

Electroweak production of single W and Z bosons in ATLAS and CMS

Marco A. Lisboa Leite*†

University of Sao Paulo, Institute of Physics

E-mail: leite@cern.ch

Results on the production of single Z and W bosons with two jets at high invariant mass at a centre-of-mass energy of 8 TeV are presented using data corresponding to 20.3 fb⁻¹. Integrated and differential cross sections are measured in many different phase space regions with varying degree of sensitivity to the electroweak production in vector boson fusion by both ATLAS and CMS. The results have also been used to derive limits on anomalous triple gauge couplings in the single Z production.

38th International Conference on High Energy Physics 3-10 August 2016 Chicago, USA

^{*}Speaker.

[†]On behalf of ATLAS and CMS collaborations

1. Introduction

The production of a W or Z boson in association with 2 jets (W j j or Z j j) via t-channel exchange of an electroweak gauge boson is a rare pure electroweak process when compared to the copious production of Zjj or Wjj via strong process, which has about 10 times higher production cross section [1]. The electroweak production of gauge bosons associated with two jets encompasses three process: vector boson fusion (VBF), boson bremsstrahlung and non-resonant. While it is not feasible to experimentally disentangle these three processes due to a large interference between them, it is possible to explore the VBF characteristic kinematic topology of two jets separated by a large rapidity gap (with the leptons from the boson decay within the gap) to define a signal region with an enriched contribution from electroweak Zii or Wii. The fusion of electroweak bosons is an important process for measuring particle properties, such as the couplings of the Higgs boson and for searching for new particles beyond the Standard Model [2]. Moreover, the VBF process is of particular interest because of the similarity to the VBF production of a Higgs boson and the sensitivity to anomalous WWZ triple gauge couplings, and can be used to derive limits for some of these couplings in the case of the Zij production. The next sections will present some aspects of these studies performed by ATLAS and CMS Collaborations in proton proton collisions at $\sqrt{s} = 8$ and 13 TeV.

2. Measurements of electroweak production of two jets in association with a Z boson in pp collisions at \sqrt{s} = 8 TeV

Measurements of electroweak production of a single Zjj was performed by the CMS Collaboration [3] in the electron and μ channel in proton-proton collision at $\sqrt{s} = 8$ TeV using data corresponding to an integrated luminosity of 19.7 fb⁻¹ [5]. Signal events are simulated at leading order using the MADGRAPH v5.1.3.30 generator, interfaced to PYTHIA v6.4.26. The QCD background is also modeled with MADGRAPH. The interference contribution between the QCD and electroweak processes is estimated by generating a third MADGRAPH sample taking into account the interference effect. Other backgrounds (single top, $t\bar{t}$ di-bosons and W) are generated using MADGRAPH and POWHEG. Event selection requires two isolated leptons of same flavor and opposite sign and at least two high p_T reconstructed jets. Three analysis strategies (A, B and C) are used combining different phase space selections, Z decay channels and background modeling. A multivariate analysis technique (MVA) is used in all three strategies to provide separation of QCD and electroweak Zjj components. The analysis makes use of boosted decision tree (BDT) discriminators to achieve the best expected separation between the background and signal and in order to improve the estimative of QCD background, alternative models using either a Monte Carlo based or a data driven modeling are explored. Figure 1 presents the BDT output for the 3 analysis, showing a good agreement between the data and predictions.

The measured signal cross section is extracted from the combination of electron and μ channels in strategy A, yielding a value of $\sigma(EW) = 174 \pm 15(\text{stat}) \pm 40(\text{syst})$ fb, compatible with the Standard Model prediction value of $\sigma_{LO}(EW) = 208 \pm 18$ fb. The background-only hypothesis is excluded with a significance greater than 5σ .

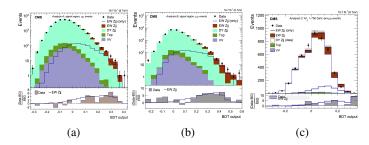


Figure 1: Distribution for the BDT discriminants in the $\mu\mu$ events obtained in the signal region for the analysis A (a), B (b) and for *ee* and $\mu\mu$ events for the analysis C (c), obtained by CMS *Zjj* analysis [5]. The bottom panels of the figures show the differences between the data and the expected electroweak *Zjj* contribution with respect to the background [5].

The ATLAS Collaboration [4] has also performed measurements of electroweak Zij production cross section in the electron and μ channels, using 20.3 fb⁻¹ of proton-proton collision data collected at a centre-of-mass energy of $\sqrt{s} = 8 \text{ TeV}$ [6]. Signal events are simulated using SHERPA v1.4.3 (LO) and POWHEGBOX interfaced to PYTHIA6 (NLO) and backgrounds from single top, $t\bar{t}$ di-bosons and W are modeled by MC@NLO v4.03 and SHERPA v1.4.3. The interference between the QCD and electroweak Zjj production is taken into account as an additional systematic in the extraction of the signal and is estimated using an additional SHERPA sample containing the interference effect. The event selection requires two isolated leptons of same flavor and opposite charge and the presence of two or more reconstructed jets. The ATLAS analysis defines five fiducial regions - each one with a different sensitivity to the electroweak Z_{jj} production - using different kinematic regions for selection of leptons and jets. These regions range from a baseline region (most inclusive) to a search region, defined to optimize the expected significance of the electroweak Zjj signal. An additional region defined to suppress the contribution of electroweak Zjj signal is used as control region. An iterative Bayesian unfolding procedure is applied to the data to produce the particle level distributions, with the response matrices constructed using the SHERPA predictions. Figure 2 presents the unfolded $\frac{1}{\sigma} \frac{d\sigma}{dmjj}$ distribution from baseline and search regions. One can note that in the baseline region, the POWHEG prediction (NLO) provides a better description of the data at high values of mij than SHERPA (LO), while in the search region both generators provide a satisfactory description of the data if both strong and electroweak Z_{jj} productions are considered.

The electroweak Zjj cross section is then extracted using a template fit of mjj in the search region combining electron and μ samples, providing a value of $\sigma(EW) = 54.7 \pm 4.6 (\text{stat})^{+9.8}_{-10.4} (\text{syst}) \pm 1.5 (\text{lumi})$ fb, consistent with the prediction from POWHEG of $\sigma(EW) = 46.1 \pm 0.2 (\text{stat})^{+0.3}_{-0.2} (\text{scale}) \pm 0.8 (\text{PDF}) \pm 0.5 (\text{model})$ fb. Using pseudo experiments, the background-only hypothesis is rejected at greater than 5σ significance.

The ATLAS analysis also derives limits on anomalous triple gauge couplings (aTGC) using a more restricted *search* region, by applying the requirement of mjj > 1TeV, to minimize the effects of background normalization and signal shape in the template fit procedure used to extract the signal yield. Using a unitarization scale of $\Lambda = 6$ TeV, a 95% confidence level intervals for the observed values of aTGC were obtained ($\delta g_{1,Z} = [-0.65, 0.33]$ and $\lambda_Z = [-0.22, 0.19]$), consistent

with the expected intervals from Standard Model (modeled with SHERPA) of $\delta g_{1,Z} = [-0.58, 0.27]$ and $\lambda_Z = [-0.19, 0.16]$.

3. Measurement of production cross sections of a Z boson in association with jets in pp collisions at \sqrt{s} = 13 TeV

As already noted in the previous sections, the good modeling of the OCD background is crucial for the extraction of the electroweak signal from the data. ATLAS measurements of Z boson production associated with jets in the new kinematic regime of $\sqrt{s} = 13$ TeV proton-proton collisions[7] allows a first validation of several Monte Carlo predictions. In this analysis, the signal predictions are based on leading order generators ALPGEN v2.14 interfaced to PYTHIA v 6.426 (with up to five additional partons modeled by the matrix elements) and with MADGRAPH MG5 AMC@NLO v2.2.2 (with up to four additional partons in the matrix elements) interfaced to PYTHIA v8.186, for the modeling of parton shower using the CKKWL merging scheme. An additional sample using MG5 AMC@NLO interfaced to PYTHIA v8.186 was produced (using matrix elements for up to two jets at NLO and with parton showers beyond this) using the FxFx merging scheme. A third

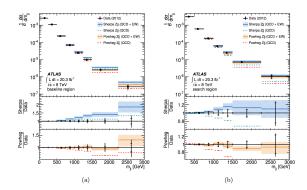


Figure 2: Unfolded $\frac{1}{\sigma} \frac{d\sigma}{dmjj}$ distribution in the (a) *baseline* and (b) *search* regions. The data are shown as filled (black) circles. The vertical error bars show the size of the total uncertainty on the measurement, with tick marks used to reflect the size of the statistical uncertainty only. Particle-level predictions from SHERPA and POWHEG are shown for combined strong and electroweak Zjj production (labelled as QCD+EW) by hatched bands, denoting the model uncertainty, around the central prediction, which is shown as a solid line. The predictions from SHERPA and POWHEG for strong Zjj production (labelled QCD) are shown as dashed lines [6].

simulation sample using SHERPA 2.1 generator (with matrix elements calculated for up to two additional partons at NLO and up to four partons at leading order) was produced using the COMIX and OPENLOOPS matrix element generators and merged with the SHERPA parton shower using the ME+PS@NLO prescription. Finally, parton-level fixed-order predictions at NLO are calculated by the BLACKHAT+SHERPA collaboration for the production of Z bosons with up to four jets. The background from top quark, W and di-boson production was also inferred from Monte Carlo generators as described in [7], while the multi-jet contribution was estimated using a data-driven technique.

Data corresponding to an integrated luminosity of 3.16 fb⁻¹ allows the comparison between the inclusive and differential cross sections of a Z boson produced in association with up to seven jets the electron and μ channels. The events are selected to contain two isolated and opposite sign leptons of same flavor in the presence of reconstructed jet hadrons. The measurements are unfolded to particle level, with the response matrices constructed using the ALPGEN+PYTHIA6 predictions. Figure 3 presents the measured differential cross sections $d\sigma/d\Delta\phi_{jj}$ and $d\sigma/dm_{jj}$. These distri-

butions, relevant for future studies involving the QCD background modeling in single boson electroweak production at $\sqrt{s} = 13$ TeV, indicates that both SHERPA and ALPGEN provides the best description for these kinematic distributions.

4. Measurements of electroweak production of two jets in association with a W boson in pp collisions at \sqrt{s} = 8 TeV

The study of the electroweak Wjj was performed by CMS collaboration in the electron and μ channel using a dataset corresponding to approximately 19.2 fb⁻¹[8]. Signal samples are calculated at leading order using MAD-GRAPH5_AMC@NLO 2.1, while the QCD background is calculated by MADGRAPH5 and normalized to NNLO prediction from FEWZ 3.1. In order to estimate the effect of interference, a separate simulation sample is produced including the interference effect. The difference between this sample and the individual QCD and electroweak signal samples is then accounted as an additional background.

Events containing one isolated lepton, two jets and $E_{\rm T}^{\rm miss}$ are selected for the analysis after being reconstructed using a particle-flow (PF) technique

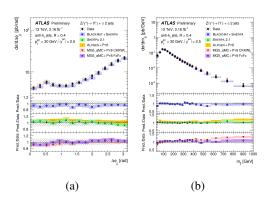


Figure 3: Measured differential cross section $d\sigma/d\Delta\phi_{jj}$ (a) and $d\sigma/dm_{jj}$ (b) for inclusive $Z+\geq 2$ jets events. The data are compared to the predictions from BlackHat+Sherpa, Sherpa 2.1, Alpgen+Py6, MG5_aMC+Py8 CKKWL, and MG5_aMC+Py8 FxFx. The error bars correspond to the statistical uncertainty, and the hatched bands to the data statistical and systematic uncertainties (including luminosity) added in quadrature [7].

[9]. A boosted decision tree (BDT) method is then deployed to distinguish between signal and background events. After this selection, the dijet invariant mass distribution of signal and each background component is parametrized by a two parameter power-law function and fitted using an unbinned maximum-likelihood to extract the signal yield, as presented in Figure 4.

The signal yield obtained from the fit is used to estimate the fiducial cross section for the electroweak production of Wjj, resulting in $\sigma(EW) = 0.42 \pm 0.04 (\mathrm{stat}) \pm 0.09 (\mathrm{syst}) \pm 0.01 (\mathrm{lumi})$ pb for the combination of electron and μ channels, and is consistent with the predict value of $\sigma(EW) = 0.50 \pm 0.02 (\mathrm{scale}) \pm 0.02 (\mathrm{PDF})$ pb, with a statistical significance of approximately 4σ . The main systematics for this measurement arises from the interference effect estimate and from the QCD W+jets shape and normalization in the fit.

5. Conclusions

The results presented by ATLAS and CMS on the single electroweak boson production at proton-proton collision at $\sqrt{s} = 8$ TeV are consistent with the Standard Model expectations, allowing to reject the background only hypothesis using several search and control regions with a

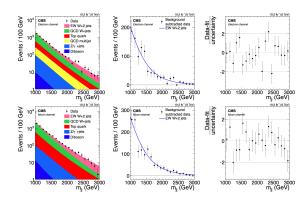


Figure 4: Distribution of the two-jet invariant mass (m_{jj}) for electron (upper) and μ (lower) channels. Fitted projections of signal and background processes are plotted as shaded regions (left plots). The m_{jj} distributions are shown after subtraction of all components except the EW W+2-jets process (center plots). Finally, the (data – fit)/uncertainty distributions are shown (right plots). Here the error bars represent the statistical uncertainties of the data [8].

statistical significance of 5σ (4σ) for the Zjj (Wjj) channel. The ATLAS Zjj analysis also performed a complimentary test of aTGC using a high purity sample ($m_{jj} > 1$ TeV) and the coupling parameters are consistent with Standard Model prediction within a 95% confidence level.

References

- [1] D. L. Rainwater, R. Szalapski, and D. Zeppenfeld, "Probing color singlet exchange in Z + 2 jet events at the CERN LHC", Phys. Rev. D 54 (1996) 6680, doi:10.1103/PhysRevD.54.6680, arXiv:hep-ph/9605444.
- [2] A. G. Delannoy et al., "Probing Dark Matter at the LHC using Vector Boson Fusion Processes", Phys. Rev. Lett. 111 (2013) 061801, arXiv: 1304.7779 [hep-ph].
- [3] CMS Collaboration, "The CMS experiment at the CERN LHC", JINST 3 (2008) S08004, doi:10.1088/1748-0221/3/08/S08004
- [4] ATLAS collaboration, "The ATLAS experiment at the CERN Large Hadron Collider", 2008 JINST 3 S08003.
- [5] CMS Collaboration, "Measurement of electroweak production of two jets in association with a Z boson in proton-proton collisions at $\sqrt{s} = 8$ TeV", Eur. Phys. J. C 75 (2015) 66, doi:10.1140/epjc/s10052-014-3232-5, arXiv:1410.3153.
- [6] ATLAS Collaboration, "Measurement of the electroweak production of dijets in association with a Z boson and distributions sensitive to vector boson fusion in proton-proton collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector", JHEP 04 (2014) 031, doi:10.1007/JHEP04(2014)031, arXiv:1401.7610.
- [7] ATLAS Collaboration, "Measurements of the Production Cross Section of a Z Boson in Association with Jets in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector", ATLAS-CONF-2016-046, https://cds.cern.ch/record/2206128
- [8] CMS Collaboration, "Measurement of electroweak production of a W boson and two forward jets in proton-proton collisions at $\sqrt{s} = 8$ TeV", CMS-SMP-13-012, arXiv:1607.06975v1
- [9] CMS Collaboration, "Particle-flow event reconstruction in CMS and performance for jets, taus, and E_T^{miss} ", CMS Physics Analysis Summary CMS-PAS-PFT-09-001, 2009.