assessed for the MadGraph 4F and 5F predictions by varying their values simultaneously by a factor of two. The MadGraph 4F (5F) distributions are rescaled so that the normalisation matches the NLO (NNLO) cross section provided by aMC@NLO (FEWZ [35]) and the envelopes are considered as uncertainty bands.

- The uncertainties associated with the matching scale are assessed by varying it by ±15% for MadGraph 4F and by a factor of two for the 5F case.

- The shape uncertainties associated with the choice of PDF set are found to be negligible. The effect of PDF variations are included as normalisation uncertainties as described in the next item.

- For MadGraph 4F and ALPGEN predictions the normalisation uncertainty is given by the corresponding aMC@NLO cross section uncertainty. The latter is obtained by varying the factorisation and renormalisation scales simultaneously by a factor of two, and by replacing the MSTW2008 PDF set with CT10. For MadGraph 5F the normalisation uncertainty is given by the corresponding NNLO cross section uncertainty [35].

- For aMC@NLO the uncertainty associated with the parton shower is assessed from the difference between PYTHIA (D6T tune) with virtuality-ordered showers and HERWIG.
- The statistical uncertainty due to the finite size of the simulated sample is propagated for all theoretical predictions.

7 Results

The measured differential cross sections as a function of the three angular variables and the angular asymmetry variable are shown in figures 5 and 6 for all p_T^Z and for $p_T^Z >$ 50 GeV, respectively. Figure 5 shows that the ΔR_{BB} collinear region is better described by ALPGEN, while the four- and five-flavour MadGraph as well as aMC@NLO predictions tend to underestimate the data. At large ΔR_{BB}, all predictions are in good agreement with the data. The fraction of the cross section with collinear b hadrons increases for $p_T^Z > 50$ GeV and in this case ALPGEN also gives the best description of the measured distributions.

Similar conclusions can be drawn from the $\Delta\phi_{BB}$ distribution. In the nonboosted case, data are above all MC predictions in the region of back-to-back b-hadron pairs by approximately one standard deviation. This discrepancy vanishes for $p_T^Z > 50$ GeV. The simulated minΔR_{ZB} and A_{ZBB} generally agree with the data. Some discrepancy is observed at min$\Delta R_{ZB} > 2$ in both ranges of p_T^Z, and at low A_{ZBB}. The data are found to be above the predictions primarily in the regions where the contributions from the q$i \to$ Zb$\bar{\text{b}}$X subprocesses are expected to be dominant, as shown in figure 2.

The total hadron-level cross section is shown in figure 7 for four different regions of p_T^Z: for the inclusive spectrum, and for $p_T^Z >$ 40, 80, and 120 GeV. Data points are generally above all simulations by about 15%, apart from aMC@NLO for which the discrepancy can be as large as 50% at large p_T^Z.

8 Conclusions

The first measurement of angular correlations in the process pp $\to$ Zb$\bar{\text{b}}X$ has been performed. The analysed data set corresponds to an integrated luminosity of 5.1 fb^{-1} recorded by the CMS experiment in 2011 at a centre-of-mass energy of 7 TeV. Z bosons are reconstructed in the e$^+$e$^-$ and $\mu^+\mu^-$ decay modes. The use of the inclusive vertex finder, which exploits the excellent CMS tracking performance, allows the full angular range to be probed, including configurations with collinear b hadrons.

The production cross sections are measured as functions of four angular variables: ΔR_{BB}, $\Delta\phi_{BB}$, minΔR_{ZB}, and A_{ZBB}. The measurements are compared with tree-level predictions by the MadGraph and ALPGEN MC generators implementing different flavour number schemes. The variables most sensitive to the b-hadron production process, ΔR_{BB} and $\Delta\phi_{BB}$, show that the four-flavour prediction implemented in ALPGEN provides the best description of CMS data.

JHEP12(2013)039

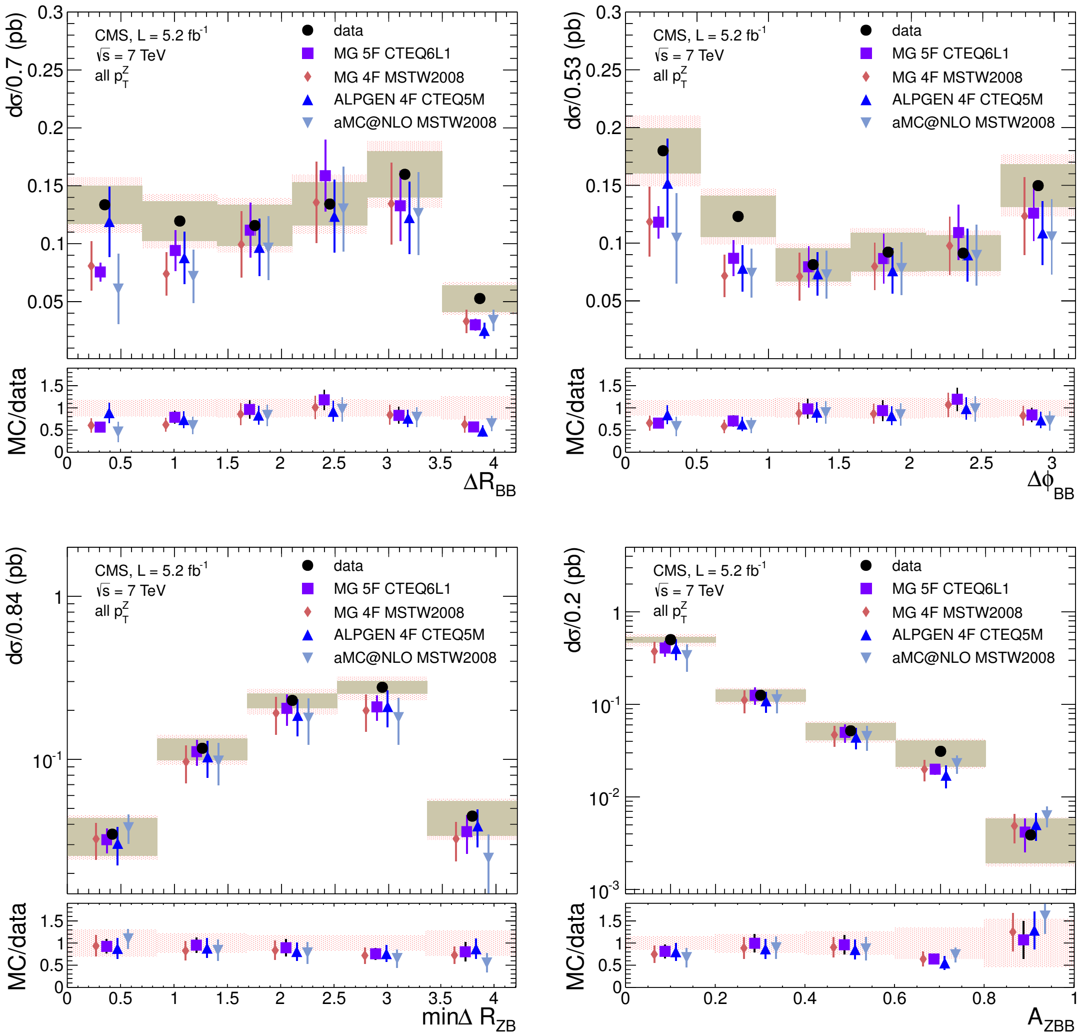

Figure 5. Differential cross sections for all p_T^Z, as a function of $\Delta R_{\rm BB}$ (top left), $\Delta\phi_{\rm BB}$ (top right), min$\Delta R_{\rm ZB}$ (bottom left), and $A_{\rm ZBB}$ (bottom right). The measured values are shown as black points. The dotted bands correspond to the quadratic sum of statistical and systematic uncertainties. Statistical uncertainties are shown separately as solid bands. The measurements are compared to the hadron-level predictions by MadGraph in the four- and five-flavour schemes, alpgen, and aMC@nlo. For each distribution the ratio between the Monte Carlo predictions and the measurements is also shown, with the total experimental uncertainty indicated by the dotted area.

The MG5F MC generator has been one of the standard tools used to simulate backgrounds from associated production of vector bosons and heavy quarks for Higgs boson and new physics searches as well as SM studies. The results reported here indicate that such a description may not be optimal for analyses sensitive to the production of collinear b hadrons. This fact may be particularly important in the simulation of the W$\mathrm{b\overline{b}}$ process, where collinear b-hadron production is expected to be enhanced compared to the Z$\mathrm{b\overline{b}}$ process.

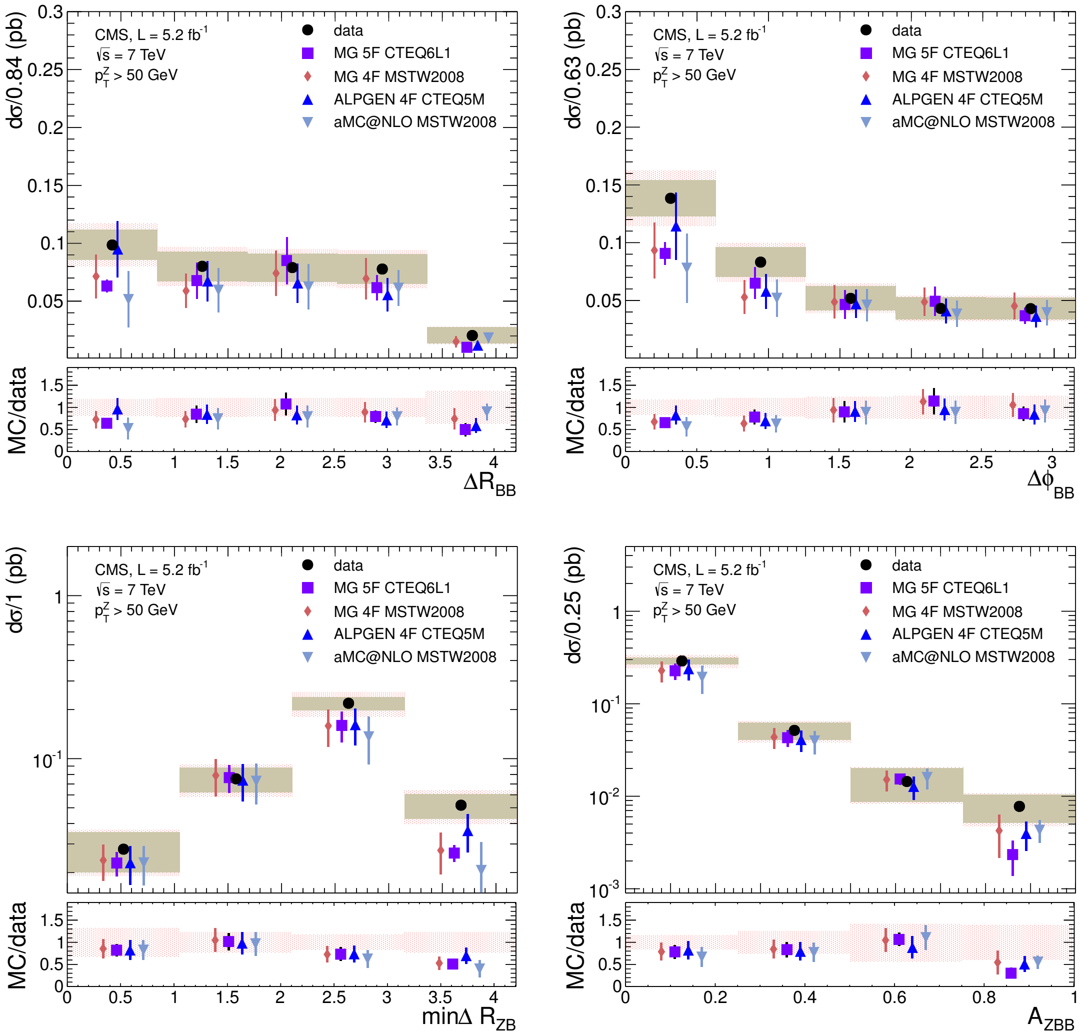

Figure 6. Differential cross sections for $p_T^Z > 50\,\text{GeV}$, as a function of ΔR_{BB} (top left), $\Delta\phi_{\text{BB}}$ (top right), minΔR_{ZB} (bottom left), and A_{ZBB} (bottom right). The measured values are shown as black points. The dotted bands correspond to the quadratic sum of statistical and systematic uncertainties. Statistical uncertainties are shown separately as solid bands. The measurements are compared to the hadron-level predictions by MadGraph in the four- and five-flavour schemes, alpgen, and amc@nlo. For each distribution the ratio between the Monte Carlo predictions and the measurements is also shown, with the total experimental uncertainty indicated by the dotted area.

This is the first time that amc@nlo predictions, in which QCD contributions are computed to NLO, have been compared with data for the $\text{Zb}\overline{\text{b}}$ process. It is found that amc@nlo underestimates the cross section at low ΔR_{BB} and $\Delta\phi_{\text{BB}}$, and at large minΔR_{ZB}. A comprehensive assessment of the amc@nlo predictions requires further studies of the scale choices and parton shower modelling. It is worth noting that the use of NLO jet matching would also improve the precision of the prediction at small values of ΔR_{BB}.

JHEP12(2013)039

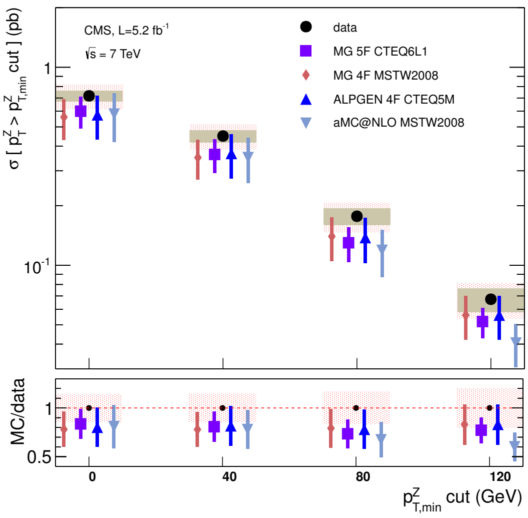

Figure 7. Total cross section as function of the cut on p_T^Z. The measured values are shown as black points. The solid bands include statistical and systematic uncertainties combined quadratically. Statistical uncertainties are shown separately as dotted bands. The measurements are compared to the hadron-level predictions by MadGraph in the four- and five-flavour scheme, alpgen, and aMC@nlo. The ratio between the Monte Carlo predictions and the measurements is also shown, with the total experimental uncertainty indicated by the dotted area.

The total hadron-level cross section $\sigma_{\text{tot}} = \sigma(\text{pp} \to \text{Zb}\bar{\text{b}}X)\mathcal{B}(\text{Z} \to \ell^+\ell^-)$ is also evaluated in different ranges of the Z boson transverse momentum. For the case where no cut is applied on the Z momentum, the total cross section is $\sigma_{\text{tot}} = 0.71 \pm 0.08\,\text{pb}$; for $p_T^Z > 40\,\text{GeV}$, $\sigma_{\text{tot}} = 0.44 \pm 0.05\,\text{pb}$; for $p_T^Z > 80\,\text{GeV}$, $\sigma_{\text{tot}} = 0.17 \pm 0.02\,\text{pb}$; and for $p_T^Z > 120\,\text{GeV}$, $\sigma_{\text{tot}} = 0.07 \pm 0.01\,\text{pb}$. The measured values are systematically larger than MC predictions, partly because of the excess observed in the collinear ΔR_{BB} region. The shape of the measured integrated cross section as a function of the minimum transverse momentum of the Z boson is in good agreement with the tree-level 4F predictions, while slightly larger discrepancies are observed for MG5F and even more for aMC@nlo, particularly at large p_T^Z.

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JHEP12(2013)039

References

[1] ATLAS collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, *Phys. Lett.* **B 716** (2012) 1 [arXiv:1207.7214] [INSPIRE].

[2] CMS collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, *Phys. Lett.* **B 716** (2012) 30 [arXiv:1207.7235] [INSPIRE].

[3] J.-M. Gerard and M. Herquet, *Twisted custodial symmetry in the two-Higgs-doublet model*, *Phys. Rev. Lett.* **98** (2007) 251802 [hep-ph/0703051] [INSPIRE].

[4] S. de Visscher, J.-M. Gerard, M. Herquet, V. Lemaitre and F. Maltoni, *Unconventional phenomenology of a minimal two-Higgs-doublet model*, *JHEP* **08** (2009) 042 [arXiv:0904.0705] [INSPIRE].

[5] R. Dermisek, *Light CP-odd Higgs and Small tan beta Scenario in the MSSM and Beyond*, arXiv:0806.0847 [INSPIRE].

[6] R. Dermisek and J.F. Gunion, *Many Light Higgs Bosons in the NMSSM*, *Phys. Rev.* **D 79** (2009) 055014 [arXiv:0811.3537] [INSPIRE].

[7] J. Alwall et al., *MadGraph/MadEvent v4: the new web generation*, *JHEP* **09** (2007) 028 [arXiv:0706.2334] [INSPIRE].

[8] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer and T. Stelzer, *MadGraph 5: going beyond*, *JHEP* **06** (2011) 128 [arXiv:1106.0522] [INSPIRE].

[9] M.L. Mangano, M. Moretti, F. Piccinini, R. Pittau and A.D. Polosa, *ALPGEN, a generator for hard multiparton processes in hadronic collisions*, *JHEP* **07** (2003) 001 [hep-ph/0206293] [INSPIRE].

[10] T. Gleisberg et al., *Event generation with SHERPA 1.1*, *JHEP* **02** (2009) 007 [arXiv:0811.4622] [INSPIRE].

[11] J.M. Campbell and R.K. Ellis, *Radiative corrections to $Zb\bar{b}$ production*, *Phys. Rev.* **D 62** (2000) 114012 [hep-ph/0006304] [INSPIRE].

[12] F. Febres Cordero, L. Reina and D. Wackeroth, *NLO QCD corrections to $Zb\bar{b}$ production with massive bottom quarks at the Fermilab Tevatron*, *Phys. Rev.* **D 78** (2008) 074014 [arXiv:0806.0808] [INSPIRE].

[13] F. Febres Cordero, L. Reina and D. Wackeroth, *W- and Z-boson production with a massive bottom-quark pair at the Large Hadron Collider*, *Phys. Rev.* **D 80** (2009) 034015 [arXiv:0906.1923] [INSPIRE].

[14] R. Frederix et al., *W and* $\mathrm{Z}/\gamma*$ *boson production in association with a bottom-antibottom pair*, *JHEP* **09** (2011) 061 [arXiv:1106.6019] [INSPIRE].

[15] S. Frixione and B.R. Webber, *Matching NLO QCD computations and parton shower simulations*, *JHEP* **06** (2002) 029 [hep-ph/0204244] [INSPIRE].

[16] F. Maltoni, G. Ridolfi and M. Ubiali, *b-initiated processes at the LHC: a reappraisal*, *JHEP* **07** (2012) 022 [*Erratum ibid.* **1304** (2013) 095] [arXiv:1203.6393] [INSPIRE].

JHEP12(2013)039

[17] CMS collaboration, *Identification of b-quark jets with the CMS experiment*, 2013 *JINST* **8** P04013 [arXiv:1211.4462] [INSPIRE].

[18] CMS collaboration, *Measurement of $B\bar{B}$ angular correlations based on secondary vertex reconstruction at $\sqrt{s} = 7$ TeV*, *JHEP* **03** (2011) 136 [arXiv:1102.3194] [INSPIRE].

[19] M. Rubin, G.P. Salam and S. Sapeta, *Giant QCD K-factors beyond NLO*, *JHEP* **09** (2010) 084 [arXiv:1006.2144] [INSPIRE].

[20] ATLAS collaboration, *Measurement of the cross-section for b-jets produced in association with a Z boson at $\sqrt{s} = 7$ TeV with the ATLAS detector*, *Phys. Lett.* **B 706** (2012) 295 [arXiv:1109.1403] [INSPIRE].

[21] CMS collaboration, *Measurement of the Z/γ^*+b-jet cross section in pp collisions at $\sqrt{s} = 7$ TeV*, *JHEP* **06** (2012) 126 [arXiv:1204.1643] [INSPIRE].

[22] CMS collaboration, *The CMS experiment at the CERN LHC*, 2008 *JINST* **3** S08004 [INSPIRE].

[23] GEANT4 collaboration, S. Agostinelli et al., *GEANT4: a simulation toolkit*, *Nucl. Instrum. Meth.* **A 506** (2003) 250 [INSPIRE].

[24] T. Sjöstrand, S. Mrenna and P.Z. Skands, *PYTHIA 6.4 physics and manual*, *JHEP* **05** (2006) 026 [hep-ph/0603175] [INSPIRE].

[25] R. Field, *Early LHC Underlying Event Data-Findings and Surprises*, arXiv:1010.3558 [INSPIRE].

[26] CMS collaboration, *Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV*, 2012 *JINST* **7** P10002 [arXiv:1206.4071] [INSPIRE].

[27] CMS collaboration, *Measurements of Inclusive W and Z Cross Sections in pp Collisions at $\sqrt{s} = 7$ TeV*, *JHEP* **01** (2011) 080 [arXiv:1012.2466] [INSPIRE].

[28] CMS collaboration, *Particle-Flow Event Reconstruction in CMS and Performance for Jets, Taus and MET*, CMS-PAS-PFT-09-001 (2009).

[29] M. Cacciari and G.P. Salam, *Pileup subtraction using jet areas*, *Phys. Lett.* **B 659** (2008) 119 [arXiv:0707.1378] [INSPIRE].

[30] R. Frühwirth, W. Waltenberger and P. Vanlaer, *Adaptive vertex fitting*, *J. Phys.* **G 34** (2007) N343 [INSPIRE].

[31] L. Lyons, D. Gibaut and P. Clifford, *How to combine correlated estimates of a single physical quantity*, *Nucl. Instrum. Meth.* **A 270** (1988) 110 [INSPIRE].

[32] A. Valassi, *Combining correlated measurements of several different physical quantities*, *Nucl. Instrum. Meth.* **A 500** (2003) 391 [INSPIRE].

[33] CMS collaboration, *Absolute Calibration of the Luminosity Measurement at CMS: Winter 2012 Update*, CMS-PAS-SMP-12-008 (2012).

[34] J. Alwall et al., *Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions*, *Eur. Phys. J.* **C 53** (2008) 473 [arXiv:0706.2569] [INSPIRE].

[35] R. Gavin, Y. Li, F. Petriello and S. Quackenbush, *FEWZ 2.0: a code for hadronic Z production at next-to-next-to-leading order*, *Comput. Phys. Commun.* **182** (2011) 2388 [arXiv:1011.3540] [INSPIRE].

JHEP12(2013)039

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JHEP12(2013)039

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JHEP12(2013)039

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JHEP12(2013)039

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JHEP12(2013)039

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JHEP12(2013)039

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JHEP12(2013)039

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JHEP12(2013)039

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JHEP12(2013)039

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JHEP12(2013)039

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JHEP12(2013)039

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JHEP12(2013)039

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JHEP12(2013)039

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JHEP12(2013)039

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38: Also at Paul Scherrer Institut, Villigen, Switzerland
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41: Also at Gaziosmanpasa University, Tokat, Turkey
42: Also at Adiyaman University, Adiyaman, Turkey
43: Also at Cag University, Mersin, Turkey
44: Also at Mersin University, Mersin, Turkey
45: Also at Izmir Institute of Technology, Izmir, Turkey
46: Also at Ozyegin University, Istanbul, Turkey
47: Also at Kafkas University, Kars, Turkey
48: Also at Suleyman Demirel University, Isparta, Turkey
49: Also at Ege University, Izmir, Turkey
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JHEP12(2013)039

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59: Also at Yildiz Technical University, Istanbul, Turkey
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JHEP12(2013)039