PROCEEDINGS OF SCIENCE

W/Z precision and differential measurements

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The W and Z particles of the Standard Model (SM) have been known and studied for decades. Yet, they have a lot to tell on the consistency of the SM, through the precise and differential measurements of their properties. In this context, the differential measurements give information on perturbative and non-perturbative Quantum ChromoDynamics, in turn reducing modeling uncertainties in measurements of $e.g.$ electroweak parameters. Precision measurements help testing the coherence of the SM $e.g.$ through the global electroweak fit. This proceeding reviews the latest contributions from the ATLAS, CMS and LHCb collaborations at the Large Hadron Collider to these measurements.

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1. Introduction

The quest for physics beyond the Standard Model (SM) has been ongoing for decades in the particle physics experiments. The Large Hadron Collider (LHC) experiments have been searching for direct signatures of new physics for more than 10 years, without finding any so far. Another way to probe such hints is to check the overall consistency of the SM, by measuring precisely its parameters and confronting them with their theoretical predictions. This is typically what is done when performing the electroweak fit and comparing the outcome to experimental values of the W mass or the top quark mass, for example. These precision measurements are building upon other ancillary measurements that enable to improve the modeling of the processes under study, constraining perturbative and non-perturbative QCD in their prediction. This is typically achieved by measuring differential cross-sections of well-known processes, for example those of the Z boson. The ATLAS [1], CMS [2] and LHCb [3] experiments at CERN have continued the work initiated in previous colliders, and have brought many new results into the light to complete the puzzle of the SM.

This proceeding reviews some of the most recent precise and differential measurements released by these collaborations studying Z and W boson properties.

2. Z boson invisible width and τ polarisation in Z boson decays

The Z boson invisible width, Γ_{inv}, allows to set important constraints to the number of light neutrino species.

It was directly measured at LEP, where a combination of the results of the ALEPH, L3 and OPAL experiments led to a value of (503 ± 16) MeV. The recent measurement by the CMS collaboration, using 36.3 fb^{-1} of data collected in 2016 at a centre-of-mass energy $\sqrt{s}$ = 13 TeV, is the most precise single direct one, and leads to a value of Γ_{inv} = (523 ± 16) MeV [4]. The measurement uses the hadronic system recoiling against the Z boson in several final states, the so-called *hadronic recoil*, u_T. The final states comprise a signal-enriched region, the $p_{\mathrm{T}}^{\mathrm{miss}}$+jets one, and also the $Z \to ee$+jets and $Z \to \mu\mu$+jets final states of neutral current Drell-Yan production. A fit is performed to simultaneously extract Γ_{inv} and constrain the W+jets background. The uncertainty is dominated by lepton identification efficiency and jet energy scale.

It should be noted that the indirect measurement of Γ_{inv} at LEP [5] leads to a result of Γ_{inv} = (499 ± 1.5) MeV. This result used the total Z boson lineshape, subtracting the contributions of the known visible final states.

The measurement of the τ lepton polarisation in Z boson decays was performed by CMS using 36.3 fb^{-1} of data collected in 2016 at $\sqrt{s}$ = 13 TeV [6]. This result is a foundation for a measurement of τ polarisation in the $H \to \tau\tau$ process, and also helps separation with exotic signals in $\tau\tau$ final state beyond-SM searches. The τ lepton asymmetry is also measured , and a value of the weak mixing angle is inferred. The analysis uses a multivariate discriminant to separate hadronic τ leptons from jets, electrons and muons. An ABCD method [7] is used to determine the multijet and W+jets backgrounds. Then, the analysis relies on angular distributions of the decay hadrons and leptons with respect to their mother particle, all combined into one optimised observable per event category (defined according to the decay modes of the two τ leptons) without loss of sensitivity.

The polarisation is measured in several pseudorapidity (η) categories and nearly all τ decay modes. The following result is obtained for the τ lepton polarisation at the Z boson mass pole, and is the most precise measurement at the LHC to date :

$$\mathcal{P}_\tau(Z) = -0.144 \pm 0.015,$$

while the inferred value of the weak mixing angle is the following :

$$\sin^2 \theta_W^{\mathrm{eff}} = 0.2319 \pm 0.0019.$$

The precision of the measurement of the τ lepton asymmetry is comparable, yet a bit larger than those obtained in the LEP experiments, as can be seen in Figure 1.

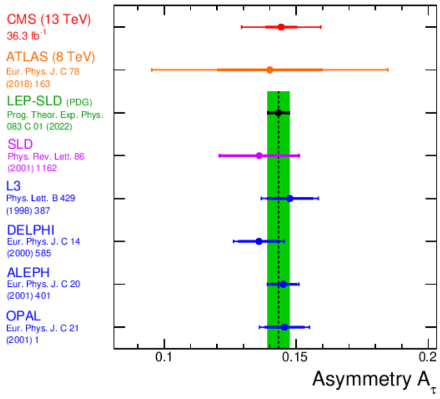

Figure 1: Comparison of measurements of the τ lepton asymmetry, A_τ [6].

3. Differential cross-section measurements in the Z boson process and interpretations: α_s, polarisation

The Z boson differential cross-section measurements are key inputs to extract fundamental parameters of the SM, like α_S, or the weak mixing angle. They also allow to constrain the parameters used in theoretical models to predict other physics processes, typically parton distribution functions (PDFs).

The LHCb experiment measured precisely the Z boson differential production cross-section as a function of y, ϕ^*_η [8–10] and p_T, using 5.1 fb^{-1} of data collected in 2016, 2017 and 2018 [11]. The ϕ^*_η and p_T cross-sections were obtained in slices of Z rapidity, making it a double differential measurement. This will be a valuable input to constrain PDF uncertainties at large and small x in the future m_W and weak mixing angle analyses. Figure 2 shows the kinematic reach of the various experiments, as well as one of the measurements performed in this work, the differential production of the Z boson production as a function of its rapidity. The publication comprises the most precise integrated fiducial cross-section measurement in the forward region to date.

The CMS collaboration also published a measurement of the mass dependence of the transverse momentum of lepton pairs in Drell-Yan production at 13 TeV [13]. The analysis is using muonic and

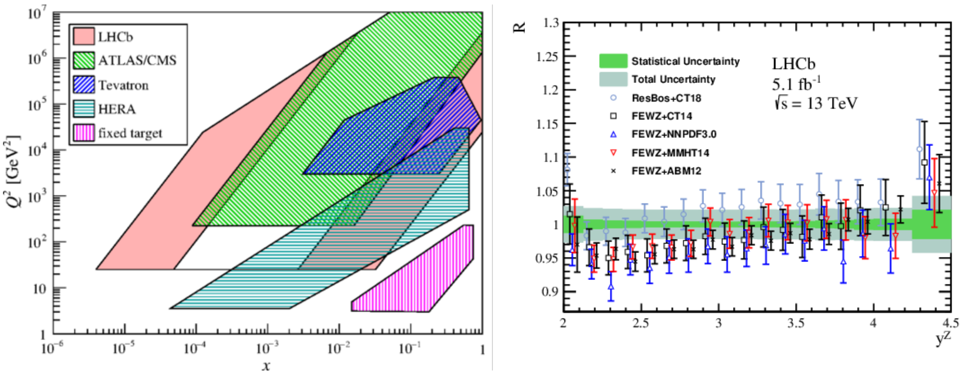

Figure 2: (Left) Kinematic reach in x, Q^2 of the various experiment [12]. (Right) Measured differential cross-section of the Z boson production as a function of its rapidity [11].

electronic decays of the Z produced in 2016, where the integrated luminosity amounted to 36.3 fb^{-1} of collected data. The measurement comprises the differential cross-sections as a function of ϕ^*_η and p_T in bins of the dilepton invariant mass $m_{\ell\ell}$, and their ratios to those obtained in the mass peak. The results are also splitted in inclusive and ≥ 1 jet categories. Such a high dimensionality allows for extensive tests of the theoretical predictions for single boson production in view of precision electroweak measurements. In this respect, the publication includes models taken from a large variety of predictions: MadGraph5_aMC@NLO + Pythia8, MiNNLO$_\mathrm{PS}$, CASCADE 3, ArTeMiDe, and GENEVA. Each of these models have different accuracies or theory calculations for the perturbative and non-perturbative QCD. The conclusions of the publication show in general better agreement of the results with high accuracy generators, in the relevant kinematic phase space (for example, high fixed order accuracy predictions have in general good agreement at high p_T).

The LHCb collaboration also released a first measurement of the Z boson angular coefficients. There are eight angular coefficients, A_i with index i running from 0 to 7, describing the polarisation of the vector boson. The LHCb analysis measured the first five coefficients, A_0 to A_4, in the forward rapidity region at 13 TeV [14], using the muon-antimuon decay channel. The coefficients were extracted as a function of Z p_T and rapidity at the Z pole. The A_2 coefficient was also measured in the low-mass and high-mass regions, providing more information on non-perturbative effects such as Transverse Momentum Dependent (TMD) PDFs. The angles are extracted thanks to a fit of the two decay angles of the reconstructed boson, $\cos\theta$ and ϕ. The PDF uncertainty is taken from the CT18NNLO eigensets. The Pythia 8 prediction deviates from the measurement at high p_T, while other predictions (Powheg+Pythia, DYTurbo, ResBos) are in reasonable agreement. The Lam-Tung violation, $A_0 - A_2 \neq 0$ starting at NNLO accuracy, is clearly observed in the experimental result.

The ATLAS collaboration made a full phase space double differential cross-section measurement as a function of Z boson p_T and rapidity, using 20.2 fb^{-1} of 8 TeV data collected in 2012 [15]. The measurement was done in 22528 bins of ($\cos\theta$, ϕ, p_T, y) extrapolated from fiducial volume to full phase space through a measurement of the angular coefficients. The measurement of the Z boson p_T is compared to N4LL predictions and displays good agreement. A preliminary value of the strong coupling constant, α_S, is extracted from these measured cross-sections at low p_T [16], and provides the best experimental determination of it to date:

$$\alpha_S = 0.11828^{+0.00084}_{-0.00088}.$$

Resummation is needed at low $p_{\rm T}$ to take care of the divergences induced by soft and collinear emissions in fixed-order predictions. The resulting Sudakov peak is found to be sensitive to the value of α_S, as shown in Figure 3. The fit uses a profiled χ^2 to the Z ($p_{\rm T}$, y) measurement for $p_{\rm T}^Z < 29$ GeV. The dominant uncertainties come from the PDFs, the experimental measurement and the scale variations. The final result is in good agreement with the world average, as seen in Figure 3.

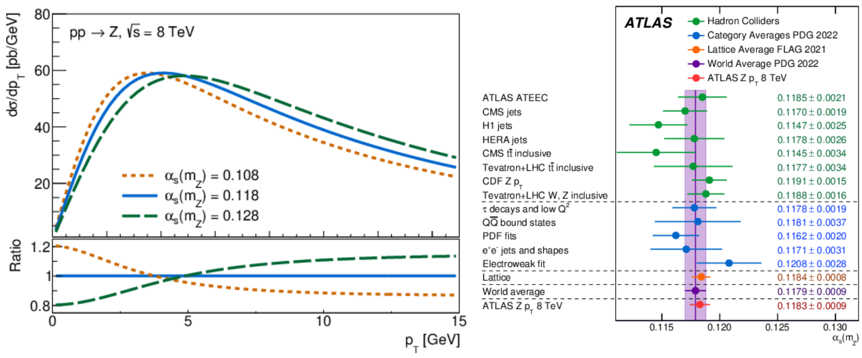

Figure 3: (Left) Sensitivity of the $p_{\rm T}^Z$ distribution to α_S. (Right) Measured values of α_S [16].

4. *W* boson transverse momentum and mass

The W boson mass, m_W, is a key parameter of the SM, and its precise measurement is crucial. It is currently the limiting parameter of the electroweak fit. Furthermore, a recent measurement from the CDF collaboration [17] with less than 10 MeV precision deviates from the SM predictions by more than 5σ, although being in tension with other measurements [18]. New, more precise measurements of m_W should clarify this tension and also improve the constraints on the SM electroweak fit. Up to now, the most precise measurements have come from the Tevatron and LHC experiments. For a long time, the LEP-Tevatron combination of m_W was the most precise result, with a total uncertainty of 15 MeV. The first ATLAS measurement, performed using 7 TeV data recorded in 2011 [19], came up with an uncertainty of 19 MeV, which was similar to the best single measurement performed by CDF at that time. LHCb released its first measurement [20] a few years after, with a total uncertainty of 32 MeV, largely dominated by the limited statistics. The most recent update of the m_W measurement is a preliminary reanalysis of the 7 TeV ATLAS result [21], using the same detector calibrations as the initial result. The main improvements rather come from the use of a more recent PDF set (CT18NNLO instead of CT10NNLO) and from the upgrade of the statistical analysis, switching from a simple χ^2 offset method to a profile likelihood. The multijet background has also been re-evaluated, and the electroweak uncertainties are now estimated at detector level, as they were previously obtained at generator level. The dominant uncertainties come from lepton calibration and PDFs, and the preliminary result is:

$$m_W = 80360 \pm 16 \text{ MeV}.$$

One key point of the m_W measurement is the modeling of the W boson p_{T}. In ATLAS or LHCb, it largely relies on tunes to Z data. The QCD parameters are well constrained with precise measurements of the Z boson p_{T}, and the extrapolation from the Z to the W implies uncertainties that rely on some assumption on the correlation between the processes. These assumptions are to be checked with a direct measurement of p_{T}^W, which is what ATLAS recently did in a preliminary result [22]. Measuring p_{T}^W precisely at low p_{T} (*i.e.* in the Sudakov peak) is challenging, because the full kinematics cannot be precisely measured. The measurement has to exploit leptonic decays of the W boson, which comprise a neutrino. Therefore, p_{T}^W is reconstructed in the detector only indirectly, through u_T. Due to the large particle multiplicity and pileup, u_T has a poor resolution and the variation of the cross-section with p_{T} is difficult to reach. To this aim, ATLAS used specific data taken at low pileup in 2017 and 2018, at two different centre-of-mass energies, 0.255 fb^{-1} at 5.02 TeV and 0.338 fb^{-1} at 13 TeV. These data required a dedicated effort on physics modeling and detector calibration. u_T was reconstructed using particle flow objects, which is an improvement over previous recoil algorithms in ATLAS. The calibration was performed $in-situ$ in Z events. Standard W and Z selections in electron and muon channels were performed, and multijet background was estimated with a data-driven ABCD method similar to previous m_W measurements. Unfolding is then applied to extract both p_{T}^W and p_{T}^Z. p_{T}^W uses an unfolding of u_T, while p_{T}^Z uses an unfolding of the dilepton transverse momentum, $p_{\mathrm{T}}^{\ell\ell}$. A check of the p_{T}^W extraction through the hadronic recoil was performed using Z events, where both the hadronic recoil and the dilepton measurements can be compared. This comparison gave a decent agreement between the two measurements using complementary observables in the same Z events. The results comprise a measurement of p_{T}^W in bins of 7 GeV width, in 8 channels with an uncertainty of about $1.5-2\%$ in the Sudakov peak. They also come with the most precise integrated W and Z boson fiducial cross-sections, thanks to the clean low-pileup events, and to new luminosity measurements that reached unprecedented precision at LHC [23]. This analysis should set the path to future m_W measurements using the same low-pileup data in ATLAS, complementary to the existing high-pileup measurements. The LHCb collaboration also released a preliminary measurement of the differential and integrated Z cross-section using similar data at 5.02 TeV [24]. The cross-section is measured as a function of Z boson p_{T}, ϕ_η^* and rapidity. The results show reasonable agreement with different SM predictions. Thanks to the different kinematics reach of the experiment, this will offer sensitivity to another complementary (x, Q^2) region.

5. Conclusion

The recent progress in the measurements of W and Z differential cross-sections and related fundamental parameters in the ATLAS, CMS and LHCb collaborations at the LHC is encouraging, but the potential for higher precision is still to be exploited further. Theory predictions are used for the experimental measurements, and differential cross-sections are invaluable inputs to the models. The results presented here reflect how the two communities are intertwined and are working together to further increase the constraints to the SM. For example, improving PDFs reduces uncertainties in the experimental m_W measurements. And these PDFs are the results of fits done by the theory community using differential cross-sections experimentally measured, typically those presented here. The same is true for Z boson polarisation coefficients: measuring those allows for comparison to their theory predictions at a given order in QCD. This justified *e.g.* the use of NNLO fixed-order models for the W polarisation in the context of the ATLAS 7 TeV m_W measurement.

Furthermore, collaborative efforts are required to combine m_W measurements from the various experiments. The complementarity of the explored observables and phase-space offer reduction in uncertainties such as PDFs, which is already one of the limiting factors in this measurement. New data will reduce uncertainties in the measurements, in particular at LHCb, where the m_W result is largely dominated by statistics. If a larger amount of low-pileup data is envisaged at LHC, it will also help precision in the p_T^W and m_W areas, since these datasets are complementary to the existing high-pileup ones and are also limited currently by statistics.

References

[1] ATLAS Collaboration, The ATLAS Experiment at the CERN Large Hadron Collider, JINST 3 (2008) S08003. doi:10.1088/1748-0221/3/08/S08003.

[2] CMS Collaboration, The CMS Experiment at the CERN LHC, JINST 3 (2008) S08004. doi:10.1088/1748-0221/3/08/S08004.

[3] LHCb Collaboration, The LHCb Detector at the LHC, JINST 3 (2008) S08005. doi:10.1088/1748-0221/3/08/S08005.

[4] CMS Collaboration, Precision measurement of the Z boson invisible width in pp collisions at s=13 TeV, Phys. Lett. B 842 (2023) 137563. arXiv:2206.07110, doi:10.1016/j.physletb.2022.137563.

[5] Workman, R. L., et al., Review of Particle Physics, PTEP 2022 (2022) 083C01. doi:10.1093/ptep/ptac097.

[6] CMS Collaboration, Measurement of the τ lepton polarization in Z boson decays in proton-proton collisions at $\sqrt{s}$ = 13 TeV, Submitted to JHEP (2023). arXiv:2309.12408.

[7] CDF Collaboration, Measurement of $\sigma b(w \to e\nu)$ and $\sigma b(Z^0 \to e^+e^-)$ in $\overline{p}p$ collisions at $\sqrt{s}$ = 1800 gev, Phys. Rev. D 44 (1991) 29–52. doi:10.1103/PhysRevD.44.29.
URL https://link.aps.org/doi/10.1103/PhysRevD.44.29

[8] A. Banfi, S. Redford, M. Vesterinen, P. Waller, T. R. Wyatt, Optimisation of variables for studying dilepton transverse momentum distributions at hadron colliders, Eur. Phys. J. C 71 (2011) 1600. arXiv:1009.1580, doi:10.1140/epjc/s10052-011-1600-y.

[9] A. Banfi, M. Dasgupta, S. Marzani, L. Tomlinson, Predictions for Drell-Yan ϕ^* and Q_T observables at the LHC, Phys. Lett. B 715 (2012) 152–156. arXiv:1205.4760, doi:10.1016/j.physletb.2012.07.035.

[10] S. Marzani, Q_T and Φ^* observables in Drell-Yan processes 49 (2013) 14007. doi:10.1051/epjconf/20134914007.

[11] LHCb Collaboration, Precision measurement of forward Z boson production in proton-proton collisions at $\sqrt{s}$ = 13 TeV, JHEP 07 (2022) 026. arXiv:2112.07458, doi:10.1007/JHEP07(2022)026.

[12] T. Boettcher, P. Ilten, M. Williams, Direct probe of the intrinsic charm content of the proton, Phys. Rev. D 93 (2016) 074008. doi:10.1103/PhysRevD.93.074008.
URL https://link.aps.org/doi/10.1103/PhysRevD.93.074008

[13] CMS Collaboration, Measurement of the mass dependence of the transverse momentum of lepton pairs in Drell-Yan production in proton-proton collisions at $\sqrt{s}$ = 13 TeV, Eur. Phys. J. C 83 (7) (2023) 628. arXiv:2205.04897, doi:10.1140/epjc/s10052-023-11631-7.

[14] LHCb Collaboration, First Measurement of the Z→μ+μ- Angular Coefficients in the Forward Region of pp Collisions at s=13 TeV, Phys. Rev. Lett. 129 (9) (2022) 091801. arXiv:2203.01602, doi:10.1103/PhysRevLett.129.091801.

[15] ATLAS Collaboration, A precise measurement of the Z-boson double-differential transverse momentum and rapidity distributions in the full phase space of the decay leptons with the ATLAS experiment at $\sqrt{s}$ = 8 TeV, Submitted to Eur. Phys. J. C (2023). arXiv:2309.09318.

[16] ATLAS Collaboration, A precise determination of the strong-coupling constant from the recoil of Z bosons with the ATLAS experiment at $\sqrt{s}$ = 8 TeV, Submitted to Nature Phys. (2023). arXiv:2309.12986.

[17] CDF Collaboration, High-precision measurement of the W boson mass with the CDF II detector, Science 376 (6589) (2022) 170–176. doi:10.1126/science.abk1781.

[18] S. Amoroso, et al., Compatibility and combination of world W-boson mass measurements (2023). arXiv:2308.09417.

[19] ATLAS Collaboration, Measurement of the W-boson mass in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector, Eur. Phys. J. C 78 (2) (2018) 110, [Erratum: Eur. Phys. J. C 78, 898 (2018)]. arXiv:1701.07240, doi:10.1140/epjc/s10052-017-5475-4.

[20] LHCb Collaboration, Measurement of the W boson mass, JHEP 01 (2022) 036. arXiv:2109.01113, doi:10.1007/JHEP01(2022)036.

[21] ATLAS Collaboration, Improved W boson Mass Measurement using 7 TeV Proton-Proton Collisions with the ATLAS Detector (2023).
URL https://cds.cern.ch/record/2853290

[22] ATLAS Collaboration, Precise measurements of W and Z transverse momentum spectra with the ATLAS detector at $\sqrt{s}$ = 5.02 TeV and 13 TeV (2023).
URL https://cds.cern.ch/record/2861057

[23] ATLAS Collaboration, Luminosity determination in pp collisions at $\sqrt{s}$ = 13 TeV using the ATLAS detector at the LHC, Eur. Phys. J. C 83 (10) (2023) 982. arXiv:2212.09379, doi:10.1140/epjc/s10052-023-11747-w.

[24] LHCb Collaboration, Measurement of Z boson production cross-section in pp collisions at $\sqrt{s} = 5.02$ TeV (2023). arXiv:2308.12940.