1. Ratio of the Z to gamma transverse momentum differential cross-section [1, 2]

The ratio of the associated production of a Z/γ^* or a γ with one or more jets has been recently measured in proton-proton collisions at 8 TeV center-of-mass energy by the CMS Collaboration at the CERN LHC [1]. In the limit of high transverse momentum of the vector boson p_T^V ($V = Z, \gamma$) and at leading order (LO) in perturbative quantum chromodynamics (QCD), effects due to the mass of the Z boson (m_{Z}) are small, and the cross section ratio of Z+jets to γ+jets as a function of p_T^V is expected to become constant, reaching a plateau for $p_T^V \geq 300$ GeV [2]. (Hereafter, production of Z/γ^* + jets is denoted by Z+jets.) A QCD calculation at next-to-leading order (NLO) for pp$\rightarrow$Z+jets and pp$\rightarrow$ γ+jets was provided by the BLACKHAT Collaboration [3]. The NLO QCD corrections tend to decrease the value of the cross section ratio. At higher energies, electroweak (EW) corrections can also introduce a dependence of the cross section on logarithmic terms of the form $\ln(p_T^{\mathrm{Z}}/m_{\mathrm{Z}})$ that become large and pose a challenge for perturbative calculations.

Searches for new particles involving final states characterized by the presence of large missing transverse energy and hard jets, use the γ+jets process to model the invisible Z decays, Z$\rightarrow \nu\bar{\nu}$, since the γ+jets cross section is larger than the Z+jets process where the Z decays to leptons. A precise estimate of EW corrections on the cross section ratio for Z+jets and γ+jets is therefore crucial to reduce uncertainties related to the Z$\rightarrow \nu\bar{\nu}$ background estimation in these searches.

In the CMS measurement [1], results are unfolded into a fiducial region defined at particle level. For Z+jets events, the leading leptons are required to have $p_T > 20$ GeV and $|\eta| < 2.4$, while jets are required to have $p_T > 30$ GeV within the region of $|\eta| < 2.4$. Electrons and muons have different energy losses due to final state radiation at particle level. In order to compensate for these differences, a "dressed" level is defined to make the electron and muon channels compatible to within 1%. This is achieved by defining in simulation a particle momentum vector by adding the momentum of the stable lepton and the momenta of all photons with a radius of $\Delta R = 0.1$ around the stable lepton. All jets are required to be separated from each lepton by $\Delta R > 0.5$. At the particle level, a true isolated photon is defined as a prompt photon, around which the scalar sum of the p_T of all stable particles in a cone of radius $\Delta R = 0.4$ is less than 5 GeV. A true isolated photon is defined as a prompt photon (not generated by a hadron decay), around which the scalar sum of the p_T of all stable particles in a cone of radius $\Delta R = 0.4$ is less than 5 GeV. When comparing the cross sections for Z+jets and γ+jets, the rapidity range of the bosons is restricted to $|y^V| < 1.4$ because this is the selected kinematic region for the photons. The ratio of the differential cross sections as a function of p_T is measured in the phase space regions: $N_{\mathrm{jets}} \geq 1$, 2, 3, and $H_T > 300$ GeV, $N_{\mathrm{jets}} \geq 1$.

Figure (1) compares several predictions for the ratio within the fiducial regions as defined above [3]. The fixed order partonic predictions computed with the ALPGEN generator are shown at LO and at approximated NLO accuracy [4], *i.e.* including the effect of virtual weak corrections in the Sudakov approximation obtained by means of the algorithm of Refs. [5, 6], as described in the previous paragraphs. The predictions for $Z+$ jets and $\gamma+$ jets are computed in the G_μ and α_0 schemes, respectively, with the set of parameters listed above for the calculation of the $\mathcal{O}(\alpha)$ corrections to the process $W + 2$ jets. The factorization scale is set to $\sum_j p_T^j + \sqrt{M^2(V) + p_T^2(V)}$. CTEQ5L is used as PDF set: it is worth noticing, however, that PDFs largely cancel in the Z/γ ratio as pointed out in Ref. [7]. More precisely, the predictions for $\gamma+$ jets and $Z+$ jets are computed by using the `phjet` and `zjet` packages, respectively: at variance with the `vbjet` package, where the external vector bosons are produced on-shell, in `zjet` the Z boson decays in a fermion-antifermion pair including all the off-shell and spin correlation effects. These packages include only the QCD contributions of order $\alpha_S^{n\,\mathrm{jets}}\alpha$ to the LO predictions. Though the

[1] Section coordinator:V. Ciulli

[2] Contributing authors: M. Chiesa, J. Lindert, A. Marini, G. Montagna, M. Moretti, O. Nicrosini, F. Piccinini, E. Takasugi, M. A. Weber

[3] We dropped the comparison for $H_T > 300$ GeV because fixed order predictions are known to fail describing high jet activity with a comparatively low vector boson p_T.

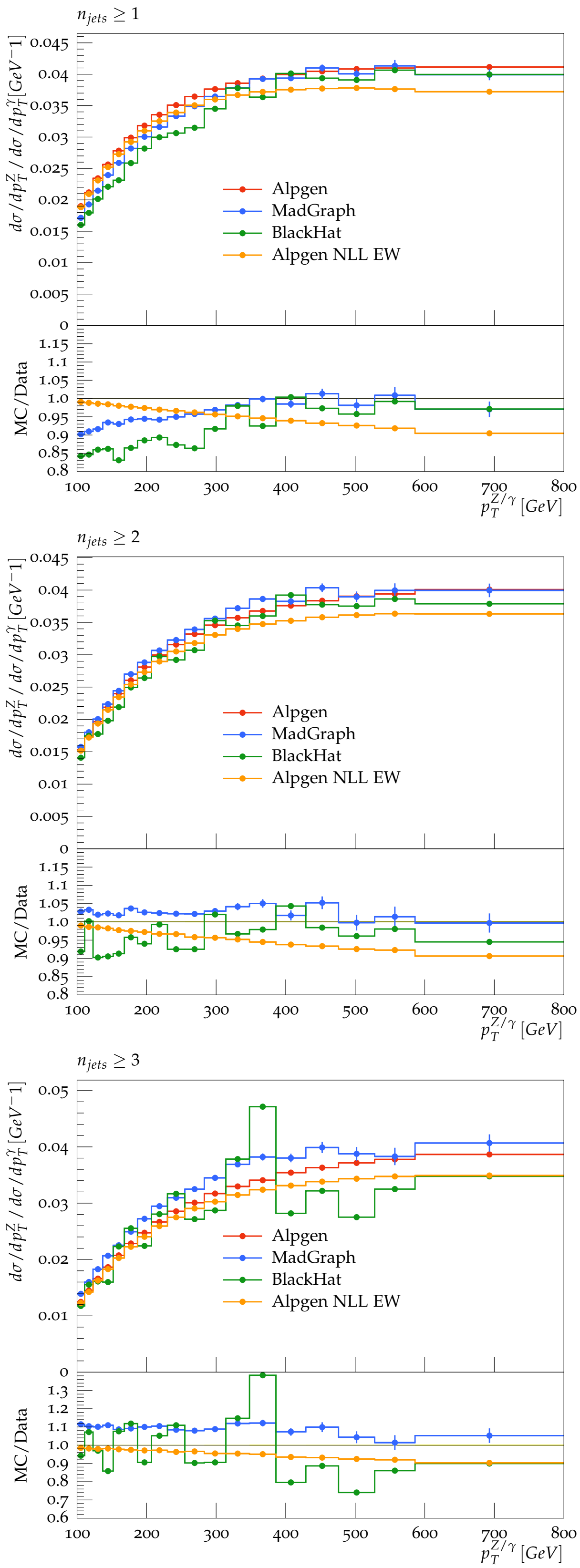

Fig. 1: Comparison of different predictions for the ratio of Z+jets over γ + jets at 8 TeV pp center-of-mass energy. From top to bottom, results are shown for events with at least 1, 2 and 3 jets accompaning the boson. For fixed order predictions this value corresponds to the number of partons in the final state at the lowest order.

LO results for $Z+$ jets include exactly off-shell and spin correlation effects, the Sudakov corrections are obtained in the on-shell approximation by using the phase space mapping described in Ref. [8].

The other predictions are also shown in the CMS paper, where a detailed description of the configuration used can be found. For Z+jets and γ+jets generated with the MADGRAPH5 [9] program, the leading-order multiparton matrix element calculation includes up to four partons in the final state. The showering and hadronization, as well as the underlying event, are modeled by PYTHIA6 [10]. The events are generated with the CTEQ6L1 [11] parton distribution functions and the ktMLM matching scheme [12] with a matching parameter of 20 GeV is applied. In addition to these Monte Carlo signal data sets, a NLO perturbative QCD calculation from the BLACKHAT Collaboration [3] is available for a boson accompanied by up to three jets. These calculations use MSTW2008nlo68cl [13] with $\alpha_S = 0.119$ as the PDF set, and the renormalization and factorization scales are set to $\mu_R = \mu_F = H_T + E_T^{\mathrm{V}}$, where H_T is the scalar p_T sum of all outgoing partons with $p_T > 20$ GeV and E_T^{V} is defined as $\sqrt{m_{\mathrm{Z}}^2 + (p_T^{\mathrm{Z}})^2}$ and p_T^{γ}, respectively, for Z+jets and γ+jets. In addition, the photons must satisfy the Frixione cone isolation condition [14].

From the plot it is clear that both NLO QCD and EWK corrections are negative with respect to the fixed order LO predictions. The NLO QCD corrections are larger for lower transverse momentum of the bosons, reaching a 15% effect for $N_{\mathrm{jets}} \geq 1$. A fraction of this effect seems to be included by MADGRAPH predictions, which include higher order real parton emissions in the matrix-element calculation. The EWK corrections increase with the boson transverse momentum, up to about 10% for $p_T > 600$ GeV in events with at least one jet. Both QCD and EWK corrections decrease for larger jet multiplicities. It can be also noticed that MADGRAPH prediction overshoot the NLO QCD ones for larger multiplicities.

In Figure (2), these predictions are compared to CMS results, showing that the agreement improves when NLO corrections are included, both in the case of QCD and EWK ones. In particular, including the EWK corrections, results are in better agreement in the high boson transverse momentum region, especially for larger jet multiplicities.

In addition Figure 3 shows, for events with a vector boson and at least one jet, fixed-order predictions from Sherpa+OpenLoops. The Z+jets prediction is obtained from an off-shell calculation for $\ell^+\ell^-$+jets including all Z/γ^* interference effects. The presented predictions are based on the recently achieved automation of NLO QCD+EW calculations [15, 16], as described in Section **??**. Related predictions for the Z+jets/γ+jets ratio (with an on-shell Z boson) from Munich+OpenLoops have already been presented in [17] and have for example been employed for background predictions in [18]. Here, we employ NNPDF2.3QED [19] parton distributions with $\alpha_S = 0.118$ and all input parameters and scale choices are as detailed in [16]. In particular, all unstable particles are treated in the complex-mass scheme [20] and renormalisation and factorisation scales are set to $\mu_{R,F} = \hat{H}_{\mathrm{T}}'/2$, where $\hat{H}_{\mathrm{T}}'$ is the scalar sum of the transverse energy of all parton-level final-state objects, $\hat{H}_{\mathrm{T}}' = \sum_{i\in\{\mathrm{quarks,gluons}\}} p_{\mathrm{T},i} + p_{\mathrm{T},\gamma} + E_{\mathrm{T},V}$. QCD partons and photons that are radiated at NLO are included in $\hat{H}_{\mathrm{T}}'$, and the vector-boson transverse energy, $E_{\mathrm{T},V}$, is computed using the total (off-shell) four-momentum of the corresponding (dressed) decay products, i.e. $E_{\mathrm{T},Z}^2 = p_{\mathrm{T},\ell\ell}^2 + m_{\ell\ell}^2$ and $E_{\mathrm{T},\gamma}^2 = p_{\mathrm{T},\gamma}^2$. The weak coupling constant α is renormalized in the G_μ scheme for the $\ell^+\ell^-$+jets prediction, while the $\alpha(0)$-scheme is used for the γ+jets prediction. Results are presented at the NLO QCD level and combining QCD and EW corrections via an additive prescription, i.e. $\sigma^{\mathrm{NLO}}_{\mathrm{QCD+EW}} = \sigma^{\mathrm{LO}} + \delta\sigma^{\mathrm{NLO}}_{\mathrm{QCD}} + \delta\sigma^{\mathrm{NLO}}_{\mathrm{EW}}$. Isolated photons in the γ+jets predictions are required to satisfy Frixione cone isolation [14] with parameters as specified in [1].

The agreement of the combined NLO QCD+EW prediction with the CMS data is remarkable over the whole spectrum. As already noted, at low transverse momentum NLO QCD corrections to the ratio are relevant due to mass effects, but sizable EW corrections due to EW Sudakov logarithms (of different size for the two processes) alter the shape of the ratio prediction already much below 1 TeV. These results show the importance of combining NLO QCD and EW corrections in a unified framework.

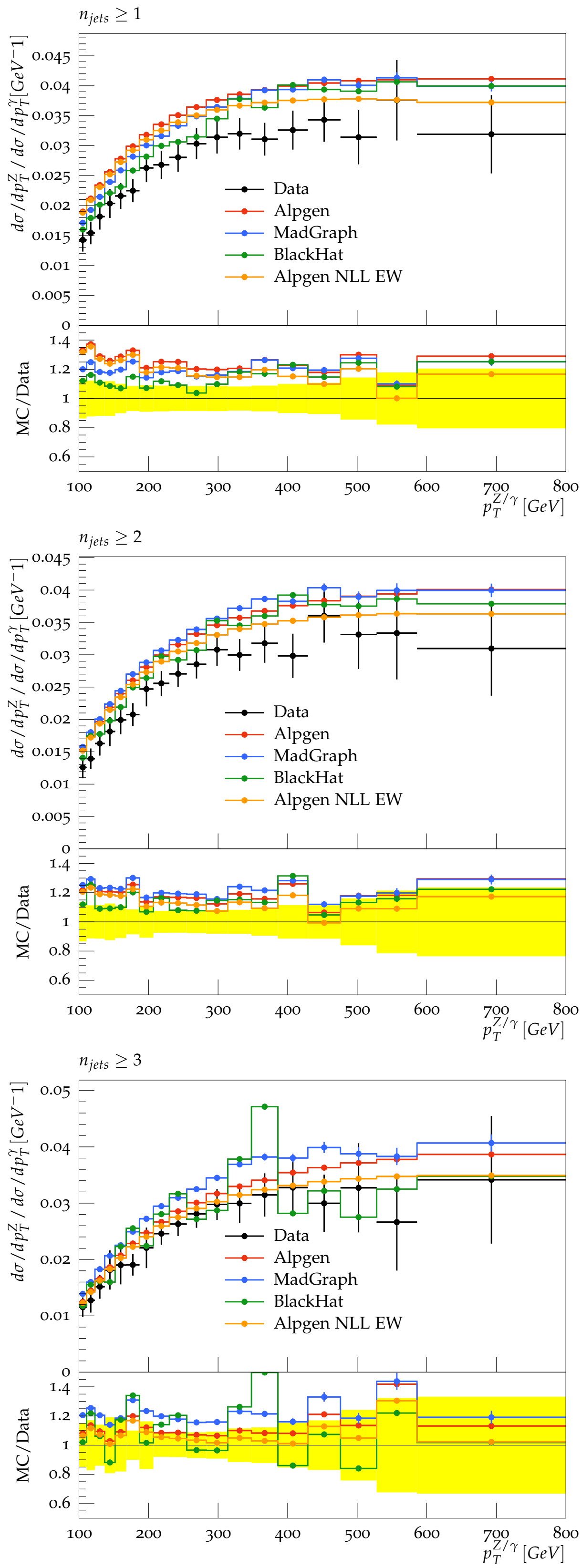

Fig. 2: Comparison to CMS data of different predictions for the ratio of Z+jets over γ + jets at 8 TeV pp center-of-mass energy. From top to bottom, results are shown for events with at least 1, 2 and 3 jets accompaning the boson. For fixed order predictions this value corresponds to the number of partons in the final state at the lowest order.

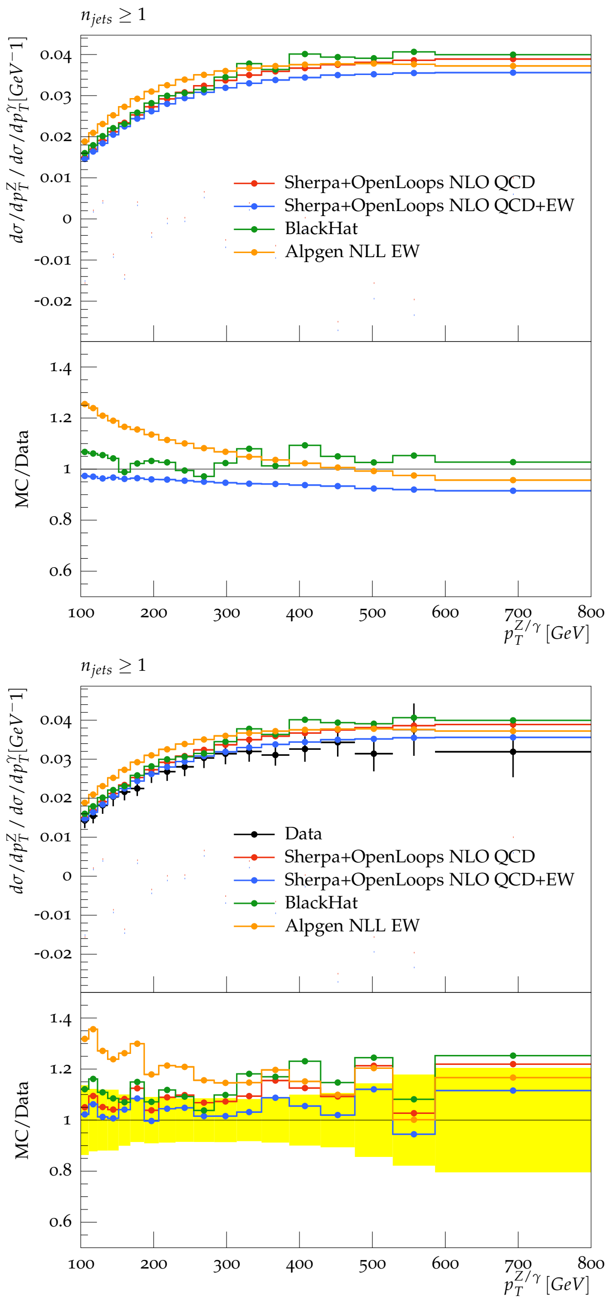

Fig. 3: Comparison of different predictions at NLO QCD, NLL EW and NLO QCD+EW order for the ratio of Z + jets over γ + jets at 8 TeV pp center-of-mass energy, in events with at least 1 jet accompaning the boson. For fixed order predictions this value corresponds to the number of partons in the final state at the lowest order. Top plot shows a comparison among the predictions. The bottom plot shows a comparison to CMS data.

References

[1] V. Khachatryan *et. al.*,, **CMS** Collaboration *JHEP* **10** (2015) 128, [1505.06520].

[2] S. Ask, M. A. Parker, T. Sandoval, M. E. Shea, and W. J. Stirling, *J. High Energy Phys.* **10** (2011) 058, [1107.2803].

[3] Z. Bern, G. Diana, L. J. Dixon, F. Febres Cordero, S. Höche, H. Ita, D. A. Kosower, D. Maître, and K. J. Ozeren, *Phys. Rev. D* **87** (2013) 034026, [1206.6064].

[4] M. Chiesa, G. Montagna, L. Barze, M. Moretti, O. Nicrosini, *et. al.*, *Phys.Rev.Lett.* **111** (2013), no. 12 121801, [1305.6837].

[5] A. Denner and S. Pozzorini, *Eur. Phys. J.* **C18** (2001) 461–480, [hep-ph/0010201].

[6] A. Denner and S. Pozzorini, *Eur. Phys. J.* **C21** (2001) 63–79, [hep-ph/0104127].

[7] S. Ask, M. A. Parker, T. Sandoval, M. E. Shea, and W. J. Stirling, *JHEP* **10** (2011) 058, [1107.2803].

[8] A. Denner, L. Hofer, A. Scharf, and S. Uccirati, *JHEP* **01** (2015) 094, [1411.0916].

[9] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and T. Stelzer, *J. High Energy Phys.* **06** (2011) 128, [1106.0522].

[10] T. Sjöstrand, S. Mrenna, and P. Skands, *J. High Energy Phys.* **05** (2006) 026, [hep-ph/0603175].

[11] J. Pumplin, D. R. Stump, J. Huston, H.-L. Lai, P. Nadolsky, and W.-K. Tung, *J. High Energy Phys.* **07** (2002) 012, [hep-ph/0201195].

[12] J. Alwall, S. Höche, F. Krauss, N. Lavesson, L. Lönnblad, F. Maltoni, M. L. Mangano, M. Moretti, C. G. Papadopoulos, F. Piccinini, S. Schumann, M. Treccani, J. Winter, and M. Worek, *Eur. Phys. J. C* **53** (2008) 473, [0706.2569].

[13] A. D. Martin, W. J. Stirling, R. S. Thorne, and G. Watt, *Eur. Phys. J. C* **63** (2009) 189, [0901.0002].

[14] S. Frixione, *Phys. Lett. B* **429** (1998) 369, [hep-ph/9801442].

[15] S. Kallweit, J. M. Lindert, P. Maierhfer, S. Pozzorini, and M. Schnherr, *JHEP* **04** (2015) 012, [1412.5157].

[16] S. Kallweit, J. M. Lindert, P. Maierhofer, S. Pozzorini, and M. Schnherr, 1511.08692.

[17] S. Kallweit, J. M. Lindert, S. Pozzorini, M. Schnherr, and P. Maierhfer, in *Proceedings, 50th Rencontres de Moriond, QCD and high energy interactions*, pp. 121–124, 2015. 1505.05704.

[18] C. Collaboration,, **CMS** Collaboration.

[19] R. D. Ball, V. Bertone, S. Carrazza, L. Del Debbio, S. Forte, A. Guffanti, N. P. Hartland, and J. Rojo,, **NNPDF** Collaboration *Nucl. Phys.* **B877** (2013) 290–320, [1308.0598].

[20] A. Denner, S. Dittmaier, M. Roth, and L. H. Wieders, *Nucl. Phys.* **B724** (2005) 247–294, [hep-ph/0505042]. [Erratum: Nucl. Phys.B854,504(2012)].