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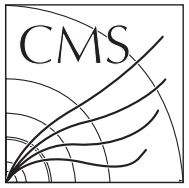

The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

06 October 2014

Production of vector bosons and jets at CMS

Fabio Cossutti for the CMS Collaboration

Abstract

The production cross section of highly boosted vector bosons (V = W, Z) recoiling against jets is studied, with CMS data, differentially as function of the transverse momentum and angular correlations of the final state particles. The mechanism of production of heavy-flavoured mesons, containing b or c quarks, in association with vector bosons, W or Z, in the Standard Model is only partially understood. The study of events with one or two well-identified and isolated leptons accompanied by b-jets or b-mesons is therefore crucial to refine the theoretical calculations in perturbative QCD, as well as validate associated Monte Carlo techniques. A measurement of the WZ and ZZ production cross sections in proton-proton collisions at 8 TeV in final states where one Z boson decays to b-tagged jets, while the other gauge boson, either W or Z, is detected through its leptonic decay is also presented.

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Production of vector bosons and jets at CMS

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Abstract

The production cross section of highly boosted vector bosons (V = W, Z) recoiling against jets is studied, with CMS data, differentially as function of the transverse momentum and angular correlations of the final state particles. The mechanism of production of heavy-flavoured mesons, containing b or c quarks, in association with vector bosons, W or Z, in the Standard Model is only partially understood. The study of events with one or two well-identified and isolated leptons accompanied by b-jets or b-mesons is therefore crucial to refine the theoretical calculations in perturbative QCD, as well as validate associated Monte Carlo techniques. A measurement of the WZ and ZZ production cross sections in proton-proton collisions at 8 TeV in final states where one Z boson decays to b-tagged jets, while the other gauge boson, either W or Z, is detected through its leptonic decay is also presented.

Keywords: LHC, vector boson, jets

1. Introduction

The associated production of vector bosons (V= W,Z) and hadronic jets, shortly V+jets, is a process occurring in proton-proton collisions that is important in several respects. Its study allows stringent tests of perturbative QCD predictions, currently available at leading (LO) and to next-to-leading order (NLO), and can be used to constrain the parton density functions (PDFs). Furthermore, this class of processes constitutes an abundant background for the production of the Higgs bosons and for several beyond standard model processes.

Recent results about these processes, obtained by the CMS experiment operating at the CERN LHC, are presented. The production of W bosons in association with jets has been studied for events produced at $\sqrt{s} = 7$ TeV, both for an inclusive jet selection [1] and for b jets, i.e. jets produced by b quark fragmentation [2]. The corresponding study of the production of Z bosons and jets has been performed both at $\sqrt{s} = 7$ [3, 4, 5] and 8 TeV [6, 7]. The comparative study of Z and photon production in association with jets has been performed in [8]. The study of the production in association with b jets has been also performed at 7 TeV [9, 10]. Finally, a measurement of the characteristics of associated production of a vector boson and a Z decaying in b quark pairs has also been performed [11].

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2. W+jets differential cross sections

Fiducial differential cross sections for the production of W+jets have been presented in [1], based on an integrated luminosity of 5 fb^{-1} collected at 7 TeV. W boson production is identified by isolated muons of transverse momentum $p_T > 25$ GeV and pseudorapidity $|\eta| < 2.1$, requiring a transverse mass for the muon - missing momentum system larger than 50 GeV. Jets are reconstructed using the anti-kT algorithm, and they are selected if they satisfy $p_T > 30$ GeV $|\eta| < 2.4$, with a minimum lepton-jet separation in the $\eta - \phi$ plane of $\Delta R > 0.5$. The experimental measurements are unfolded at particle level for detector resolution effects.

Experimental results are compared with predictions based on LO matrix elements interfaced with a parton

shower, as provided by the event generators Madgraph combined with Pythia6 and Sherpa (up to 4 additional jets, and normalised to the NNLO inclusive cross section), and with NLO fixed order parton level predictions provided by BlackHat plus Sherpa. The fiducial cross section as a function of the inclusive multiplicity shows an overall good agreement of all the predictions with data within the uncertainties, as can be seen in Fig. 1. The p_T spectrum of the highest p_T jet is shown in Fig. 2,

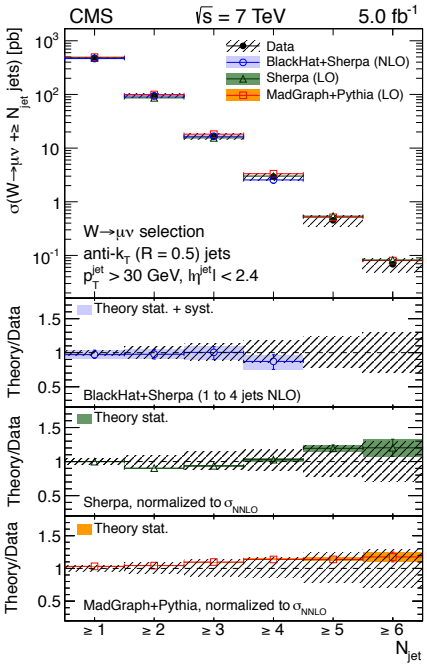

Figure 1: Fiducial cross section as a function of the inclusive jet multiplicity for the W+jets measurement.

and shows a reasonable agreement with the NLO calculation, while predictions based on LO matrix elements clearly overestimate the part of the spectrum beyond 100 GeV. Similar differences are observed also for the second jet, and are reflected in the distribution of the scalar sum of jet p_T. In this case also the NLO fixed order calculation fails to describe data at low multiplicity, due to the lack of higher order contributions. All calculations then fail to describe the distance in the azimuthal plane between the leading jet and the muon from W boson decay.

3. Z+jets differential cross sections

Measurements of fiducial differential cross sections for the production of Z+jets have been performed both

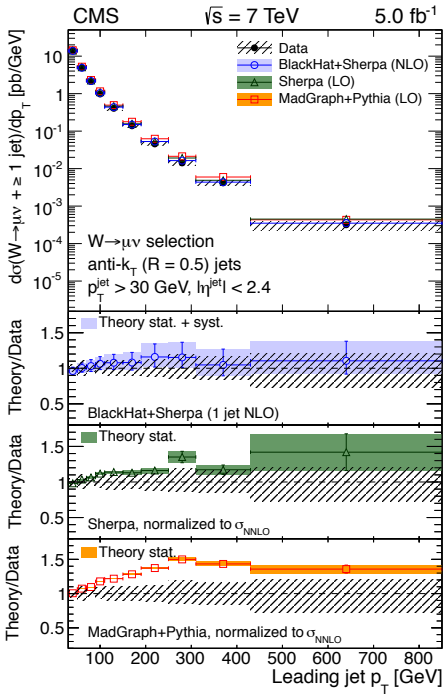

Figure 2: Fiducial cross section as a function of the leading jet p_T for the W+jets measurement.

at 7 [3] and 8 TeV [6], using integrated luminosities of 4.9 and 19.6 fb^{-1} respectively. Pairs of leptons, either electrons or muons, have been used if their kinematics satisfy the selection $p_T > 20$ GeV and $|\eta| < 2.4$, and the reconstructed dilepton invariant mass is included in the [71,111] GeV window. As for W bosons, hadronic jets are reconstructed with the anti-kT algorithm, and are included in the measurement if they satisfy $p_T > 30$ GeV $|\eta| < 2.4$, with a minimum lepton-jet separation in the $\eta - \phi$ plane of $\Delta R > 0.5$.

The measured spectra, unfolded at particle level, are compared with Madgraph plus Pythia6 predictions for both datasets (including matrix elements up to 4 additional jets, and normalised to the inclusive NNLO cross section). For the 7 TeV data, a comparison with the Z+1 jet NLO prediction of POWHEG, interfaced with Pythia6, is also shown. For both datasets comparisons with Sherpa2, implementing NLO matrix elements combined with the MEPS@NLO approach to LO matrix elements (up to 4 additional jets) are presented: at 7 TeV the NLO predictions for 0 and 1 additional jets are combined (using version 2.β2), while at 8 TeV the combination of NLO predictions includes also 2 additional jets (as implemented in version 2.0). Predic-

tions for 7 TeV data are presented with theoretical uncertainties due to scale variations associated, while for the 8 TeV one only the statistical uncertainty is available. The fiducial cross section as a function of the

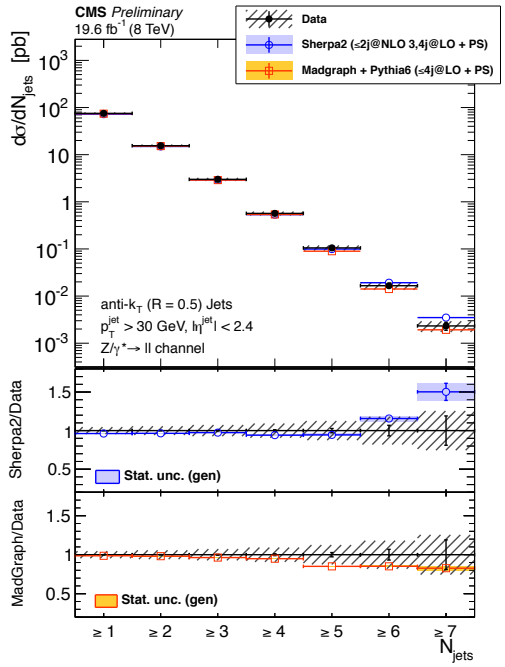

Figure 3: Fiducial cross section as a function of the inclusive jet multiplicity for the Z+jets measurement at 8 TeV.

inclusive multiplicity, shown in Fig. 3 for the 8 TeV dataset, presents an overall good agreement within uncertainties with all the predictions for both datasets. The jet p_T spectra show excesses in the prediction of Madgraph plus Pythia6 for transverse momenta above 100 GeV qualitatively similar to those observed for W bosons, as can be observed in Fig. 4 and 5. Also the POWHEG plus Pythia6 calculation tends to overestimate data, although within the uncertainties. It is interesting to notice that Sherpa underestimates the spectrum for the 7 TeV dataset, where hard jets beyond the first one are described at LO only, while, as can be seen in Fig. 5, the agreement is definitely better at 8 TeV, where also the Z+2 jets NLO prediction is included.

Similar trends can be observed in the scalar sum of the jets' p_T. The check of the variation of predictions as a function of the chosen PDF shows that there is no significant dependence of these results on the PDF itself.

At 8 TeV also the leading jet p_T double differential fiducial cross section has been measured [7], studying the spectrum as a function of the jet pseudo rapidity.

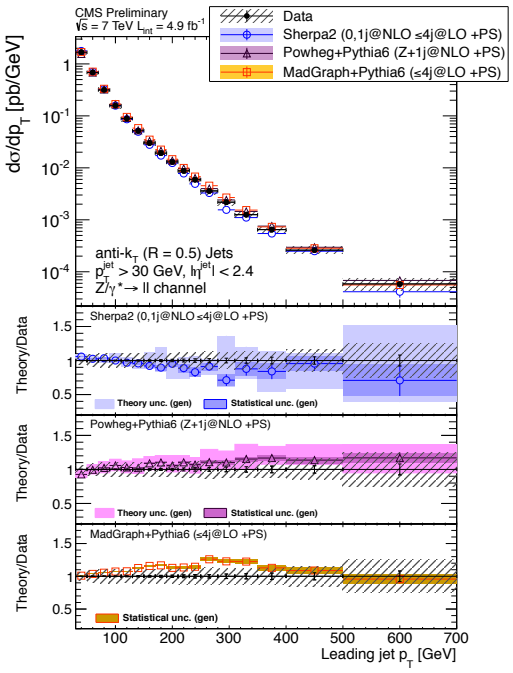

Figure 4: Fiducial cross section as a function of the leading jet p_T for the Z+jets measurement at 7 TeV.

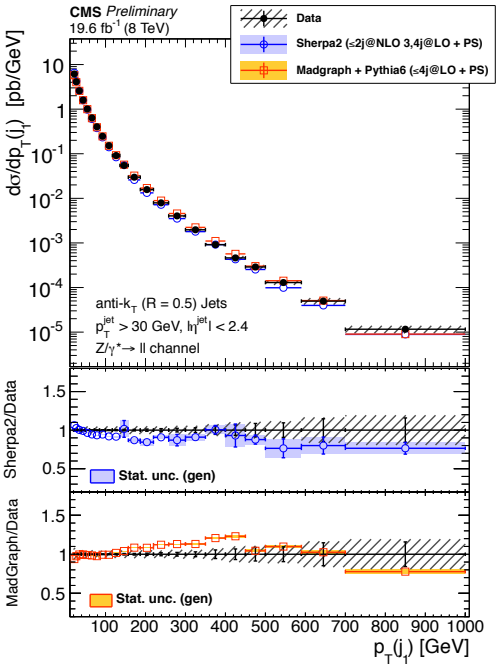

Figure 5: Fiducial cross section as a function of the leading jet p_T for the Z+jets measurement at 8 TeV.

For this measurement, the jet acceptance has been extended up to $|\eta| < 4.7$, raising anyway the p_T threshold for $|\eta| > 2.5$ up to 50 GeV. The result is shown in Fig. 6. It can be observed that Madgraph plus Pythia6 overesti-

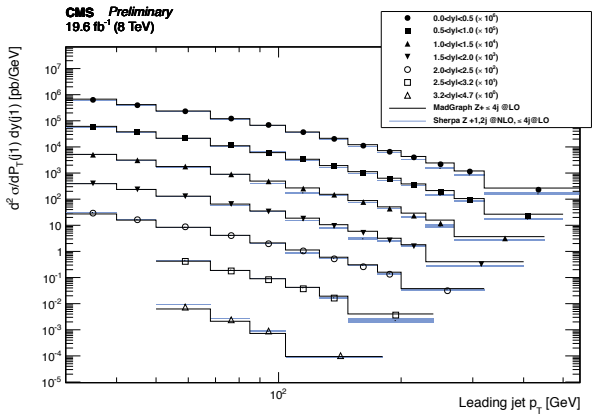

Figure 6: Double differential fiducial cross section as a function of the leading jet p_T and η for the Z+jets measurement at 8 TeV.

mates by at least 10% the cross section above 100 GeV for all pseudorapidities up to 3.2.

These studies complement the measurement of event shapes observables for Z+jets events, performed on 7 TeV data, previously presented in [5]. The fiducial differential cross section as a function of the azimuthal angle between the Z boson and the first, second and third highest p_T jet is measured, as well as a function of the angle between jets and the event thrust. The measurements are performed both for the inclusive Z boson selection, and requiring that $p_T^Z > 150$ GeV, a phase space region of particolar interest for search of physics beyond the standard model with signatures given by jets and missing energy. Z boson decays into neutrinos constitute here a major background source. Comparison with LO and NLO matrix element based event generators show the need for higher order corrections in the matrix element, as can be seen for instance in Fig. 7.

4. Z transverse momentum as a function of jet multiplicity

The study presented in [8] shows results of the Z boson p_T distribution as a function of the jet multiplicity in the event, aiming at a comparison of spectra for the associated production of jet with both Z bosons and photons. The purpose is to explore the phase space relevant for searches of physics beyond the standard model

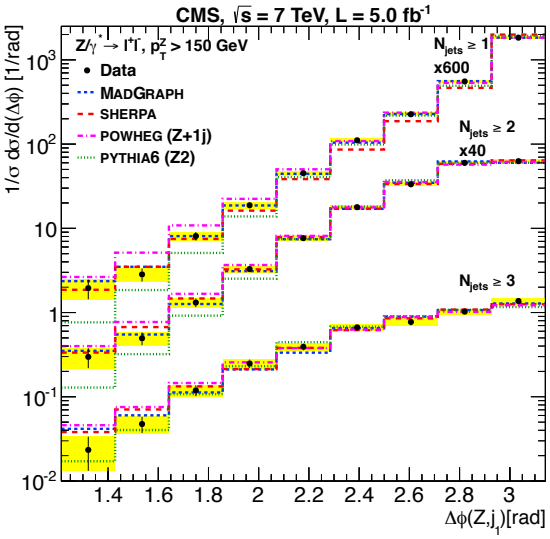

Figure 7: Differential fiducial cross section as a function of the azimuthal angle between the Z boson and the jet for the Z+jets measurement at 7 TeV.

where missing transverse energy and jets are used. The invisible decay of Z bosons is indeed the main background in these searches. The event selection is similar to the one used in [6].

The ratio of fiducial cross sections as a function of the Z boson p_T for events with at least 2 or 1 additional jets is shown in Fig. 8. A turn on of this ratio is ob-

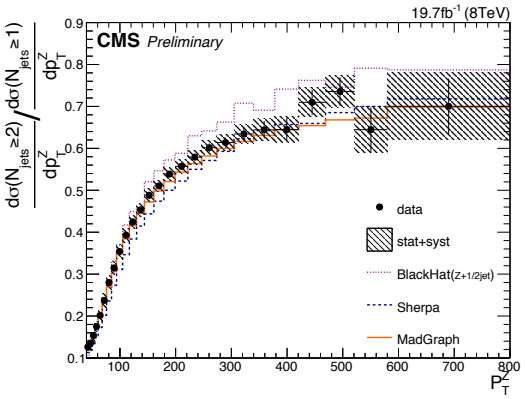

Figure 8: Ratio of fiducial cross sections as a function of the Z boson p_T for events with 2 or 1 additional jets at 8 TeV.

served until a plateau is reached at around 350 GeV. Madgraph plus Pythia6 describes well the data, while Sherpa (at LO) tends to underestimate the relative rate

of 2 jets. This study is particularly interesting as a test of the limitations of NLO predictions, for which BlackHat plus Sherpa is used. This calculation, where for every multiplicity the corresponding fixed order result is used, tends to overestimate the ratio for $p_T^Z > 100$ GeV. The studies of the ratio of the Z boson p_T and of the leading jet one, or of the ratio with the scalar sum of jet p_T, labeled H_T, are also sensitive in their high value regions to the limitations of fixed order calculations, and allow to verify quantitatively where they start to fail. An example of this check is shown in Fig. 9, where the fiducial cross section as a function of the ratio Z boson p_T^Z/H_T for events with at least 2 additional jets is clearly underestimated in the part of the spectrum where higher multiplicities matter more.

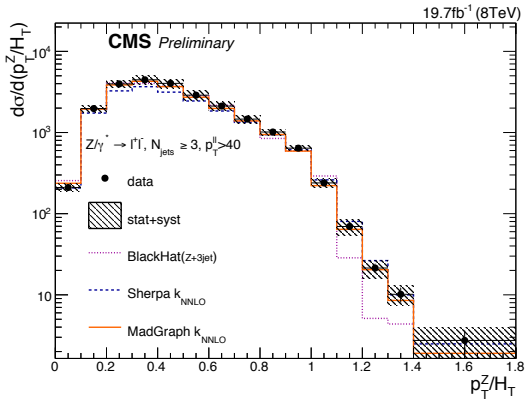

Figure 9: Fiducial cross section as a function of the ratio Z boson p_T^Z/H_T for events with at least 2 additional jets at 8 TeV.

5. W and Z in association with b jets

CMS has presented several measurements, based on data collected at 7 TeV, of the cross section and basic kinematic characteristics of the associated production of W and Z bosons and jets from b quark fragmentation. The selection of bosons from lepton decays is very similar to those already presented, with a narrower mass window [76,106] GeV for Z boson selection. The reconstruction of jets from b fragmentation uses different approaches among the various analyses. In the case of W bosons [2] the Combined Secondary Vertex algorithm is used to identify a pair of jets as coming from b quark fragmentation, where information from the explicit reconstruction of secondary vertices from b hadron decays is combined with the one from the impact parameter of tracks in the jets with respect to the primary vertex. For the study of production of at least one b jet in association with Z bosons [9], a Simple Secondary Vertex algorithm, based on the three-dimensional distance between the reconstructed primary and secondary vertices, has been adopted. The

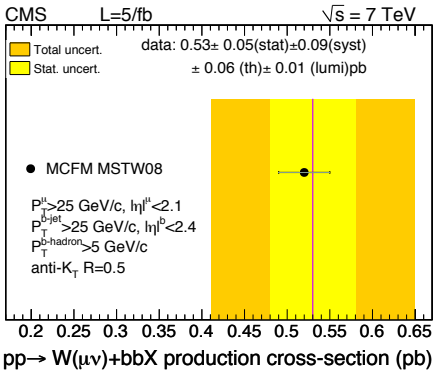

Figure 10: Cross section for the associated production of a W boson and two b jets at 7 TeV.

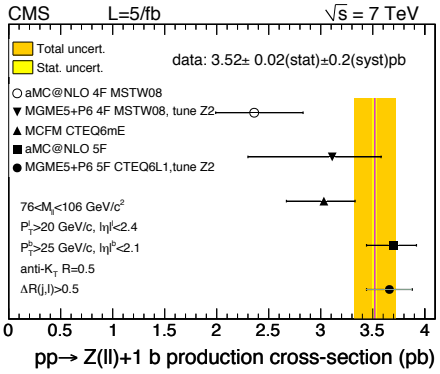

Figure 11: Cross section for the associated production of a Z boson and at least one b jet at 7 TeV.

inclusive W+2b cross section, as can be seen in Fig. 10, shows a good agreement with the NLO theoretical prediction based on MCFM, using the MSTW2008 PDF and corrected for double parton scattering effects. The kinematic distributions of the two b-tagged jets studied show a reasonable agreement between data and the Madgraph plus Pythia6 simulation, where the 5-flavour scheme with massless b quarks is used in the calculation of the hard scattering.

In the case of Z plus at least one b jet, predictions by several theoretical calculations have been compared with the data: among them, the NLO prediction by

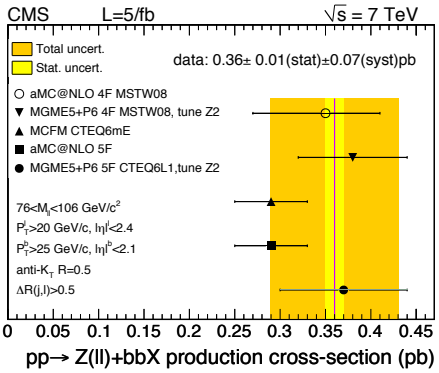

Figure 12: Cross section for the associated production of a Z boson and two b jets at 7 TeV.

aMC@NLO plus Pythia6 has been investigated in both the 5 and 4-flavour scheme, using respectively massless and massive b quarks. The results can be seen in Fig. 11 and 12 for the production of at least one or two b jets respectively. It is worthwhile to notice that while for the inclusive result all the investigated models are compatible with data within the uncertainties, in the case of exactly two b jets the aMC@NLO prediction with the 4-flavour scheme presents a significant difference with respect to data. Also Madgraph plus Pythia6 using the 4-flavour scheme and MCFM using CTEQ6mE underestimate the prediction. This might point towards an important dependence of the predictions from the way the b quark is treated within the PDFs. The kinematic observables involving the b jets are in good agreement with data.

It is anyway important to notice that, when exactly two b jets are required, one of the most interesting parts of the phase space to be studied is the one of close to collinear emission of these jets. Models of physics beyond the standard model like the two Higgs doublet model, producing heavy boosted objects decaying in b quark pairs, populates this region of the phase space, and therefore the Z+2b jets production constitute here a particularly significant background. This study has been made in [10], where no jet is explicitly reconstructed, but the presence of two b hadrons is determined by the Inclusive Vertex Finder algorithm, through the reconstruction of the secondary vertex of their decays. Various kinematic observables characterising the event topology have been studied, like the distance in the $\eta - \phi$ plane between the two b jets, between each of them and the Z boson, and the asymmetry between these latter distances. The result for the angular separation between the two b hadrons ΔR_{BB} is shown in Fig. 13.

Several theoretical predictions are compared with this

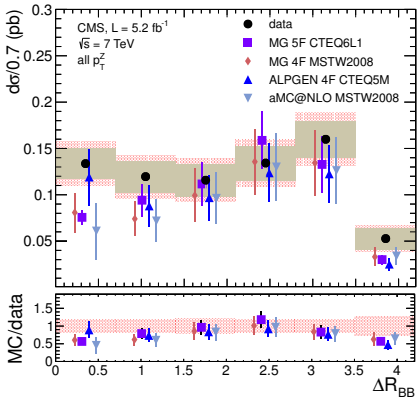

Figure 13: Cross section for the associated production of a Z boson and two b hadrons at 7 TeV as a function of their angular separation ΔR_{BB}.

result: Madgraph plus Pythia6 using both the 5 and 4-flavour scheme, aMC@NLO and Alpgen+Pyhtia6 using the 4-flavour scheme. It can be seen that most of them fail to reproduce the close-to-collinear region where $\Delta R_{BB} \simeq 0$, with the noticeable exception of Alpgen.

6. W and Z in association with a Z decaying in b quarks

The associated production of a vector boson, either W or Z, and b quarks can be mimicked also by diboson processes like WZ and ZZ, where a Z boson decays in b quark pairs. These processes have been studied in the 8 TeV dataset as discussed in [11], and they are a significant background to the associated production of the Higgs boson and a vector boson, when the Higgs boson decays in b quarks (the most abundant decay channel at the 125 GeV mass).

Vector bosons are detected through their leptonic decays in electrons, muons or, for Z, neutrino pairs, corresponding to no isolated charged lepton and transverse missing energy above 100 GeV. This translates into event categories with 0, 1 or 2 identified isolated leptons. Jets from b quarks are identified by the Combined Secondary Vertex algorithm, and the b dijet system is required to have an invariant mass comprised in the [60,120] GeV window. The measurement of the cross section has been performed for vector bosons $p_T^V > 100$ GeV. Results are corrected for acceptance using MCFM and MSTW2008 as PDF, which is used to

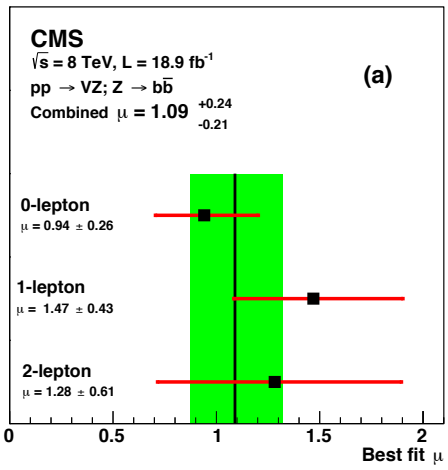

Figure 14: Ratio of the measured cross section and of the corresponding standard model prediction for each channel of the VZ, $b\bar{b}$ final state.

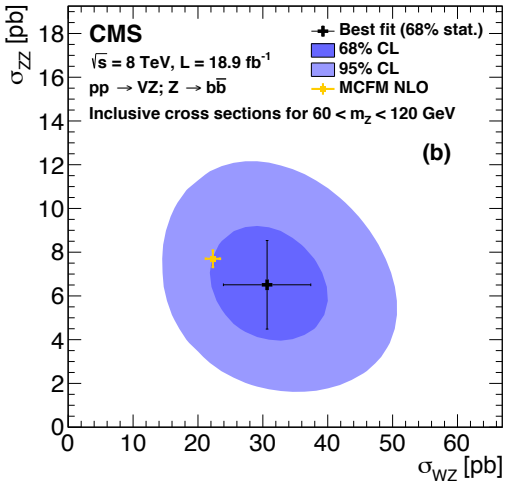

Figure 15: Ratio of the measured cross section and of the corresponding standard model prediction for each channel of the VZ, $b\bar{b}$ final state.

provide the NLO standard model reference. In Fig. 14 the ratio of the measured cross section and of the corresponding standard model prediction for each channel of the VZ, $Z \to b\bar{b}$ final state is shown. All ratios are compatible with one within the uncertainties, showing evidence for production with a combined significance of 6.3 standard deviations. The WZ and the ZZ estimated cross section are presented in Fig. 15, and they appear to be well consistent with the standard model.

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