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Recent measurements of W and Z bosons with the CMS experiment

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Marco Cipriani[a,*] **on behalf of the CMS Collaboration**

[a] *CERN,*
Esplanade des Particules 1, Meyrin, Switzerland
E-mail: marco.cipriani@cern.ch

The large amount of data collected by the CMS experiment at the CERN LHC provides unprecedented opportunities to perform precision measurements of the standard model, which allow an accurate validation of the theory and might potentially reveal hints of new physics. Thanks to their leptonic decays, W and Z bosons guarantee a clean final state, and their relatively high production cross section permits the measurement of their properties with low systematic uncertainties and usually negligible statistical uncertainty. This talk presents an overview of recent precision measurements of electroweak bosons' properties and cross sections, carried out by CMS using Run 2 data. In addition, prospects for future physics results expected from the High-Luminosity phase of the LHC, and fostered by the planned detector upgrade, are also discussed.

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1. Introduction

The production of W and Z bosons represents one of the most prominent examples of hard scattering processes at hadron colliders. Thanks to their decays into charged leptons, in particular muons or electrons, these bosons provide analysts with a clean final state to suppress the background from the otherwise overwhelming multijet production from quantum chromodynamics (QCD) processes. In addition, their large production cross section at the CERN LHC makes them suited for precision measurements of the standard model (SM), allowing for stringent tests of perturbative QCD and electroweak (EW) theoretical calculations at higher orders, and the validation of different Monte Carlo (MC) event generators in the modeling of the hard scattering or parton shower. Moreover, EW measurements are a powerful tool to constrain the parton distribution functions (PDFs) of protons, which are ubiquitous in any LHC analysis.

The detailed knowledge of the W and Z boson production cross section and other properties is a crucial ingredient in many SM precision measurements. A notable example is the measurement of the W boson mass, which demands a deep understanding of the W boson production mechanism. At the same time, an outstanding control of weak boson cross sections is paramount also in new physics (NP) searches, such as searches for dark matter particles at the LHC. Indeed, the largest irreducible backgrounds for NP processes often originate from neutrinos from W and Z boson decays. The estimation of these backgrounds often relies on data-driven techniques based on control regions enriched in W and Z boson events with decays into charged leptons. Thus, it is vital to achieve an accurate mastering of theoretical and experimental inputs such as branching ratios into different channels or cross section ratios between W and Z.

This document reviews some of the most recent precision measurements of singly produced W and Z bosons carried out by the CMS collaboration at the LHC [1]. Prospects for the future High-Luminosity phase of the LHC (HL-LHC) are also discussed.

2. Review of recent measurements

The p_T spectrum of W and Z bosons is an important feature of their production mechanism. Higher order perturbative QCD calculations provide an accurate description of this distribution above few tens of GeV, while the low p_T region is harder to predict, especially below 20 GeV, because of the appearance of divergent logarithmic terms from soft gluon radiation, which need to be dealt with using resummation techniques. Next-to-leading logarithm (NLL) corrections lead to a better description of data, but the theoretical uncertainties at low p_T remain large. Therefore, direct measurements of the boson p_T becomes crucial to constrain the uncertainties in the predictions. CMS measured the Z p_T distribution using decays into muons or elecrons, and both inclusively in the number of jets and in events with at least one jet [2]. The measurement was performed differentially in the dilepton pair mass, $m_{\ell\ell}$. Indeed, a simple dependence on $m_{\ell\ell}$ is expected from theory for the differential cross section at low p_T. Hence, the direct measurement permits the validation of the resummation approach while also testing the precision of different predictions. Results are also reported as a function of the ϕ^* variable, which is correlated with p_T^Z but only depends on the angular variables of the decay leptons, and is consequently more precisely measured than p_T^Z.

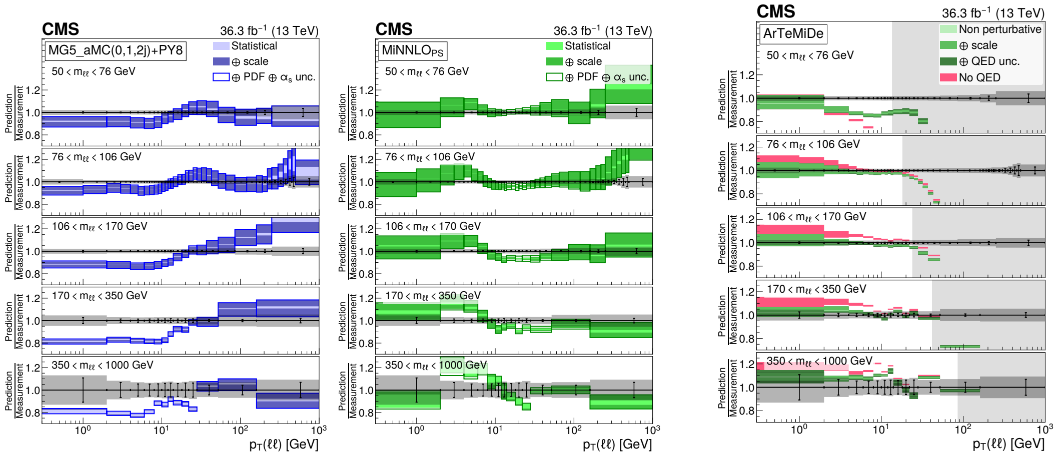

Figure 1: *Comparison of measured Z cross section differential in p_T^Z and $m_{\ell\ell}$ to MC predictions based either on a matrix element with parton shower merging (MG5_aMC + PYTHIA8 on the left and $MiNNLO_{PS}$ in the middle) or on TMD based predictions (arTeMiDe on the right). Taken from [2].*

Figure 1 shows the ratio of the predicted and measured Z boson cross section, differential in p_T^Z and $m_{\ell\ell}$. Data are compared to different predictions from generators employing matrix element calculations with parton shower merging (MG5_aMC or MiNNLO$_{\mathrm{PS}}$) or transverse momentum dependent (TMP) parton distributions (arTeMiDe). Generators employing matrix elements calculations at higher orders such as MG5_aMC correctly model the spectrum at high p_T but are less accurate at low p_T because of the lack of NLL corrections. Generators such as arTeMiDe include resummation to N^{3}LL and thus show a very good agreement with data at low p_T, while the high p_T region is poorly described because higher-order matrix element contributions are missing. Overall, MiNNLO$_{\mathrm{PS}}$ provides the best description of the data.

The differential cross section for the Drell-Yan (DY) dilepton production through $q\bar{q} \rightarrow Z/\gamma^* \rightarrow \ell^+\ell^-$ can be expressed as $d\sigma/d(\cos\theta^*) \propto 1 + \cos^2\theta^* + A_0/2(3 - \cos^2\theta^*) + A_4\cos\theta^*$, where θ^* is the angle of the ℓ^- in the Collins-Soper frame and A_0 and A_4 are angular coefficients. The $\cos\theta^*$ term is due to interference between the vector and axial-vector contributions, and results in a forward-backward asymmetry, A_{FB} [3]. The magnitude of A_{FB} increases with the boson rapidity and depends on the flavor of the initial-state quarks, thus on the PDFs. In addition, the experimental definition of A_{FB} relies on the assumption that the lepton pair is Lorentz-boosted along the direction of the quark. This definition leads to an observed dilution of the expected asymmetry due to neglecting contributions from initial-state antiquarks with larger momentum than quarks. This experimental effect reduces the analysis sensitivity to A_{FB} and entails a significant dependence on the PDFs.

The asymmetry is an increasing function of $m_{\ell\ell}$. It is negative for $m_{\ell\ell}$ below the nominal Z mass, m_Z, it reaches zero for $m_{\ell\ell} \approx m_Z$ and then becomes positive and increases with $m_{\ell\ell}$. For $m_{\ell\ell} \gtrsim 170\,\mathrm{GeV}$ the SM predicts a constant value for A_{FB} of about 0.6. However, deviations from the expected constant behavior can be induced by new phenomena, such as the presence of a new massive Z′ gauge boson. Even if the Z′ mass were outside the energy reach of the LHC, its presence could still be inferred through off-shell interference with the Z, which would modify A_{FB} at masses

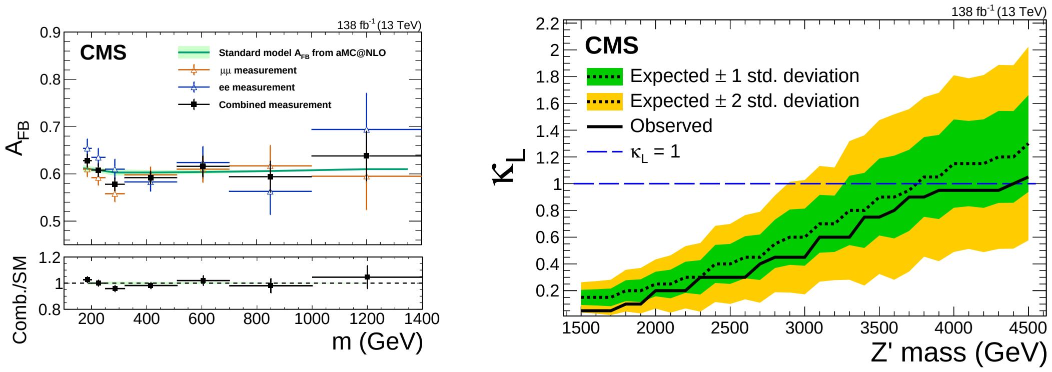

Figure 2: *(left) Forward-backward asymmetry (A_{FB}) as a function of the dilepton mass for ee and $\mu\mu$ channels, and their combination, compared to the SM prediction from* aMC@NLO*. (right) Exclusion limits at 95% CL on the coupling parameter k_L for a* Z′ *gauge boson as a function of its mass. The value $k_L = 1$ corresponds to the same coupling as the SM Z boson. Taken from [3].*

significantly lower than the Z′ mass. This feature makes this analysis complementary with direct searches for Z′ $\rightarrow \ell\ell$.

Rather than just counting forward-backward events, the measurement exploits a template fit method, where simulated signal templates are built to represent the different terms in the cross section formula. With this strategy the dilution of A_{FB} and other detector effects are automatically accounted for in the definition of the templates, permitting the unfolding to the generator-level A_{FB} directly within the fit procedure. The measured A_{FB} is shown in Fig. 2 (left). Good agreement within uncertainties is found between the muon and electron channels, which are also in agreement with the SM prediction. The analysis also includes the measurement of the A_0 angular coefficient, as well as upper limits on the coupling of SM particles to the Z′ boson as a function of its mass. The latter are shown in Fig. 2 (right). Assuming the same coupling as the SM Z boson, Z′ masses up to 4.4 TeV are excluded. These limits are less stringent than those from direct Z′ searches. However, they are valid also for wide resonances, while direct searches are typically sensitive only to narrow widths. The uncertainty of these measurements is dominated by the statistical uncertainty in data and PDFs. Therefore, a large gain is expected from the extension of the analysis to new future data from Run 3 and especially the HL-LHC, also with the inclusion of in-situ constraints of the PDFs.

The large size of W and Z boson samples collected at the LHC provides a natural path to test lepton flavor universality (LFU) by counting the number of events in each leptonic decay channel, which could potentially reveal a small difference among them after correcting for kinematic differences and other experimental effects. A simultaneous measurement of the W boson leptonic and hadronic branching ratios (BR) was performed by CMS [4]. The hadronic width also depends on other SM parameters, such as the strong coupling constant at the W boson mass or the elements V_{ij} of the Cabibbo–Kobayashi–Maskawa (CKM) matrix that controls mixing in the flavor sector. An indirect determination of these quantities can thus be achieved. The unitarity condition of the CKM matrix implies that $\sum_i |V_{ui}|^2 = \sum_i |V_{ci}|^2$, with the index $i = d, s, b$ representing down-type quarks and u, c being the index for up and charm quarks. Some of these elements are currently less constrained from direct measurements, such as V_{cs}.

Figure 3 (left) shows the measured W leptonic BR, also compared with the corresponding LEP

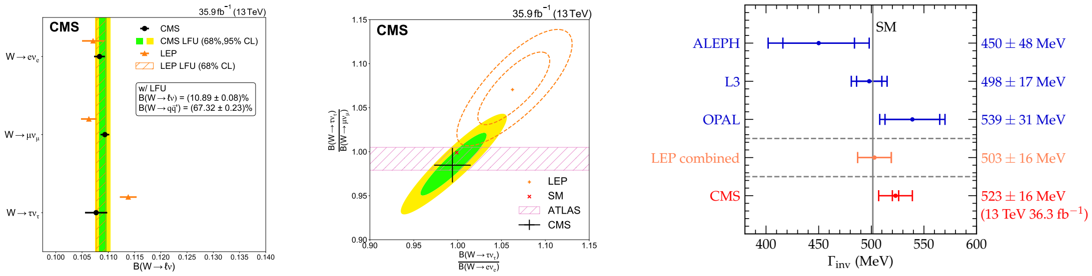

Figure 3: *(left) Measured W leptonic branching fractions, compared to the SM prediction and analogue results from LEP. (middle) Two-dimensional distribution of the ratios of the* $W \longrightarrow \tau\nu$ *to* $W \longrightarrow \mu\nu$ *or* $W \longrightarrow e\nu$ *branching fractions. (right) Summary of existing direct measurements of Z invisible width from LEP and CMS. Taken from [4, 5].*

results. Results are in good agreement with LFU, and remove the tension that was present in the LEP measurements for $W \longrightarrow \tau\nu$ decays. This is further illustrated in Fig. 3 (middle), which presents the two-dimensional distribution of the ratios of the $W \longrightarrow \tau\nu$ branching fraction to the analogue ones for decays into electrons or muons. It is interesting to observe that the precision achieved by CMS for the $W \longrightarrow \mu\nu$ and $W \longrightarrow e\nu$ BRs is better than the LEP one. This is primarily due to the much smaller statistical uncertainty in CMS.

It is remarkable that EW measurements conducted at a hadron collider can compete with lepton colliders in terms of precision. This is a consequence of the higher center-of-mass energy and instantaneous luminosity, which grant a much larger size of data sample, and also of the extraordinary performance of the accelerator and the experiments. A nice example of the high potential of EW physics at hadron colliders is given by the CMS measurement of the invisible width of the Z boson [5]. The result is obtained from a simultaneous fit to the recoil distribution for two data samples: one enriched in Z boson decays to invisible particles and the other dominated by Z boson decays to muon and electron pairs. It exploits the measured cross section ratio between the visible and invisible channels, then multiplied by the $Z \longrightarrow \ell\ell$ partial widths precisely measured at LEP. Control regions enriched in single lepton events from W boson decays are also used to constrain the recoil distribution in the Z invisible decay channel. This is the first measurement of the Z invisible width at a hadron collider, and the single most precise direct measurement to date[1]. A summary of the existing direct measurements from LEP and CMS is reported in Fig. 3 (right). The CMS result is limited by systematic uncertainties and has negligible statistical uncertainty.

3. Physics prospects at the HL-LHC

The data collected at the HL-LHC is expected to exceed the size of the Run 2 data set by about 20 times, thanks to the giant leap in the instantaneous luminosity of the beams. This will also entail daunting levels of simultaneous pp collisions (pileup) up to 200 compared to the Run 2 average of about 35, which will reflect into much higher trigger rates and more intense radiation damage.

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[1] The indirect method exploited at LEP, which is based on the total width extracted from the Z boson line shape and the subtraction of the precisely measured partial decay widths from all visible final states, is still the most precise one, with a precision of 1.5 MeV.

Particle identification and assignment to the correct vertex will constitute major challenges. Therefore, the CMS detector will be upgraded to increase spacial granularity and guarantee a robust event reconstruction. This will be complemented by a complete overhaul of trigger and DAQ systems, which is crucial to tame the higher particle rates. Faster front-end electronics will be deployed, permitting the usage of tracking algorithms in the first stage of the trigger selection, which is hardware-based. Improved timing capabilities provided by new detectors will also facilitate the development of more sophisticated particle identification algorithms. This will result in better discrimination between signal and background events, allowing trigger rates to be kept below sustainable levels without considerably raising the lepton p_T thresholds, which otherwise would dramatically reduce the selection efficiency for W and Z bosons. In addition, the new tracker will extend the current fiducial pseudorapidity coverage from $|\eta| = 2.4$ to 4.0, resulting in better constraints of PDFs and enhanced sensitivity to physics in the forward region.

4. Summary

A selected list of recent precision measurements of W and Z boson properties and cross sections has been presented. These are based on data collected in proton-proton collision at $\sqrt{s} = 13$ TeV with the CMS experiment at the CERN LHC. These results represent precious inputs to test theoretical calculations, and are also vital in other SM measurements and searches for NP. Some measurements have negligible statistical uncertainty, and reducing systematic uncertainties is thus mandatory to improve upon existing results.

The HL-LHC will provide new extraordinary physics opportunities to further constrain the SM. In order to reap this benefit and exploit the full potential of the much larger data set that will be collected, a major upgrade of the detector is foreseen. This will help offset the performance degradation that would arise from the more challenging data-taking conditions due to the giant leap in instantaneous luminosity.

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