Measurement of the production cross sections of Z bosons in association with b jets in pp collisions at $\sqrt{s} = 7$ TeV

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The mechanism of production of heavy-flavoured mesons, in association with vector bosons like Z+b in the Standard Model is only partially understood. The deep understanding of these processes is furthermore required by Higgs and BSM analysis with similar final states. Using the 2.1 fb^{-1} LHC proton-proton collision data collected in 2011 at a centre of mass energy of 7 TeV by the CMS detector [1], the final measurements of Z+b inclusive, Z+1b exclusive and Z+2b inclusive cross sections are determined for b hadron jets having $p_T > 25$ GeV and $|\eta| < 2.1$. Results and kinematics are compared to Monte Carlo predictions.

1 Introduction

The production of the Z boson in association with b quarks is an important measurement at the LHC, both as a benchmark channel to the production of the Higgs boson in association with b quarks, as well as a Standard Model background to Higgs and new physics searches in final states with leptons and b jets. The dominant contributions for proton-proton collisions at the LHC centre of mass energy of 7 TeV originate from the gluon-gluon production processes, with a smaller contribution from multiple parton interactions.

The processes are currently computed in two ways: the four-flavour scheme which allows only u, d, s, c quarks and gluons to participate in the hard scattering process, with the b quarks produced explicitly in pairs from gluon splitting; and the five-flavour scheme allowing the b quark to participate directly in the hard scattering, by integrating the gluon splitting process into the PDF. NLO calculations have been performed in Ref. [2] using massless b quarks. To all orders in perturbation theory, both schemes can be made exactly identical. Still, at any finite order the results might differ significantly, depending on the ordering.

2 Reconstruction, selection and backgrounds

The signal is defined as one Z boson in association with exactly one or at least two b quarks, inclusive with respect to the number of additional non-b-flavoured jets.

The total luminosity analyzed is $\mathcal{L} = 2.13 \pm 0.09$ fb^{-1}.

The Z boson is reconstructed from 2 leptons, electrons or muons, both required to be reconstructed offline with a $p_T > 25$ (20) GeV and a pseudorapidity $|\eta| < 2.5$ (2.1). An isolation criteria is applied to reject the background.

Jets are reconstructed using the particle-flow objects[3]. Individual particles are reconstructed by considering information from all subdetectors and subsequently clustered into jets using the anti-k$_T$ jet clustering algorithm[4] with a distance parameter of 0.5. The reconstructed jets are required to have $p_T > 25$ GeV, $|\eta| < 2.1$, and to be separated from the leptons by $\Delta R \geq 0.5$. Jets originating from b quarks are tagged by taking advantage of the long b hadron lifetime through a Simple Secondary Vertex (SSV) algorithm[5], requiring at least 2 tracks per secondary vertex and discriminating on the flight distance significance from the reference primary vertex.

The Monte Carlo samples used are derived from MadGraph5F[6] interfaced with Pythia[7]. The Z+jets MC sample is split into three subsamples, according to the underlying production of b jets, c jets, or jets originating from gluons or u,d,s quarks (hereafter called light jets). The MC expectations are re-weighted according to scale factors for pile-up, b-tag and lepton reconstruction efficiencies, in order to match the observations in data. The number of 2 tracks secondary vertices per jet is shown in Figure 1, after the dilepton+jet(s) selection.

Events not originating from Z+b jets production processes but nevertheless contributing to the final reconstructed event yield after the full event selection are expected to originate from ttbar, Z+jets and ZZ production as visible in the Figure 1. ZZ, the smallest contribution, will be estimated from the Monte Carlo yield after selection, normalized to the CMS cross section measurement[8].

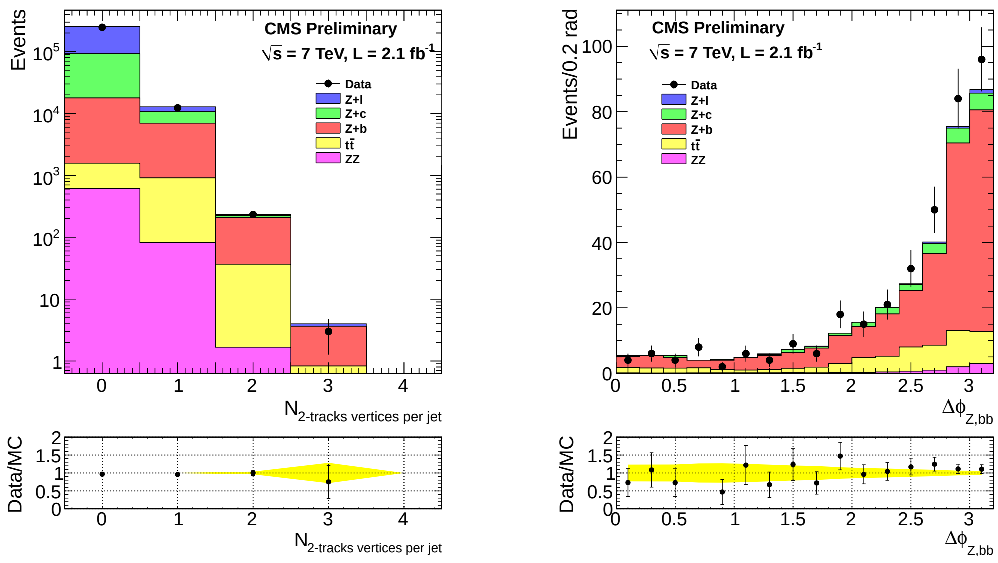

Figure 1: Left: Number of two-tracks secondary vertices per jet within $\Delta R = 0.3$ of the jet axis in dilepton+jet(s) events. Right: the polar angle Φ between the Z boson and the bb system. The yellow bands in the lower plots represent the statistical uncertainty on the MC yield.

To improve the selection efficiency, especially when requiring two jets, all secondary vertices built from two tracks or more are considered. The discriminant value to define b jets[5] is chosen such that the rate of tagging a light quark (mistagging rate) is below 1%.

The remaining background due to mistagging light jets is estimated from the distribution of the secondary vertex masses, $m(SV_{1,2})$, of the leading and sub-leading b-tagged jets. The method is an extension of the method used in the preceding paper[9]: templates are estimated from MC to model the $m(SV_{1,2})$ distributions for the different jet flavours and are used in likelihood fits to extract the bb-purity from the data.

The almost exclusive contribution of the ttbar MC component in the Missing Transverse Energy (MET) above 50 GeV justifies the veto above this value in order to reduce the ttbar background. In this study, MET is calculated by forming the negative vectorial sum of the transverse momenta of all objects in the events. The dilepton invariant mass distribution is also used to suppress the background from ttbar, by narrowing the mass window to the range 76-106 GeV.

The remaining background originating from ttbar production is estimated using the dilepton invariant mass spectrum. The shape of the distributions of the Drell-Yan and the ttbar contribution are estimated from MC, and parameterized as binned PDFs, propagating the statistical uncertainties of the MC templates to the fitted fraction.

After subtracting the estimated background contribution the signal yield after selection is found to be : $N^{sig}_{\mathrm{Z}(\mu\mu)+\mathrm{bb}} = 133 \pm 21$ and $N^{sig}_{\mathrm{Z(ee)+bb}} = 95 \pm 15$.

3 Unfolding and results

In order to extract a cross section at the particle level, the background-subtracted yields for the Z+1b jet and the Z+2b jets categories are corrected for the efficiencies of the selection of the dilepton-pair and the b-tagged jets, as well as for the detector resolution effects. Both the application of b tagging, as well as jet reconstruction may induce migrations between the category of events containing one b jet and those containing more than one: the number of generated b jets and the number of correctly reconstructed b jets is in general not the same. In order to estimate the cross sections according to the different b jet multiplicities, the efficiency corrections are hence performed as a function of the number of b jets.

The sum of these two cross sections provides the inclusive cross section of a Z boson in association with any number of b jets: $\sigma(Z+b) \equiv \sigma(Z+1b) + \sigma(Z+2b)$.

The final cross section is obtained from the unfolded yields per multiplicity bin divided by the integrated luminosity. The results are summarized in Table 1. They are found to be compatible between the ee and $\mu\mu$ channels, and are combined into a single measurement.

Table 1: Cross section for the production of Z in association with exactly 1 b jet and at least 2 b jets, and the combination of the two (at least 1 b jet).

Multiplicity bin	Combination
σ_{hadron}(Z+1b,Z$\rightarrow \ell\ell$)(pb)	3.41 ± 0.05 (stat.) ± 0.27, (syst.) ± 0.09(theory)
σ_{hadron}(Z+2b,Z$\rightarrow \ell\ell$)(pb)	0.37 ± 0.02 (stat.) ± 0.07, (syst.) ± 0.02(theory)
σ_{hadron}(Z+b,Z$\rightarrow \ell\ell$)(pb)	3.78 ± 0.05 (stat.) ± 0.31, (syst.) ± 0.11(theory)

After correction to the full lepton acceptance, the combined cross section is found to be 5.72 ± 0.09 (stat.) ± 0.47 (syst.) ± 0.39 (theory) pb, which is in agreement with the MadGraph event generator predictions [6].

4 Prospects: Kinematics

In spite of a general fair data/MC agreement and a reasonable modeling of the Multiple Parton Interactions (with the $\Delta\Phi_{Z,bb}$ distribution), as seen on Figure 1, the momentum distributions show some tensions after both Z+b selection [9] and Z+2b selection [10]. The tensions can be observed in Figure 2, in the p_T distribution of the dilepton that shows a harder spectrum for data than MC, and in the p_T distribution of the leading b jet presenting discrepancies at low p_T. An additional jet veto does not remove the overall excess of data compared to expectations.

The discrepancy between data and MC possibly originates from the modeling of the spectra: either from the scheme used (five-flavour), which could be revealed by a check with a four-flavour sample, or from the order it was computed (LO), which could be checked with NLO comparisons.

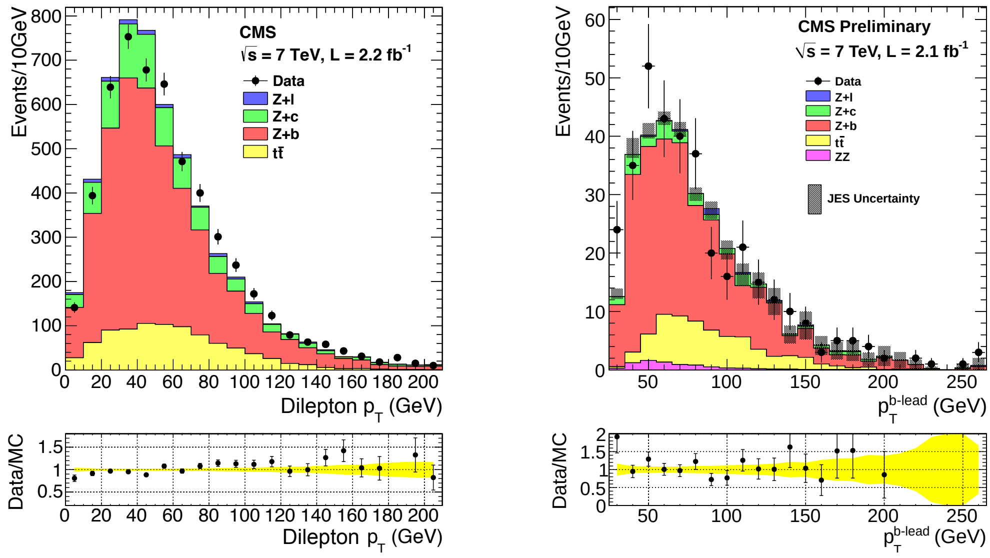

Figure 2: Left: transverse momentum distribution of the Z boson after Z+b selection. Right: transverse momentum distribution of the leading b jet after Z+2b selection. The yellow bands are the statistical uncertainty on the MC yield. The grey bands on the right plot represent the systematics effect due to the jet energy uncertainty.

Those results need in either case to be further studied with higher statistics which was done in the subsequent paper [11].

Acknowledgments

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