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PRECISION MEASUREMENT OF THE W BOSON MASS: STATUS AND PROSPECTS

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Abstract

In this talk, I will review the current status of the direct measurement of the W boson mass, with particular emphasis on recent results and opportunities from future measurements.

1 Introduction

A precision measurement of the W boson mass (m_W) plays an important role in the test of the electroweak theory [1]: as of today, the indirect determination of m_W is more precise (by a factor of about two) than its direct measurement [2], so that even a twofold reduction in the experimental uncertainty, albeit challenging from an experimental standpoint, would have a non-negligible impact on the global fit of the electroweak theory.

It is well-known that the SM tree-level prediction of m_W can be expressed in terms of just three parameters, which can be chosen to be e.g. the well-measured values of the Fermi constant (G_μ), of the eletromagnetic running coupling at the Z mass ($\alpha(m_Z)$,) and of the Z boson mass itself (m_Z). Radiative corrections to the tree-level prediction introduce a further dependence on the Higgs boson and on the top-quark masses, overall shifting the predicted value by about 500 MeV. Overall, the SM prediction has a relative precision of 10^{-4}, where the dominant sources of uncertainty come from missing higher-order EWK corrections (~ 4 MeV) and the limited precision of the direct top-quark and Z boson mass measurements [1]. However, contributions from new particles of a yet-unknown physics sector, where new interactions might contribute to the breaking of the custodial symmetry (e.g. new Higgs multiplets with $T > \frac{1}{2}$, new non-degenerate $SU(2)$-doublets, extra $U(1)'$ symmetries, etc..) could, at least in principle, modify the SM prediction.

Recently, the CDF Collaboration has released a new measurement of m_W which improves over their previous result, and happens to be largely inconsistent with the SM prediction of m_W, as well as in substantial tension with other existing measurements at the LHC [3]. The current situation is well illustrated by Figure 1.

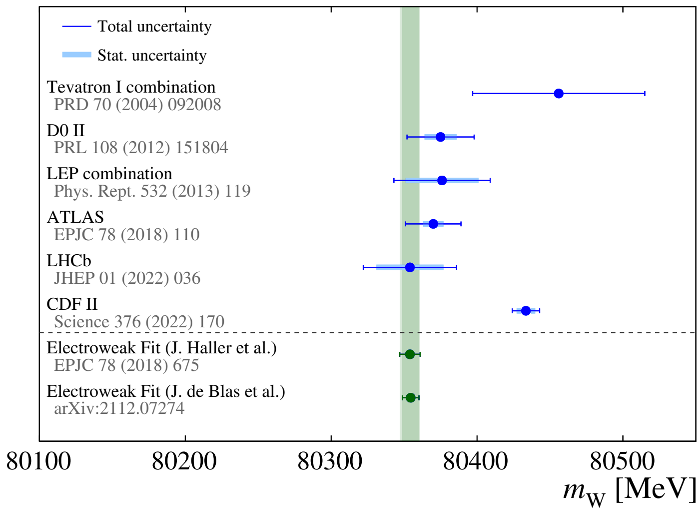

Figure 1: *Status of W boson mass measurements* [4].

2 W boson production at colliders

Differently from other short-lived particles, m_W cannot be reconstructed from the full decay chain of W bosons, being the neutrino from the decay undetectable and the initial velocity of the decaying boson unknown on an event-by-event basis. This leads to a dependence of any possible mass estimator on the mechanism of production and decay of W bosons. The latter can be however calculated in pQCD: perturbative calculations, jointly with modern predictions of the proton PDFs, an improved treatment of soft and collinear gluon radiation, and the inclusion of higher-order EWK corrections, can now achieve an oustanding level of accuracy [5].

Interestingly, the two accelerators which can nowadays measure m_W (Tevatron and LHC) differ enough in terms of both the initial-state and the environmental conditions so that common sources of systematic uncertainty affect the two measurements usually at different levels and with different correlation schemes. In particular, while uncertainties on the modeling of the hard-scattering event can be assumed uncorrelated between the two experiments because of the substantially different center-of-mass energy and flavour composition of the initial-state, the PDFs should be the same (if PDFs are really meant to provide a universal description of the proton).

While the result of a measurement should be code-independent (provided that any of the codes in use is bug-free and that the quoted uncertainties provide the right coverage), recent studies have shown that this is not always the case, and special care should be put to understand the impact of specific codes to the central values as well as to the uncertainty budget quoted by the experiments. Finally, the necessity to tune the QCD prediction to match the well-measured kinematic distributions of Z decays (a practice which is common to all existing measurements) represent a potential source of common "bias", the size of which has been estimated on different grounds by each experiment, but without a conclusive theoretical understanding.

In the following, the most recent measurements of m_W at hadron colliders will be shortly reviewed in a comparative way.

2.1 CDF-II

The recent measurement by CDF-II [3] is based on their full data sample of electron and muon events. The analysis relies on MC-based templates of three kinematic quantities. These templates are obtained by using a rather old generator (`ResBosP`) and PDF set (`CTEQ6M`). A correction to a more modern PDF set (`NNPDF3.1`) is accomplished by shifting the measured value of m_W based on a theory-to-theory comparision. Non-perturbative parameters of `ResBosP` are tuned to match the measured q_T spectrum in Z events. A custom simulation of the CDF detector is used to allow for a fast generation of events. Based on the comparision between measured and simulated mass distributions of reconstructed J/Ψ, $\Upsilon(1s)$ and Z events, the absolute momentum scale of charged-particle tracks in data is adjusted by a relatively large (and still unexplained) factor, amounting to a relative correction of about 10^{-3}. The surpisingly large value of this correction, as well as the validity of the linear extrapolation assumed to correct the momentum scale over a broad range of values, has been extensively debated within the community. The final uncertainty on m_W is estimated to be 9 MeV.

2.2 D0

The latest D0 [6] result is based on the electron-channel only. It uses the `ResBosCP` program interfaced to the `CTEQ6.6` PDF set. Non-perturbative parameters of `ResBosCP` are tuned to the measured Z data. The uncertainty on m_W is estimated to be 23 MeV. Differently from CDF, the D0 collaboration won't be able to update its 2012 result on a larger sample.

2.3 ATLAS

The ATLAS Collaboration has published a measurement of m_W based on their 7 TeV data [7]. The physics modeling is based on the `Powheg` event generator interfaced to `Pythia8` and the `CT10` PDF set. The helicity cross sections are corrected differentially in rapidity and transverse momentum of the W boson, as to match the predictions of `DYNNLO`, which is has higher-order accuracy on the angular coefficients. Non-perturbative parameters of `Pythia` are tuned to the measured Z p_T spectrum. The absolute momentum and energy scale of simulated muons and electrons is corrected to match the mass distributions measured in Z decays. A total of 28 statistically independent channels are combined to give an overall uncertainty of about 19 MeV.

2.4 LHCb

The LHCb Collaborations has published a measurement of m_W based on a sub-sample of their Run2 data [8]. The physics modeling is based on the `Powheg` event generator interfaced to `Pythia8` and the `NNPDF3.1` set. The `DYTurbo` program is used to correct the angular coefficients. Non-perturbative parameters of `Pythia` are profiled by including the ϕ^* [9] spectrum measured in $Z \to \ell\ell$ events into a combined fit with the data sensitive to m_W, which is chosen to be the distribution of q/p_T (where q is the charge of the muon). A nuisance parameter which rescales the overall value of the A_3 coefficient [10] is included in the fit. The total uncertainty on m_W is estimated to be 32 MeV.

2.5 Towards a combined result

The use of different codes and prescriptions to tame modeling uncertainties poses a non-trivial problem in sight of a common interpretation of the results. A joint effort between Tevatron and LHC collaborations has been addressing this problem [5]. The proposed solution is to compute δm_W shifts to the published values which effectively update (or correct) to more recent codes. This solution allows to treat the various measurements on the same footing, paving the way towards a proper combination and assessment of a combined theory uncertainty. Interestingly, a non-negligible, i.e. $O(10)$ MeV, impact of using an outdated version of their generator (`ResBos1`) instead of a more recent one (`ResBos2`) has been highlighted in the context of the D0 measurement.

3 Tevatron vs LHC

It is instructive to compare the breakdown of the systematic uncertainties affecting the Tevatron and LHC measurements. Considering just the two best measurements from each collider [3, 7], which happen to have very similar statistical uncertainty, one can easily see that the LHC measurements are affected on average by larger systematic uncertainty both of modeling and experimental origin. While the latter can be ascribed to the cleaner environment at the Tevatron (e.g. lower pileu-up and $\sqrt{s}$ and less material budget in the tracking volume), the variability in the estimation of modeling uncertainties can be only in part accounted for by environmental effects: the largest source of difference still arises from specific choices made by each collaboration in terms of code and correlation schemes between theory nuisance parameters. For example, if the LHC Collaboration had chosen to apply the full-NLO scale variation uncertainty on A_3 instead of fitting a unique freely-floating parameter, the error budget on m_W from just this parameter would have increased from 9 MeV to about 30 MeV [8]. Likewise, if a same nuisance parameter were chosen to modify the input value of α_s in the `Pythia` generator of W and Z events, instead of two independent parameters, the shift on the measured value of m_W would have been of about 40 MeV, which is larger than the overall uncertainty quoted by the LHCb measurement. Similar features are reported by the ATLAS Collaboration [7].

While most of these choices are claimed to improve the overall agreement between data and simulation in either the signal region or in closely related calibration regions, the tuning of model parameters in the context of a shape-based analysis like this one should be taken with some caution, since tuning come with the risk of hiding intrinsic limitations of the models.

The implication of the CDF-II choice of using a rather old code is still under investigation and no conclusive statement has been made yet. However, from all studies to date, [5] there doesn't seem to be an easy way to change the modeling in the recent CDF measurement such to reconcile it with the SM expectation.

In the near future, we will hopefully get new insights on the impact of mixed QCD-EWK corrections [11] (so far neglected by all codes) and on the flavor-dependence of the non-perturbative corrections [12].

4 The role of CMS

The CMS Collaboration has already given proof of its capability to measure m_W with competitive precision thanks to an end-to-end measurement of m_Z in the so-called W-like topology [13], i.e. in fully reconstructed di-lepton events where one lepton at the time is treated as a neutrino. Since then, the guideline followed by CMS has been to reduce model-uncertainties by means of more (and more-differential) data and the use of state-of-the-art developments in pQCD calculations. Along this road, the measurement of the rapidity cross section of $W^{\pm}$ at 13 TeV for two helicity states stands up as an intermediate milestone towards m_W [14]. Indeed, this measurement has proved that a strong *in situ* constraint of the PDFs is possible with just a tiny fraction of the Run2 data collected by CMS. The measurement of m_W from the same data was precluded by the lack of a precise enough calibration of the muon momentum scale and by limitations of the MC samples available at that time.

5 Future measurements

The planned Phase2 upgrades of the ATLAS and CMS experiments offer the potential to improve on some of the weak points affecting the present measurements. In particular, an extended low-PU run during the HL-LHC era (or earlier, during the Run3) might provide a powerful data sample to perform a precise measurement of m_W, especially if joined with the extended pseudo-rapidity coverage offered by the upgraded tracking detectors and improvements on the theory and PDF side [15].

Finally, one should not give up on the idea of using the larger-than-ever statistical power of the high-PU data collected during the Run2 and 3 of the LHC. To this aim, however, something has to be done to evade the model-dependence of the traditional approach. For example, the idea behind the ASYMOW project [16] is to replace the prediction of a paticular code by a theory-agnostic QCD model, which can be e.g. written in terms of double-differential helicity cross sections:

$$\frac{\Delta^2\sigma}{\Delta p_T^\ell\,\Delta\eta^\ell} = \sum_{\Delta q_T,\Delta|y|} \frac{\Delta^2\sigma_{-1}}{\Delta q_T,\Delta|y|}\left[T_{-1}(p_T^\ell,\eta^\ell\,;\,m_W) + \sum_{k=0\ldots4} A_{k,\Delta q_T,\Delta|y|} T_k(p_T^\ell,\eta^\ell\,;\,m_W)\right], \qquad (1)$$

where T_k are normalized templates defined in a narrow bin of q_T and $|y|$ of the W boson, and as such virtually independent from the QCD model used to build them. The dependence of the templates on m_W is parametric. Within this framework, m_W and the production model can be disentangled at the price of an increased statistical uncertainty on the former. We remark that a (large) MC sample is still needed to account for QED FSR and detector effects. Preliminary studies show that the data collected at the Run2 and Run3 of the LHC should be enough to achieve a statistical-only uncertainty of about 6 MeV from this new method.

Finally, it should be mentioned that the ultimate precision on m_W is expected to come from the next generation of lepton-lepton colliders. For example, with a two-year run at the WW production threshold, FCC-ee is expected to achieve a sub-MeV precision on m_W [17].

6 Conclusions

The recent result by CDF has turned a tempting tension into a stunning anomaly. While BSM interpretations of the observed excess seem feasible, the inconsistency between this measurement and the LHC ($\approx 3.5\sigma$) or D0 measurement ($\sim 2.5\sigma$) still deserves some deeper understanding. The CMS Collaboration has now the potential to corroborate or exclude the CDF-II result. Yet, the modeling of W production remains the bottleneck of this analysis. Although a major effort of the theory community is ongoing to tackle this problem, it's likely that only more data in the future will be able to set a final word.

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