# $W$, $Z$ and photon production at the LHC

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Recent results on $W$, $Z$ and photon production at the Large Hadron Collider are presented. Inclusive $W$ and $Z/\gamma^*$ production, their production in association with jets and heavy flavors, and prompt photon, $\gamma\gamma$ and $\gamma$+jets production are discussed.

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# 1 Introduction

During the LHC Run 1 data-taking, both ATLAS and CMS experiments collected $pp$ collision data corresponding to approximately 5 fb$^{-1}$ at $\sqrt{s} = 7$ TeV (up to 2011) and 20 fb$^{-1}$ at $\sqrt{s} = 8$ TeV (in 2012). Among the various studies of Standard Model (SM) processes, $W$, $Z$ and $\gamma$ productions are particularly interesting since they involve electoweak probes in $pp$ interaction which is dominated by the strong interaction. They give clean experimental signatures with leptonic decay modes (including a neutrino inferred by missing transverse energy, $E_{\mathrm{T}}^{\mathrm{miss}}$) and serve as benchmarks of SM validation at the highest energy. The large masses of $W$ and $Z$ assure the existence of a hard scale that justifies the predictions based on perturbative QCD (pQCD). The measurements span to extreme kinematics (transverse momentum $p_{\mathrm{T}}$ up to $\approx 1$ TeV) or topologies (like number of jets) and they allow tuning of tools for SM predictions, such as Next-to-Leading Order (NLO) calculations and Monte Carlo (MC) event generators. All these validations are crucial in the searches for beyond-SM physics, the signal of which often involves $W/Z/\gamma$ (and many jets/$E_{\mathrm{T}}^{\mathrm{miss}}$).

# 2 Inclusive $W$, $Z/\gamma^*$ production

CMS made a measurement of inclusive $W$ and $Z$ production at 8 TeV using a special data set corresponding to 18.2 pb$^{-1}$ with low pile-up (multiple $pp$ collisions occurring in the same bunch crossing) [1]. The ratio of the inclusive cross sections is found to be $R_{W/Z} = 10.63 \pm 0.11$ (stat.)$\pm 0.25$ (syst.), while the SM prediction is $10.74 \pm 0.04$ using the FEWZ [2] NNLO (Next-to-NLO) calculation with the MSTW2008 [3] Parton Distribution Function (PDF). The ratio of $W^+$ and $W^-$ cross sections is found to be $R_{W^+/W^-} = 1.39 \pm 0.01$ (stat.) $\pm 0.02$ (syst.) to be compared with the prediction $1.41 \pm 0.01$. Both measurements agree well with SM.

The LHCb experiment also measured $W$ production using its detector that has an acceptance in the forward region (pseudorapidity of the muon $2 < \eta(\mu) < 5$, where $\eta = \ln\tan(\theta/2)$ with $\theta$ being the polar angle with respect to the beam direction) [4]. This measurement nicely extends the ATLAS/CMS measurements in the central pseudorapidity region and is sensitive to PDF predictions.

In the Drell-Yan process, $q\bar{q}$ annihilate to $\gamma^*/Z$ (they have the same quantum numbers and thus interfere) and convert/decay to $e^+e^-$ or $\mu^+\mu^-$. CMS measured the 8 TeV cross section in a wide mass range (see Fig. 1) and also the double-differential cross sections in mass and lepton-pair rapidity [5]. ATLAS has performed Drell-Yan measurements in the low mass region, also including the 2010 data set in which the energy thresholds for leptons were as low as 6 and 9 GeV. In the lowest invariant-mass bin, the measurement agrees better with the prediction from NNLO calculation than that from NLO (see Fig. 2) [6].
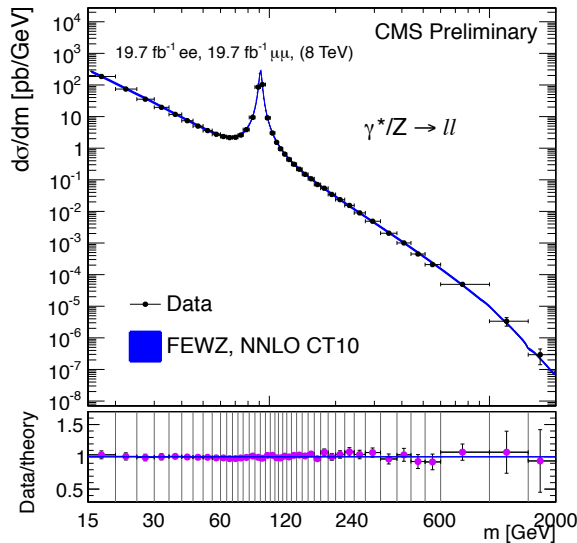
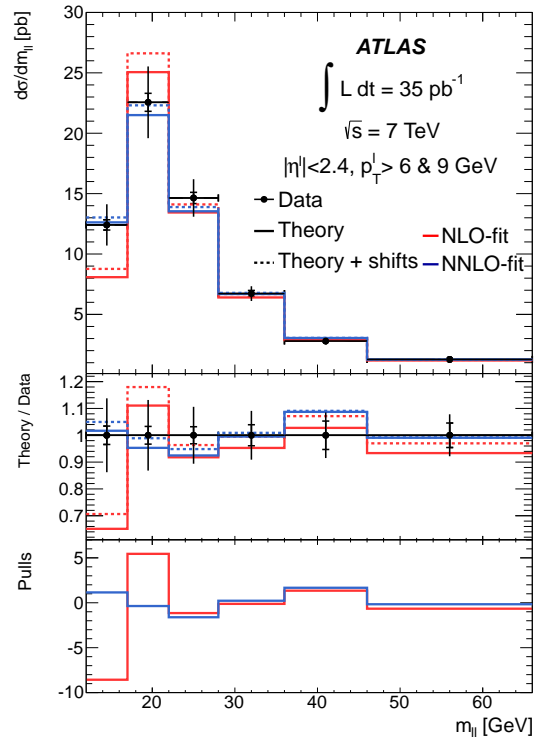Figure 1: Drell-Yan differential cross section as a function of the di-lepton mass [5].

Figure 2: Low-mass Drell-Yan cross section compared to NLO and NNLO predictions [6].

In the $Z$ production, the $p_T$ and rapidity distributions were measured by CMS [7] using the 8 TeV data. In the large $p_T$ region of $Z$ boson, the data show a softer distribution than the prediction. ATLAS used the measurements in the low $p_T$ region ($< 26$ GeV) to tune the MC generators (PYTHIA8 [8] and POWHEG [9]+PYTHIA8) with respect to the parton shower parameters [10]. The tuned MC prediction agrees with the measurement up to 50 GeV better than 2%.

Although the leptonic decays are usually used to reconstruct $Z$ bosons, one can also see them in hadronic decay mode, despite the large QCD multijet background. ATLAS used $b$-tag to suppress background and measured the $Z \to b\bar{b}$ signal in the region of di-jet $p_T > 200$ GeV [11]. ATLAS also analyzed the jet substructure and obtained the signal of $W/Z$ decay to $q\bar{q}$ in the distribution of the jet mass (see Fig. 3) [12]. Boosted $W/Z$ will be important in searches for heavy particles.

The $Z \to 4\ell$ peak was already seen in the Higgs observation papers [13]. It is a rare SM process, and ATLAS measured its branching ratio with large statistics collected in 2011 and 2012 [14]. A clear signal is seen (see Fig. 4) and the measured branching ratio of $(3.20 \pm 0.25 \,(\text{stat.}) \pm 0.13 \,(\text{syst.})) \times 10^{-6}$ agrees with the SM prediction of $3.33 \times 10^{-6}$. An earlier measurement by CMS from 7 TeV data is found here [15].
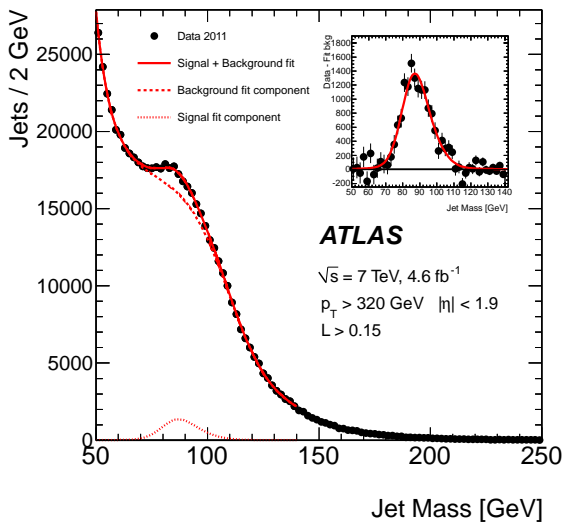
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Figure 3: Jet mass distribution for selected $W/Z$ jets overlaid with the fit result [12].
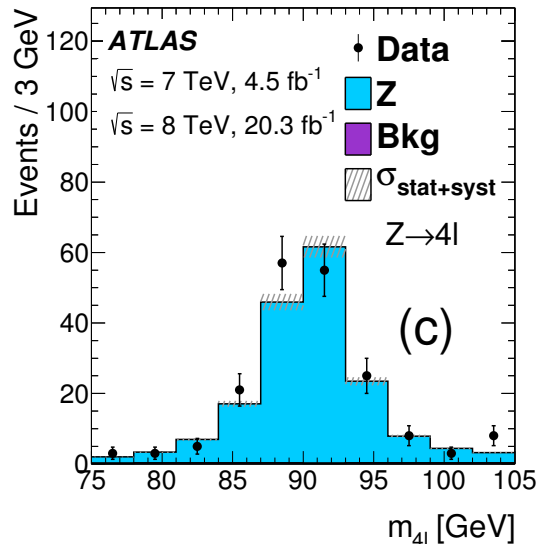


Figure 4: Four-lepton invariant mass for the $Z \to 4\ell$ candidates [14].

# 3    $W$+jets, $Z$+jets production

Figure 5 shows the distribution of inclusive number of jets produced in association with $Z$ boson, measured by CMS from 8 TeV data [16]. The measurement extends to events with seven and more jets. The differential cross sections are obtained as functions of variables such as $p_T$ and $\eta$ of the jets, individually for jet multiplicities up to five. Also double-differential cross sections are obtained in $p_T$ and rapidity of the jets [17]. Generally the NLO calculation using Sherpa2 [18] describes the data better than the Leadng-Order (LO) prediction from MadGraph [19]. There is also an ATLAS measurement from 7 TeV [20] and a LHCb measurement with forward di-muons and jets [21].

Measurements of $W$ production in association with jets are made by both AT-LAS [22] and CMS [23] with 7 TeV data. NLO BlackHat [24]+Sherpa [18] does a good job in describing most distributions, but it is a fixed-order calculation and thus higher jet multiplicities are missing. Discrepancies with data are seen in distributions that are sensitive to this feature, for example in the $E_T$ sum of all jets. This is improved in Sherpa2, as confirmed in the $Z$+jets analysis above. Discrepancies are also observed in variables such as di-jet mass and azimuthal difference between the jet and the muon from $W$. The measurements are thus crucial in tuning the state-of-the-art pQCD calculations and MC generators.

Since $W$+jets and $Z$+jets cross sections are measured, one can take a ratio

$R_{\text{jets}} = \sigma_{W+\text{jets}}/\sigma_{Z+\text{jets}}$ for the same jet kinematics. Some experimental uncertainties and effects such as hadronization are largely reduced by taking a ratio, so that the precisions are improved. Figure 6 shows $R_{\text{jets}}$ as a function of the inclusive number of jets [25]. The first bin corresponds to the inclusive cross section without requiring jets (see Section 2) and the ratio is slightly lower when requiring jets. Generally BlackHat+Sherpa reproduces the data well, including the di-jet mass distribution (in contrast to the individual measurements mentioned in the previous paragraph).
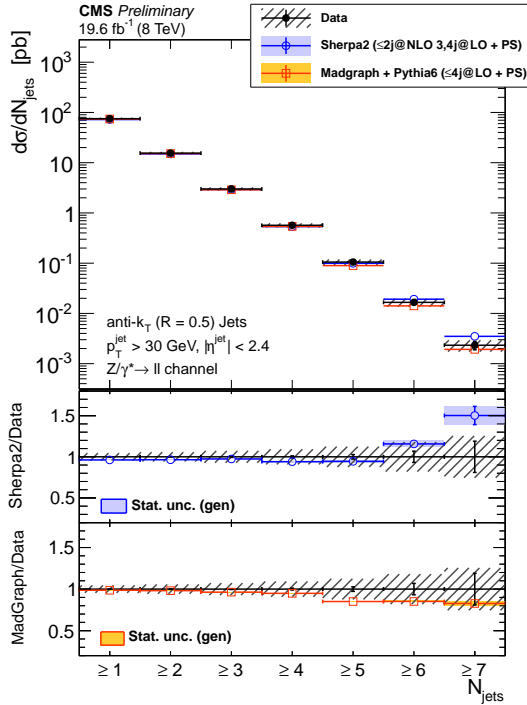


Figure 5: $Z$+jets cross section as a function of inclusive jet multiplicity, compared with Sherpa2 and MadGraph predictions [16].
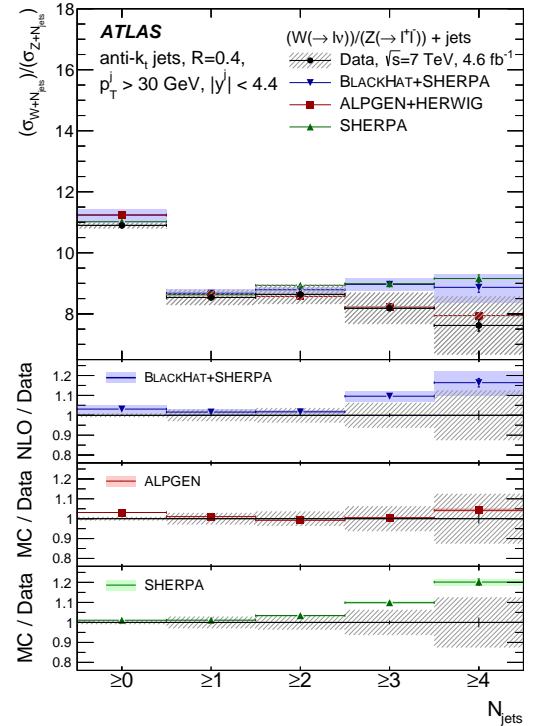
Figure 6: Ratio of $W$+jets/$Z$+jets cross sections as a function of inclusive jet multiplicity [25].

# 4  $W/Z$ +heavy flavor production

The production of heavy flavor jets in association with $W/Z$ has a larger theoretical uncertainty than light quark jets, thus its measurement is important. The processes $Z(W)+b\bar{b}$ constitute also (irreducible) background to the search for $ZH(WH)$ production followed by a $H \to b\bar{b}$ decay. For the bottom-production calculation, there are two schemes, namely four flavor-number scheme (4FNS) and five flavor-number

scheme (5FNS), which treat $udsc + g$ and $udscb + g$ as the intrinsic parton component of the proton, respectively. The measured $Z$ with one or more $b$-jets production cross section from ATLAS [26] seems to agree with 5FNS predictions better than 4FNS, while in the case of $Z$ with two or more $b$-jets, the precisions are not good enough to draw a conclusion. The MCFM [27] fixed-order NLO calculation fails to describe the azimuthal difference between $Z$ and $b$, while the prediction by aMC@NLO [28] describes the data well, especially in 5FNS. (Fig. 7). Also CMS measured $Z + b$ cross sections [29].

In the $W + b\bar{b}$ measurement by CMS [30], the largest background comes from the $t\bar{t}$ production. By requiring two well separated $b$-jets, the theoretical uncertainty is reduced. The measured cross section agrees very well with the MCFM prediction. ATLAS also made a measurement of $W + b$ cross sections [31].

LHCb made a search for $Z$ and $D$-meson production, in which both particles are reconstructed exclusively in $Z \to \mu^+ \mu^-$ and $D^0 \to K^- \pi^+$, $D^+ \to K^- \pi^+ \pi^+$ (+charge conjugate) modes. Signals of handful of events are observed as invariant mass peaks, and the obtained cross sections are compared with the predictions from Single Parton Scattering and Double Parton Scattering calculations [32].
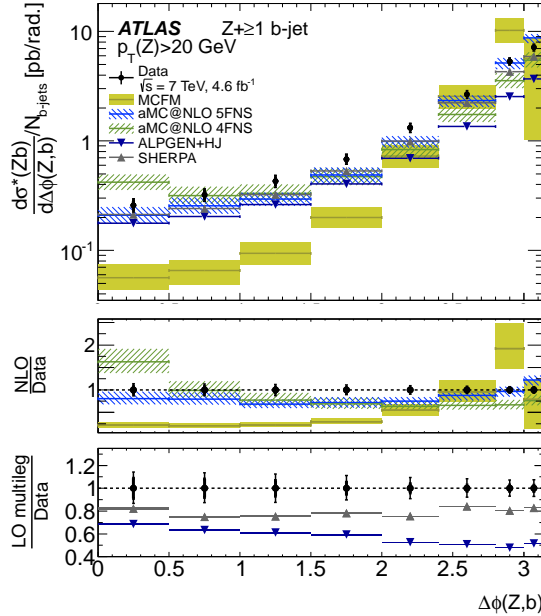
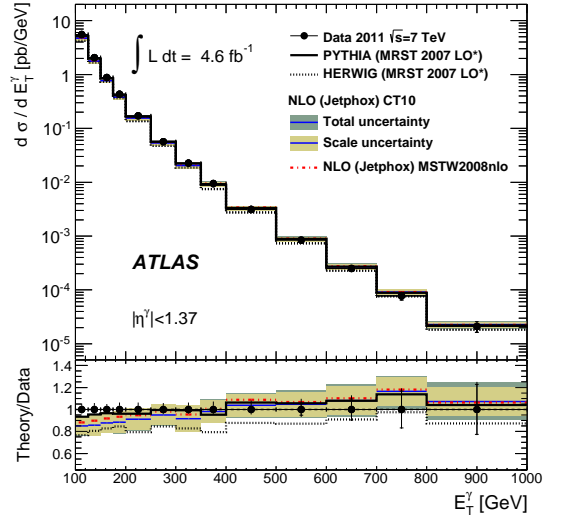Figure 7: Inclusive $b$-jet cross section as a function of azimuthal difference between $Z$ and $b$ [26].

Figure 8: Inclusive prompt photon cross section as a function of photon $E_{\mathrm{T}}$ in the barrel region [33].

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# 5 Prompt $\gamma$ and $\gamma\gamma$ pair production, $\gamma$+jets

The lowest-order processes of prompt photon production are $qg \to q\gamma, q\bar{q} \to g\gamma$. The measurements are sensitive to the gluon PDF. To extract the signal from misidentified hadrons and non-prompt photons, the isolation energy around the photon candidate is used. In the ATLAS measurement [33], the maximum photon $E_T$ reaches about 1 TeV (see Fig. 8), and the distributions are compared with NLO calculations and LO MC generators. Both describe the data distributions well, although the predictions are lower than the data by about 20% in magnitude.

The pair production of photons occur by $q\bar{q} \to \gamma\gamma$ in LO, and contributes to the background in the $H \to \gamma\gamma$ measurement. Both CMS [34] and ATLAS [35] measured various distributions, with $E_T$ thresholds for the two photons at (40, 25)GeV and (25, 22)GeV, respectively. Among the predictions compared to data, Sherpa and $2\gamma$NNLO [36] describe the data pretty well.
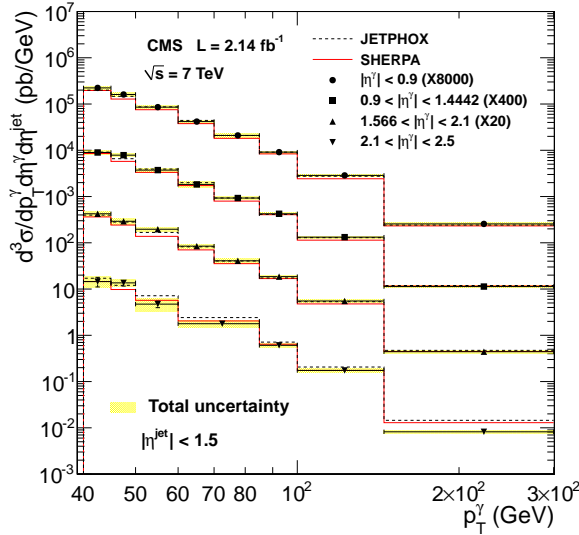


Figure 9: Photon+jets differential cross sections as functions of $p_T$ and $\eta$ of $\gamma$, for $|\eta^{\text{jet}}| < 1.5$ [37].
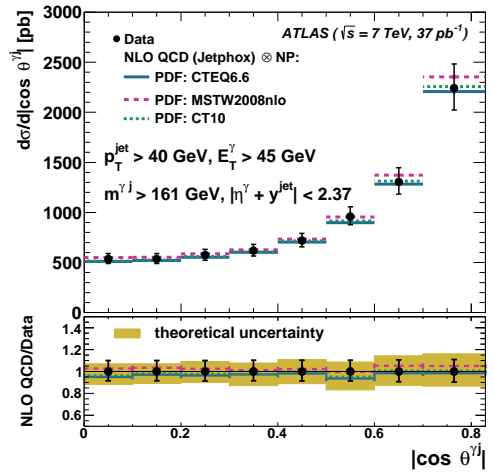
Figure 10: Isolated-photon cross section as a function of $|\cos\theta^{\gamma j}|$ (see text for definition) [39].

CMS measured the $\gamma$+jets triple-differential cross sections in $p_T$, $\eta$ of the photon and $\eta$ of the jet [37]. Predictions from Jetphox [38] and Sherpa agree with the data, except for the highest photon $p_T$ and largest photon $\eta$ (see Fig. 9). The ATLAS analysis [39] investigated the dynamics in $\gamma$+jets production. In the $qg \to q\gamma$ process, a spin-1/2 $t$-channel quark propagator is exchanged, while in the di-jet production, the propagator is dominantly spin-1 gluon. This is illustrated in the distribution of $|\cos\theta^{\gamma j}|$, which is the scattering angle in the two-parton center-of-mass system, as shown in Fig. 10. Concerning the azimuthal separation between $\gamma$ and jet, the NLO

calculation (Jetphox) has difficulty in predicting events with small separation, since the $\gamma$ and jet cannot be in the same hemisphere in the calculation by construction. For this distribution LO PYTHIA with parton shower describes the data well.

Finally, the $\gamma$+jets and $Z$+jets measurements are combined together. In the CMS analysis on rapidity distribution [40], the (absolute) average of vector-boson rapidity and jet rapidity ($y_{\mathrm{sum}}$) and the (absolute) difference of the two ($y_{\mathrm{dif}}$) are investigated. $y_{\mathrm{sum}}$ reflects the total boost of the system, and is sensitive to the PDF, while $y_{\mathrm{dif}}$ reflects the scattering dynamics, for which various predictions differ at large $y_{\mathrm{dif}}$ values. For both $Z$ and $\gamma$, the NLO predictions (by MCFM and Owens [41], respectively) agree well with the data at large $y_{\mathrm{dif}}$ value, as shown in Fig. 11.
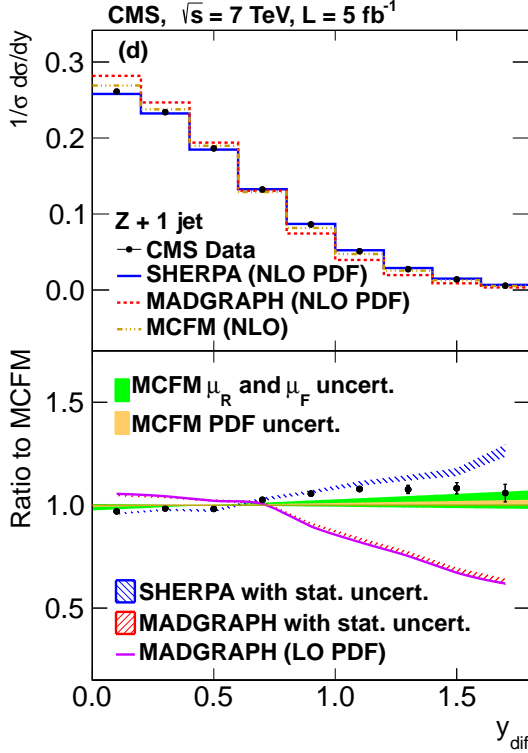


Figure 11: Normalized distribution of $y_{\mathrm{dif}} \equiv |y_Z - y_{\mathrm{jet}}|/2$ in $Z$+1 jet events [40].
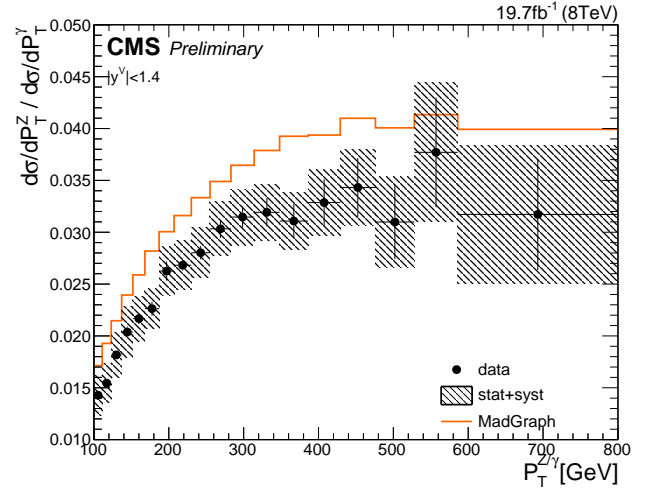
Figure 12: Differential cross-section ratio of leptonic $Z$ over $\gamma$ as a function of the vector boson $p_{\mathrm{T}}$ [42].

CMS also compared the $Z/\gamma^*$+jets and $\gamma$+jets cross sections at the same vector boson kinematics [42]. The ratio of $Z$ to $\gamma$ reaches a plateau, at about 0.03, for $p_{\mathrm{T}}$ of the vector boson $\gtrsim 300$ GeV, as shown in Fig. 12. MadGraph reproduces its shape. This fact is useful in the new physics search with $E_{\mathrm{T}}^{\mathrm{miss}}$ and jets, in which the irreducible background comes from $(Z \to \nu\bar{\nu})$+jets process. It validates the estimation of such background from the $\gamma$+jets event kinematics.

# 6　Conclusion

A wealth of results has been obtained in $W/Z/\gamma$ production at the LHC from Run 1 data. The SM (electroweak+QCD) has been tested at the highest energy for extreme kinematics (up to $\approx 1$ TeV) and topologies (with many jets, heavy flavors, etc.). These are crucial inputs for developments of theoretical predictions (NLO, NNLO, etc.) and MC generators, which show the readiness for new physics searches in Run 2, starting in 2015.

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