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W mass: a theory overview

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The measurement of the W boson mass represents a very important test for the internal consistency of the standard model of particle physics, and could also possibly highlight signals of New Physics. We provide a concise theory overview on the topic, presenting the typical measuring strategies, the known perturbative and non-perturbative theoretical ingredients used to predict the relevant observables, the treatment of theoretical systematics in recent experimental measurements and some future prospects to reduce modelling uncertainties.

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1. The W boson in the electroweak sector

The electroweak sector of the Standard Model of elementary particles is fully determined by fixing the Higgs mass, the fermion masses and three additional parameters: the gauge couplings g, g' and the vacuum expectation value v of the Higgs field. All the electroweak observables can be written in terms of them, i.e. $m_W = v|g|/2, m_Z = v\sqrt{g^2 + g'^2}/2, \theta_W = \tan^{-1}(g'/g)$. The comparison of theoretical predictions with experimental measurements provides a valuable test of the Standard Model.

A common and convenient choice to fix (g, g', v) is the following set of experimental measurements: the Fermi constant G_F, extracted from the muon lifetime [1], the fine structure constant α, obtained from the anomalous magnetic moment of the electron [2], and the mass m_Z of the neutral massive vector boson, measured with high accuracy at the Large Electron Positron collider [3] from the Z lineshape. The high experimental precision attained for this set of measurements allows to minimise the parametric uncertainty of theoretical predictions.

The muon decay width can be calculated within the Fermi model [4–6] (including two-loops QED corrections to the effective interaction vertex [7–9]) and within the full Standard Model. Matching the two results lead to a well-known $m_W - m_Z$ interdependence,

$$m_W^2 \left(1 - \frac{m_W^2}{m_Z^2}\right) = \frac{\pi\alpha}{\sqrt{2}G_F}(1 + \Delta r)\,. \tag{1}$$

The last term on the r.h.s of Eq. 1, $\Delta r = \Delta r(\alpha, G_F, m_W, m_Z, m_H; m_f; CKM)$, contains all the radiative corrections to the tree-level result. In the past decades, a huge effort has been devoted to its computation at various perturbative orders both in the EW theory [10–15] and in QCD [16–20]. The state of the art is at present the full two-loop accuracy, reached through a series of publications by several groups [21–36]. Partial three-loop and four-loop results are also available [37–41].

Missing higher-order contributions lead to a *theoretical uncertainty* $\delta m_W = 4$ MeV in the on-shell renormalisation scheme [42] and $\delta m_W = 3$ MeV in the $\overline{MS}$ renormalisation scheme [43]. An additional uncertainty comes from variation of the input parameters contained in Δr: a 1σ variation for each of them leads to a *parametric uncertainty* $\delta m_W = 5$ MeV. In view of a very precise ($\delta m_W/m_W \approx 10^{-4}$) measurement at the LHC, it would thus be highly desirable to reach at least a full three-loop accuracy in theoretical predictions to further reduce these uncertainties.

An indirect determination of the W mass can be obtained through a *global electroweak fit*, which combines all the information coming from many experiments into one single χ^2 fit: leaving one (or more) parameters free, one can find the best matching value to all other observables. The HEPFIT collaboration reports an expectation value $m_W^{SM} = 80.3545 \pm 0.0057$ GeV [44], while the GFITTER collaboration quotes $m_W^{SM} = 80.356 \pm 0.006$ GeV [45]: the two extractions are thus consistent within the quoted uncertainties.

2. Measuring the W mass at hadron colliders

The measurement of m_W at hadron colliders is performed by studying the charged *lepton transverse momentum* p_T^ℓ distribution and the lepton pair *transverse mass* m_T distribution, defined as

$$m_T = \sqrt{2p_T^\ell p_T^\nu(1-\cos(\phi^\ell-\phi^\nu))}, \tag{2}$$

where the neutrino four-momentum p_T^ν and the ϕ^ν angle are inferred from the transverse momentum imbalance in the event. The mass of the W boson is obtained by a *template fit* procedure, in which experimental distributions are compared to the corresponding theoretical predictions with m_W kept as a free parameter.
In particular, given an experimental distribution, one

- computes the corresponding theory distribution at the highest available accuracy for several $m_W^{(k)}$ values,
- compute a χ^2 for each $m_W^{(k)}$ in a certain fitting interval,
- find the minimum of the χ^2 distribution, which gives the measured value for m_W.

The result of the fit depends on the hypotheses used to compute the templates (choice and variation of perturbative scales, choice and uncertainty of collinear PDFs, non-perturbative ingredients, ...): these hypotheses should be treated as theoretical systematic errors.

Missing transverse energy (p_T^ν) is typically not used in template fits because of poor experimental resolution. Hadronic decays of the W are not considered as well, mainly because of the multi-jet background. The extractions thus focus on p_T^ℓ and m_T.

The p_T^ℓ distribution exhibit a Jacobian peak around $\approx m_W/2$, while the transverse mass has an endpoint near m_W: the position and shape of the distributions at both the peak and the endpoint are significantly impacted by radiative corrections. In particular, the details of p_T^W modelling at low transverse momenta play a relevant role in the study of p_T^ℓ. The m_T observable, instead, is less affected by soft radiation but is limited by the experimental resolution of the hadronic recoil.

In both cases, a determination of m_W at the 10^{-4} level requires to control the shapes of the above distributions at permille level [46, 47]. In the following section we will discuss the state of the art for the theoretical predictions (and related uncertainties) relevant to the production and decay of the W boson in proton-proton collisions.

3. Theoretical modelling and related uncertainties

Theoretical predictions are computed through convolutions of collinear PDFs and a partonic cross section. The precision program at the LHC requires both perturbative (EW and QCD fixed-order and all-order calculations) and non-perturbative (collinear PDFs, non-perturbative intrinsic transverse momentum of partons) ingredients to be computed at the highest accuracy.

We start with the perturbative part of the predictions. The basis for any analysis is the fully differential Drell-Yan cross section, which can be written as follows:

$$\begin{aligned}\frac{d\sigma}{d^3p_1d^3p_2} &= \left[\frac{d\sigma(m_{ll})}{dm_{ll}}\right]\left[\frac{d\sigma(y_{ll})}{dy_{ll}}\right]\left[\frac{d\sigma(p_T,y_{ll})}{dp_T}\frac{1}{\sigma(y_{ll})}\right]\\ &\times \left[(1+\cos^2\theta)+\sum_{i=0}^{7}A_i(p_T,y_{ll})P_i(\cos\theta,\phi)\right],\end{aligned} \tag{3}$$

In the above formula, p_1 and p_2 are the four-momenta of the (massless) decay leptons. The invariant mass, transverse momentum and rapidity of the dilepton system are indicated by m_{ll}, p_T and y_{ll}, respectively. The angles θ and ϕ denote the polar and the azimuthal angle of one lepton in the rest frame of the lepton pair. Finally, helicity and polarization effects are embodied in the eight spherical harmonics P_i of order zero, one and two, weighted by the eight numerical coefficients A_i.

Two-loops QCD corrections have been computed for the total cross section [48, 49], the rapidity distribution [50] and the fully differential cross section including leptonic decays [51–54]. A few years ago, three-loop accuracy has been achieved for the total cross section [55–57]. Pure NLO electroweak corrections, mixed QCD-EW and mixed QCD-QED corrections are also available [58–79]: it turns out that QED final state radiation have a strong impact on the determination of m_W. Summing things up, the perturbative ingredients for most of the terms in Eq.3 are known up to $O(\alpha_s^3)$ and $O(\alpha\alpha_s)$, but a complete $O(\alpha^2)$ result is still missing. Selected subleading corrections are available in SANC [80], WINHAC (interfaced to PYTHIA) [81] and POWHEG [82–84] frameworks.

As already stated, a m_W measurement relies on observables in the transverse plane (p_T^ℓ and m_T in particular), whose kinematical peaks at $p_T^\ell \sim m_W/2$ and $m_T \sim m_W$ are heavily affected by soft emissions from initial states that induce a non-zero transverse momentum of the W boson. An accurate prediction of the third term in Eq. 3, including both fixed-order and resummed results, is thus essential. At large transverse momenta ($q_T \sim m_{ll}$), fixed-order QCD corrections are known analytically up to $O(\alpha_S^2)$ [85–89] and numerically up to $O(\alpha_S^3)$ [90–94]. In the low-q_T region, the presence of large logarithms of the type $\ln(q_T^2/m_{ll}^2)$ spoils the convergence of the perturbative series: one thus needs to resum these contributions to all orders [95–100]. Many results are available, at different logarithmic accuracy, are available in the formalism of q_T resummation (both in direct and conjugate space) [101–110], and also within the Soft Collinear Effective Theory [111–120] and transverse-momentum dependent (TMD) factorisation [121–129]. The state of the art is at present the full N^{3}LL accuracy at low-q_T, consistently matched to NNLO accuracy at high-q_T. Partial results including N^{4}LL contributions are also available [130, 131].

Finally, the interplay of QCD and QED corrections and the impact of QED final state radiation on the peak of the charged lepton transverse momentum have been investigated [132–134].

As for the non-perturbative part of the theoretical cross section, the largest model uncertainty in the m_W determination is due to collinear PDFs.

The impact of different choices of PDF sets and/or different choices of Hessian eigenvectors (or Monte Carlo replicas) for a given PDFset has been studied for both m_T (mild impact) and p_T^ℓ (relevant impact) [46, 47, 135–137]. Taking advantage of anti-correlation effects among forward (LHCb) and central (ATLAS, CMS) detectors, an uncertainty reduction has been obtained for a combined measurement [138]. A further step in reducing PDF uncertainty has been suggested in [139] by considering bin-to-bin correlation with respect to PDF variation.

Another uncertainty of non-perturbative origin arises from the treatment of heavy quarks. For example, the bottom quark can be considered either as a massless component of the proton (in the so-called *5-flavour scheme*) or can be perturbatively produced in the final state (in the so-called *4-flavour scheme*): this induces a δm_W shift in the 3-5 MeV range [140].

Finally, effects due to a possible flavour-dependent intrinsic-k_T of the quarks in the initial state have been studied in [141, 142] and found to be comparable in size to those generated by PDF variations.

4. Hadron collider measurements

The W mass has been measured by the D0 [143] and CDF [144] collaborations at the Tevatron $p\bar{p}$ collider, with a center of mass energy of $\sqrt{s}$ = 1.96 TeV, and by the ATLAS [145, 146] and LHCb collaborations [147] collisions at the LHC through pp collisions at $\sqrt{s}$ = 7 TeV and $\sqrt{s}$ = 13 TeV. In the following we will briefly discuss the estimate of theoretical uncertainties contained in the various analyses.

D0 measurement: $m_W = 80375 \pm 23$ MeV.

PDF uncertainty is estimated through a template fit on ensembles generated with the error set of the default PDF used (CTEQ6.6 [148]). QED effects are analysed through a comparison of the default generator PHOTOS [149] used for QED FSR with the alternative generators WGRAD [150] and ZGRAD [151]. Non-perturbative effects associated to the p_T^W distribution result from the propagation to p_T^ℓ and m_T of the parametric uncertainties of the BLNY parameterisation fitted on Z data [152].

CDF measurement: $m_W = 80435 \pm 9$ MeV.

The analysis of PDF uncertainties take into account several different PDF sets other than the default one (CTEQ6.6): ABMP16 [153], CJ15 [154], CT18 [155], MMHT2014 [156] and NNPDF3.1 [157]. QED uncertainties comparing the default generator PHOTOS with the HORACE code [158]. The estimate of non-perturbative uncertainty is made similarly to the D0 collaboration, but with a new simultaneous fit of the strong coupling and the non-perturbative parameters on Z data. The anti-correlation between the resulting uncertainties on α_S and the BLNY parameters has been used to further reduce the uncertainty stemming from NP modelling. The p_T^W/p_T^Z modelling uncertainty is estimated by propagating the envelope of renormalisation, factorisation and resummation scale uncertainties obtained with the DYqT code [159, 160] at NNLL perturbative accuracy.

LHCb measurement: $m_W = 80354 \pm 31$ MeV.

Electroweak and QED effects on the final state leptons are computed with HERWIG, PYTHIA and PHOTOS: the spread among predictions generate the corresponding uncertainty. PDF uncertainties are estimated through the arithmetic average of three independent fits performed with NNPDF3.1, CT18 and MSHT20 [161]. Modelling uncertainties on p_T^W are computed using alternative codes (PYTHIA standalone, HERWIG [162] standalone, POWHEG + HERWIG and DYTURBO [163]) instead of the default choice (POWHEG [164] + PYTHIA 8 [165]) for predictions, and taking into account renormalisation and factorisation scale variations for the angular coefficients.

ATLAS measurement: $m_W = 80360 \pm 16$ MeV.

PDF uncertainties are estimated through the Hessian method on the default CT10nnlo set [166], and on the additional CT14, CT18, MMHT2014, MSHT20, NNPDF3.1 PDF sets: the corresponding uncertainties are then summed in quadrature. Electroweak and QED effects (and corresponding uncertainties) are generated with WINHAC [81], supplemented with PHOTOS for QED final state radiation and PYTHIA for QED initial state radiation. Modelling uncertainties on p_T^W come from the propagation of PYTHIA parameters tuned to Z data to lepton distributions, initial state charm and bottom quark mass effects and perturbative scale variations for the angular coefficients.

A summary of the shift in m_W generated by the different sources of theoretical uncertainty is reported for each experimental measurement in Table 1.

Experiment	D0 [143]		CDF [144]	
Observable	p_T^ℓ[MeV]	m_T [MeV]	p_T^ℓ[MeV]	m_T [MeV]
PDF	11	11	4	4
EW&QED	7	7	3	3
p_T^W modelling	2	5	2	1
Experiment	ATLAS [146]		LHCb [147]	
Observable	p_T^ℓ[MeV]	m_T [MeV]	p_T^ℓ[MeV]	
PDF	8	15	9	
EW&QED	6	6	7	
p_T^W modelling	5	10	11	

Table 1: Impact of theoretical uncertainties on hadron collider measurements of the W mass.

5. Future Prospects

A lot of work has been devoted in recent years to improve the analysis strategies from the theoretical point of view.

An obvious possibility would be to include additional differential distributions (lepton rapidity, hadronic recoil) to the fitting procedure, in order to achieve a reduction of modelling uncertainties.

Alternative observables have also been suggested: in [167], for instance, the authors define an asymmetry around the p_T^ℓ jacobian peak, that proves to be particularly sensitive to m_W and yields a sensible reduction of modelling uncertainties.

Modelling systematics would also benefit from the recent advances in the investigation of hadron structure: effects related to the intrinsic-k_T of partons, thanks to TMD PDF fits performed at high perturbative accuracy [125–129], can now be studied in great detail and possibly disentangled from those originating from collinear PDFs.

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