The W boson mass measurement at the CMS experiment

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Summary. — The W boson mass, m_{W}, is predicted by the standard model (SM) of particle physics with a precision of 6 MeV. However, new particles or forces in quantum loops could alter the value of m_{W}. Therefore, direct measurements of m_{W} serve both as tests of the internal consistency of the SM and as potential windows into new physics. The CMS experiment recently released a new measurement, on $W \to \mu\nu$ events with proton-proton collision data collected in 2016 at the LHC. The measured value is compatible with the SM prediction and has a precision of 9.9 MeV, comparable to the most recent CDF measurement, which instead disagrees with the prediction. To reach SM precision, a deep understanding of numerous systematic experimental effects was needed, and cutting-edge techniques for modeling W boson production and decay were also employed. The CMS m_{W} measurement is described in this article, with a particular focus on the strategy adopted to carefully estimate the muon reconstruction efficiencies, which are vital to correct the simulations and to fine-tune their agreement with data in the observables used to extract m_{W}.

1. – Introduction

The W boson is the particle mediator of the charged weak interaction. By the effect of the Higgs mechanism, this particle has a non zero mass, m_{W}, that is a free parameter in the electroweak sector of the standard model (SM) of particle physics. The SM provides a relation, verified at tree level, between m_{W} and the other free parameters, namely the Fermi constant G_μ, the Z boson mass m_{Z} and the fine structure constant α. An extension of this relation to include loop terms in the W boson propagator introduces contributions which depend on the top quark mass m_t and the Higgs boson mass m_{H}. By giving as input the experimental measurements of these five parameters, the SM relations produce a predicted value of m_{W}, the most recent being $m_{\mathrm{W,\,SM}} = 80.353 \pm 0.006$ GeV [2].

If new particles or interactions not predicted by the SM are present, they may affect the W boson propagator, adding terms to the aformentioned loop corrections and

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consequently altering the value of m_W. Therefore, probing this parameter with direct measurements is both a test of the internal consistency of the SM and a potential window into new physics.

1˙1. *State of the art before the CMS measurement.* – The most precise m_W measurement was performed by the CDF experiment in 2022 [3]: the reported result has an uncertainty of 9.4 MeV and the central value is significantly different from the SM prediction. In recent years, at the LHC, new measurements have been released by the LHCb and ATLAS collaborations [4, 5], reporting uncertainties of 32 MeV and 15.9 MeV, respectively. Recently, the CMS collaboration performed a measurement of m_W whose uncertainty approaches the one achieved by CDF.

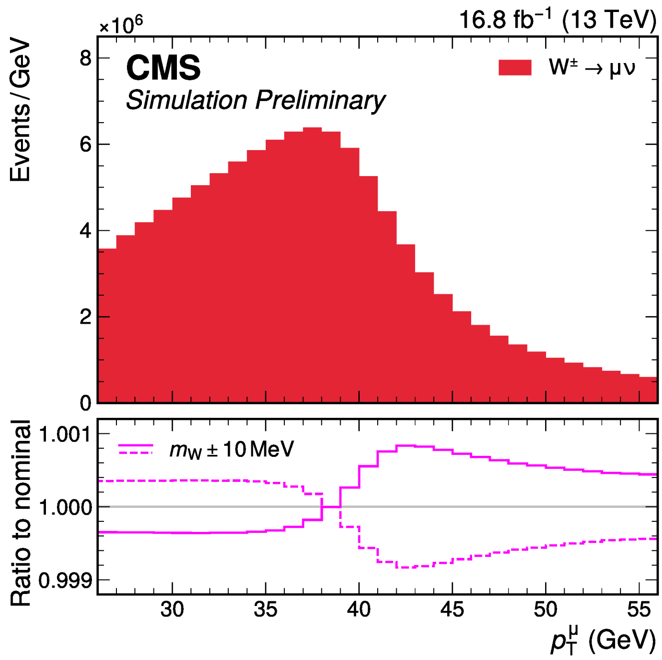

Fig. 1.: Muon transverse momentum distribution, simulated by CMS using only signal events with a nominal value of m_W and with its variation of ±10 MeV. The ratio of the variations to the nominal is presented in the lower panel.

1˙2. *Measurement technique at hadron colliders.* – For experiments at hadron colliders, the only process exploitable to measure the W boson mass with 10^{-4} relative precision is its decay channels into muons or electrons, $W \to \mu\,\nu_\mu$, $W \to e\,\nu_e$; the decay channels into quarks are not suitable for this task due to the limitations in the jet energy scale reconstruction and the complications brought by "pileup" interactions (simultaneous proton-proton interactions). However, the final-state invariant mass is not accessible in reconstructed leptonic decay events due to the presence of the neutrino; therefore, the strategy relies on the precise measurement and analysis of the charged lepton kinematic distributions that are sensitive to m_W. The distribution exploited by CMS in this measurement is the charged lepton transverse momentum p_T^ℓ: its distribution presents the so-called Jacobian peak at $m_W/2$. The boson is generally not at rest in the laboratory frame, and as a result the reconstructed distribution of p_T^ℓ, which is not a Lorentz invariant, has a strong dependence on the W boson transverse momentum and polarization. It can be shown that a variation of m_W of 10 MeV induces a variation in the shape of only 0.1% (figure 1): therefore, to obtain an uncertainty comparable to the most recent experimental measurements, all the experimental and theoretical effects that alter this distribution must be treated with an exceptional control.

2. – Measurement at CMS

The CMS measurement is performed on a dataset of 16.8 fb^{-1} of integrated luminosity, recorded in the year 2016 at $\sqrt{s} = 13$ TeV, during the LHC Run 2. The measurement targets only the process $W \to \mu\,\nu_\mu$ and exploits the excellent muon reconstruction performance provided by making use of multiple CMS subdetectors [6]: the tracker system, made entirely of silicon modules and immersed in a solenoidal 3.8 T magnetic field, provides a precise estimate of the muon transverse momentum; outside the calorimeters and the coil, the gas detectors, called muon chambers, improve the muon identification. A cut on the transverse mass is also applied to reduce the background events. The selected sample contains around 100 million events, with an estimated signal purity of 87%. In this section, the methods developed to manage some of the various systematic effects will be briefly presented. The muon momentum scale calibration and the estimation of nonprompt-muon background will not be treated in this report.

TABLE I.: Main sources of uncertainty in the CMS m_W measurement (adapted from [7]).

Type	Source of uncertainty	Impact [MeV]
Theoretical	W/Z angular coefficients	3.3
	Higher-order corrections EW	2.0
	p_T^V modeling	2.0
	PDF	4.4
Experimental	Momentum scale calibration	4.8
	Reconstruction efficiencies	3.0
	Nonprompt background	3.2
	MC sample size	1.5
	Data sample size	2.4
	Total	9.9

2·1. *Theoretical systematics.* – As mentioned in the previous section, the precise and accurate characterization of the W boson production is crucial to enhance the sensitivity of the reconstructed p_T^μ distribution to m_W. When a W boson is produced in a proton-proton collision, its kinematics is affected by gluon emission in the transverse plane, and by the parton distribution functions (PDFs) along the longitudinal axis.

For the modeling of the boson transverse momentum distribution p_T^V, a key concept has been exploited: the variation of many theoretical parameters, that regulate the boson production modeling and the PDFs, has an impact on the p_T^μ distribution different in shape to a pure m_W variation. This allows the data itself to constrain those parameters *in situ*, during the fit procedure. Therefore, the p_T^V model has been developed accurately, making use of the state-of-the-art Monte Carlo (MC) generators available at the time. The $Z \to \mu\,\mu$ process is later used only as validation of the procedure. In addition, to reduce the dependence on the PDFs, which indirectly affect the reconstructed muon transverse kinematics, the analysis is performed differentially in 48 bins of muon pseudorapidity η^{μ}.

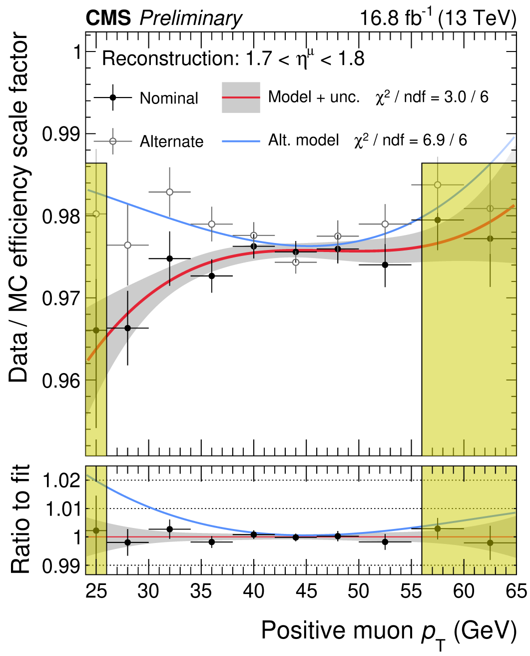

Fig. 2.: Muon efficiency scale factors of the "reconstruction" step, for a single η^{μ} bin, for both the nominal and alternative strategy (consisting, in this case, of a variation of the signal model in the tag-probe invariant mass fit). The smoothing polynomial of third order is shown. The yellow bands indicate two p_{T}^{μ} regions that are used only for the scale factors measurement and smoothing, but not for the m_{W} measurement.

2·2. *Efficiency scale factors measurement.* – MC templates are fundamental for the extraction the m_{W}. While the detailed simulation produced by the experiment typically repoduces well all the main detector effects, some local corrections, referred to as *scale factors* (SFs), must be applied to improve its agreement with data over the entire $\eta^{\mu} - p_{\mathrm{T}}^{\mu}$ acceptance of the measurement, before the fit. For this purpose, the data/MC SFs for the muon reconstruction efficiencies have been accurately measured.

The strategy implemented for the efficiency measurement is the tag-and-probe technique on $Z \to \mu\mu$ events. In these events, the "tag" is a well reconstructed muon, while the "probe" is a muon candidate that passes or fails specific requirements: in particular, the reconstruction efficiency is studied in five steps, corresponding to subsequent muon selection stages, as function of the probe p_{T}, η and charge. The efficiencies ε are measured on data and simulation, with the SF defined as the ratio $\varepsilon_{\mathrm{data}}/\varepsilon_{\mathrm{MC}}$.

A fundamental condition for the correct use of this technique is that the selection of the tag must not be correlated with the probe selection. This is not verified for the efficiency steps that request the probe to be isolated (as well as the tag), because of the hadronic recoil of the Z boson: when $p_{\mathrm{T}}^{\mathrm{tag}} > p_{\mathrm{T}}^{\mathrm{probe}}$, the probe is produced closer to the hadronic recoil, causing a drop of the measured efficiency. This effect depends on the p_{T}^{Z} distribution and on the tag-probe angle in the transverse plane; these distributions are different with respect to $W \to \mu\nu$ events. The mitigation solution that has been applied consists in measuring the efficiencies of the "trigger" and "isolation" steps further differentially in the u_{T} variable, with $u_{\mathrm{T}} = \left(\mathbf{p}_{\mathrm{T}}^{Z} \cdot \mathbf{p}_{\mathrm{T}}^{\mu}\right)/\left|\mathbf{p}_{\mathrm{T}}^{\mu}\right|$.

On data, a background subtraction procedure is needed not to introduce a bias in the measured efficiencies: therefore, the tag-probe invariant mass is computed, and a likelihood fit is performed on this distribution, having provided a signal and a background model. For the nominal strategy, the signal model is derived from the MC template of the target events, with a Gaussian smearing to cover residual uncorrected modeling of detector reconstruction; as a background model, an analytic shape is used. By changing signal or background model for the fit on data, "alternative" scale factors are measured and used for the definition of the systematic error associated to the scale factors: for all the steps, a systematic uncertainty is estimated by measuring the efficiencies with an analytical shape as signal model; an additional uncertainty is applied on the first two steps, namely the "reconstruction" and "tracking" steps, by using a MC-based model for the background rather than the analytical shape.

A "smoothing" procedure is performed to the scale factors as a function of p_{T}^{μ} (and u_{T}, where present), since they are expected to be regular in this variable(s). For each single η^{μ} bin, the scale factors are fitted with a polynomial curve and, from the diagonalization of the post-fit covariance matrix, multiple independent variations are extracted; these variations are treated as the statistical error component on the scale factors. The ratio between the alternative and the nominal scale factors (both after the smoothing procedure) is instead treated as systematic uncertainty on the SFs (figure 2). In total, this whole procedure results in more than 3000 nuisance parameters in the final likelihood.

3. – Validation tests and unblinding

To validate all the experimental inputs and the stability of the theoretical model, two ancillary measurements of the Z boson mass on $Z \to \mu\mu$ events, have been set up: the "dilepton" and the "W-like" analyses. In the former, aiming to validate the calibration, the extraction of m_{Z} is made from the invariant mass of two opposite charge muons $m_{\mu\mu}$ ([1]). In the latter, one of the two muons is treated as a neutrino, and the Z boson mass is extracted from the transverse momentum distribution of the other muon: the similarity with the analysis for the W boson mass is extremely useful to validate in particular the scale factors and the p_{T}^{V} modeling, in a background free environment. Both the measured values are compatible, within the uncertainty, with the Z boson mass tabulated by the PDG [2].

The likelihood fit for the extraction of the W boson mass is then performed and the measured value is

$$m_{\mathrm{W}} = 80360.2 \pm 9.9 \text{ MeV}. \tag{1}$$

([1]) This is not intended as a proper m_{Z} measurement, since the calibration procedure is in part tuned to match the Z resonance.

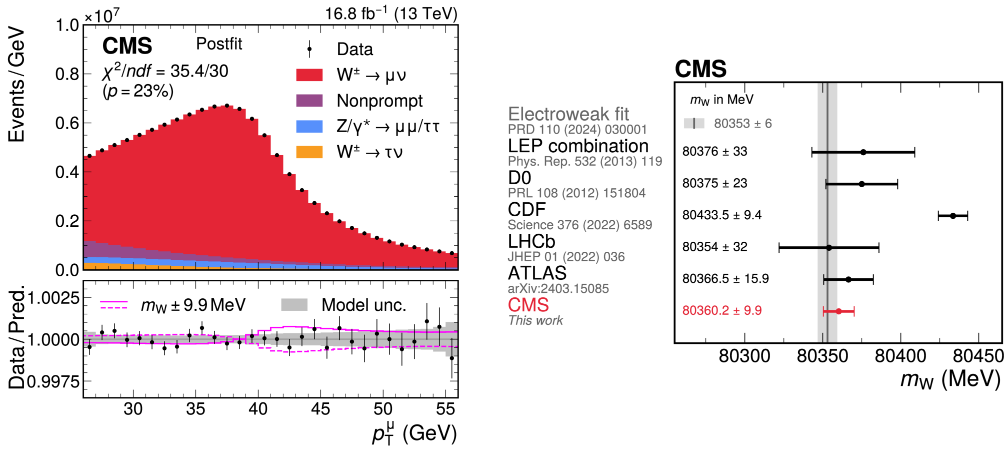

Fig. 3.: Results of the fit on m_W. On the left: p_T^μ distribution for data and simulation, with the latter one having the parameters at the Likelihood maximum; the relative variation corresponding to a m_W shift equal to the total uncertainty is shown in the lower panel, superimposed to the experimental points. On the right: comparison of this measurement with the results from other experiments and the SM prediction.

4. – Conclusion

The W boson mass measurement presented by the CMS experiment is the most precise at the LHC, and its value is compatible with the standard model prediction (fig. 3). The precision is comparable to the CDF measurement and in significant tension with it. For this analysis, advanced techniques for the characterization of the various experimental and theoretical systematic uncertainties have been developed and applied. New possible developments for future measurements have been studied as well: for example, the usage of a larger dataset collected during Run 2 (the measurement here presented covers roughly 12% of it), or the reduction of the dependence of the analysis on theoretical inputs.

REFERENCES

[1] CMS Collaboration, *The CMS experiment at the CERN LHC*, *JINST*, **3** (2008) S08004
[2] Particle Data Group, S. Navas et al., *Review of particle physics*, *Phys. Rev. D*, **110** (2024) 03001
[3] CDF Collaboration, *High-precision measurement of the W boson mass with the CDF II detector*, *Science*, **376** (2022) 170
[4] LHCb Collaboration, *Measurement of the W boson mass*, *JHEP*, **01** (2022) 036
[5] ATLAS Collaboration, *Measurement of the W-boson mass and width with the ATLAS detector using proton-proton collisions at $\sqrt{s} = 7$ TeV*, *Eur. Phys. J. C*, **84** (2024) 1309
[6] CMS Collaboration, *Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV* *JINST*, **13** (2018) P06015
[7] CMS Collaboration, *High-precision measurement of the W boson mass with the CMS experiment at the LHC*, 2024, arXiv:2412.13872v1. Submitted to Nature.