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Measurement of the W boson mass with the ATLAS detector

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The W boson mass (m_W) is a fundamental parameter of the Standard Model (SM) and was measured by several experiments at high energy e^+e^- and $p\bar{p}$ colliders. This parameter's measurement has the biggest impact on indirect searches for new particles or interactions, by comparing the measurement of this parameter with the prediction from the SM. Its current value, which combines several independent measurements, is 80385 ± 15 MeV. It was measured recently by the ATLAS experiment at LHC, using data recorded in 2011, with a centre of mass energy of 7 TeV. This measurement provides the following value for m_W : 80370 ± 19 MeV. This proceeding reviews some aspects of the measurement and includes some considerations for future measurements at the LHC.

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1. Introduction

It is widely known in the high energy physics community that there is a strong motivation to measure the W boson mass (m_W) with a relative accuracy at the level of 10^{-4}. The possible values for m_W from the Standard Model (SM) predictions using direct measurements of the Higgs boson mass and of the top quark mass set a natural goal of 8 MeV for the precision on the experimental m_W result [1]. Currently, the most precise value of m_W is obtained by combining several results from experiments at the LEP and Tevatron colliders into a world average of 80385 $\pm$ 15 MeV [2].

Recently, the first measurement of m_W at the LHC collider was performed by the ATLAS collaboration [3], using data recorded in 2011 at a centre of mass energy of 7 TeV. While benefitting from a large statistics of W and Z bosons, the LHC experiments, exploiting proton-proton (pp) collision data, have to deal with additional challenges with respect to those faced by the previous measurements in terms of systematic uncertainties. As an exemple, one can quote the uncertainty arising from the knowledge of proton parton distribution functions (PDFs) : in a pp collider, the fraction of heavy quarks involved in the W and Z boson production, for which the PDF uncertainties are higher than those of the light quark's, is bigger than in a $p\bar{p}$ collider. In addition, the production of W and Z boson happens at higher boson rapidities, therefore being sensitive to PDFs in less known phase space regions (smaller proton transverse momentum fraction x).

The strategy for the measurement is to obtain predictions with simulated events for signal and background (except for the multijet background, which is data-driven). Then, to extract the result, data and predictions for distributions sensitive to m_W are compared. These distributions are commonly the lepton transverse momentum (p_{T}^{ℓ}), the transverse mass of the boson (m_{T}) and the missing transverse momentum (p_{T}^{miss}). The latter one is more difficult to exploit at the LHC due to higher pile-up rates and is therefore only used as a cross-check in the analysis. A very accurate calibration of the detector and a very accurate prediction of the two observables, p_{T}^{ℓ} and m_{T}, had to be done in view of this measurement.

An overview of the experimental aspects of this measurement is given in section 2 ; then, the modeling aspects will be briefly described in section 3. For a more detailed description of these two aspects, the reader should refer to [3]. In section 4 the result together with its uncertainties are summarised, as well as the impact on the electroweak (EW) fit. Some considerations for future measurements at the LHC are also given.

2. Experimental aspects

2.1 Object definitions and event selection

Topologies with a W boson in the final state make a clear signature in the ATLAS detector. The decay channels of interest (those that allow sufficient precision for the measurement) are the cases when W bosons decay into a dilepton pair, where this pair is composed of an (anti-) electron or a (anti-) muon, and of the anti-neutrino (neutrino) of the same flavor. In the following we will use the word "lepton" for electrons, muons and their anti-particles only. The leptons are detected in the calorimeter (electron channel), in the muon spectrometer (muon channel) and in the inner detector (both channels). The neutrino is indirectly detected via the reconstruction of the hadronic recoil. The hadronic recoil, $\vec{u}_{\mathrm{T}}$, is the vector sum of calorimeter deposit excluding the lepton deposits. The neutrino missing transverse momentum, $\vec{p}_{\mathrm{T}}^{miss}$, is accessible from the recoil and $\vec{p}_{\mathrm{T}}^{\ell}$: $\vec{p}_{\mathrm{T}}^{miss} = -(\vec{u}_{\mathrm{T}} + \vec{p}_{\mathrm{T}}^{\ell})$. m_{T} is commonly defined as $m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{miss} cos\Delta\phi}$ where $\Delta\phi$ is the difference in azimuthal angle between the reconstructed lepton and the reconstructed neutrino.

The event selection requires exactly one lepton passing criteria for their identification and are required to be well isolated objects. There is a cut on p_{T}^{ℓ}, required to be greater than 30 GeV, and on the pseudo-rapidity (η) to be in the detector acceptance. Each lepton is required to match the associated object that fired the trigger system during data taking. The following cuts are applied : $u_{\mathrm{T}} < 30$ GeV, to limit the impact of the modeling of the W boson p_{T} ; $m_{\mathrm{T}} > 60$ GeV and $p_{\mathrm{T}}^{miss} > 30$ GeV to better reject backgrounds, and those arising from Z and multijet events in particular.

2.2 Lepton calibration

The calibration of the muon momentum scale and resolution uses Z boson events. It is then extrapolated to W events using the p_{T}^{ℓ} spectrum in these events, parametrising the calibration as a function of p_{T}^{ℓ} to extract the uncertainty due to this extrapolation. The muon sagitta bias correction uses $Z \to \mu\mu$ events and $W \to e\nu$ events, using the resonance peak for the former one and the E/p response for the latter one. Both methods compare the data to the prediction for the different charge categories as a function of η, thus accessing the sagitta bias correction. The total uncertainty due to the muon calibration and selection efficiencies is 10 MeV.

The electron energy scale and resolution calibration uses Z events and an overall average relative uncertainty of 9.4×10^{-5} is reached. A modulation of the detector response to electrons as a function of their azimuthal angle due to mechanical deformation under gravity is detected and corrected using W and Z events. The uncertainties on electron scale factors and calibration leads to an uncertainty on m_W of 14 MeV.

2.3 Hadronic recoil calibration

The hadronic recoil has to be precisely determined, since it enters in the definition of m_{T}, one of the two observables used to extract m_W, but also because there is an event selection cut on this variable, as well as p_{T}^{miss}, also calculated from the recoil. Hence any calibration uncertainty on the hadronic recoil will have some impact on the accuracy of the measurement. The hadronic recoil is very sensitive to pile-up, which is substantially higher at LHC than in previous hadron colliders. For the data considered here, recorded in 2011, the average number of collisions per bunch crossing was 9.1, and in 2012, it went up to 20.7, which should make the recoil calibration even more challenging when analysing 8 TeV data in the future. The calibration includes corrections to the pile-up as well as the underlying event activity, and residual response and resolution corrections are obtained in-situ using Z events, and extrapolated to W events with an uncertainty due to this extrapolation. The uncertainty coming from this calibration is 2.6 MeV and 13.0 MeV in the p_{T}^{ℓ} and m_{T} fits respectively.

2.4 Multijet background

The multijet background is estimated using a data-driven technique. Templates are built in two different background-enriched regions to fit multijet fraction. Three different observables are used, and the fit is performed in 6 different isolation regions. The background fraction is obtained with a linear extrapolation of these 6 results to the well-isolated signal region. It amounts to 0.6-1.7% and 0.5-0.7% depending on the η region in the electron channel and muon channel respectively.

3. Modeling aspects

3.1 Introduction to the modeling

In the W and Z prediction, the differential cross-section is factorised under 4 terms :

$$\frac{d\sigma}{dp_1 dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T,y)}{dp_T dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+cos^2\theta)+\sum_{i=0}^{7}A_i(p_T,y)P_i(cos\theta,\phi)\right] \tag{3.1}$$

where p_1 and p_2 are the decay lepton and anti-lepton momenta. This approximation was checked to be valid at the level of 2.0 $\pm$ 1.6 MeV for m_W. The boson mass dependence, dσ(m)/dm, is modeled using the well-known Breit-Wigner analytic formula. For the other terms, the signal simulation is reweighed according to various accurate predictions :

- the boson rapidity dependence, dσ(y)/dy, uses a fixed-order NNLO prediction ;
- the boson p_{T} at a given rapidity uses Pythia 8 with the AZ tune [4] ;
- the fourth term describes the angular distribution of the decay leptons. Here, θ and ϕ refer to the kinematics of the negatively charged decay lepton in W^- and Z events, and of the neutrino in the case of W^+ events. P_i are spherical harmonics of order 0, 1 and 2. The description of the numerical polarisation coefficients, A_i uses also a fixed-order NNLO prediction.

3.2 Fixed-order predictions : polarisation and rapidity

The DYNNLO program [5] is used to predict the boson rapidity spectrum and the polarisation. For the rapidity, the agreement with the data was validated in the 7 TeV ATLAS W, Z cross-section measurements [6]. The PDF set used is CT10nnlo, as it leads to the best agreement with the data. The MMHT14nnlo and CT14nnlo sets are used to assess the uncertainties ; the other sets are disfavoured by the data.

The prediction from DYNNLO of the polarisation was validated in the ATLAS Z polarisation measurement [7], except for A_2 for which there is an additional uncertainty. The uncertainties are propagated from the Z to the W.

3.3 Boson transverse momentum

This prediction uses the Pythia 8 generator tuned to Z p_{T} ATLAS data. To predict the W p_{T} spectrum, the ratio of W to Z differential cross-sections is used. Good agreement with the data is found for this ratio in the phase space of interest. Uncertainties on the parton shower (PS) include :

- tune uncertainties
- c-quark and b-quark masses uncertainties
- factorisation scale variation
- Leading order PS PDF uncertainty

Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T - p_T^ℓ, $W^\pm$, e	80349.8	9.0	0.0	14.7	3.3	6.1	8.3	5.1	9.0	22.9	12/11
m_T - p_T^ℓ, $W^\pm$, μ	80382.0	8.6	10.7	0.0	3.7	4.3	8.6	5.4	10.9	21.0	10/15
m_T - p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

Table 1: Some results of the m_W measurements [3] with the statistical uncertainties, together with all experimental uncertainties, divided into muon-, electron-, recoil- and background-related uncertainties, and all modelling uncertainties, separately for QCD modelling including scale variations, parton shower and angular coefficients, electroweak corrections, and PDFs. All uncertainties are given in MeV.

3.4 Electroweak and QCD uncertainties

QED and EW effects mainly come from photons radiated in the final state (FSR). These are implemented with Photos [8]. NLO EW corrections are checked with Winhac [9] and taken as an uncertainty. The impact of FSR photon pair production is checked with Photos and Sanc [10]. The resulting uncertainty from all EW effects is about 5 MeV for the p_T^ℓ fit and 3 MeV in the m_T fit.

The uncertainty from the PDFs on the fixed-order predictions dominates the total uncertainty of the measurement and amounts to 8.0 MeV in the p_T^ℓ fit, and to 8.7 MeV in the m_T fit.

4. Result and outlooks

Once all the detector calibrations, and accurate predictions are obtained, χ^2 template fits to the data in each category (charge, lepton channel, $|\eta|$ bin) are done using the reconstructed observables m_T and p_T^ℓ. All categories give consistent result with a χ^2/dof of $29/27$, which shows the strength of the detector calibration and of the physics modeling. The 28 determinations are combined using the BLUE method, properly taking into account the correlations between the categories. The result is :

$$m_W = 80370 \pm 7\ (\text{stat.}) \pm 11\ (\text{exp. syst.}) \pm 14\ (\text{mod. syst.})\ \text{MeV}. \tag{4.1}$$

Table 1 gives the breakdown of the uncertainties on final result. No particular source is strongly dominating it. It is therefore needed to improve on several sides to gain accuracy in the future. The result agrees well with the SM prediction given by the electroweak fit, and is also in good agreement with the world combination, as can be seen on Fig 1.

With a goal for the precision on the m_W parameter of less than 10 MeV, it is essential to think of of the future of the measurement and how to improve it. The use of data taken at 8 and 13 TeV can bring more information on this physics parameter. It will be challenging as the analysers will have to deal with environments with more pile-up and more radiations, but they will also be probing different kinematic regions, which is good for combinations – for exemple, the PDF sensitivity should be different.

More progress is also expected on the theory side. Ideally, predictions using well-defined techniques like resummation should be used[1]. A better handle on PDFs is possible by using profiled PDF sets with ATLAS data, and by including parton shower effects in these profilings.

[1]These techniques could not be used in the measurement due to disagreements of the prediction for the W p_T with the data ; improvements will likely come in the next years.

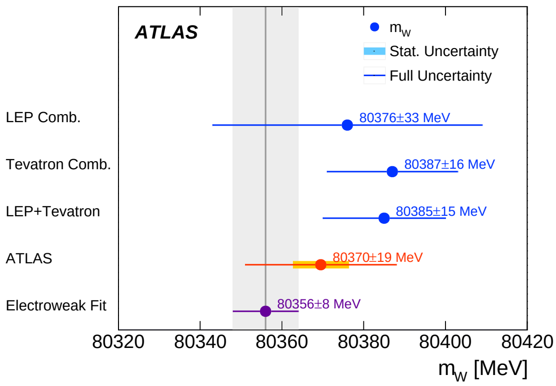

Figure 1: The present measurement of m_W is compared to the SM prediction from the global electroweak fit [1] updated using recent measurements of the top-quark and Higgs-boson masses, $m_t = 172.84 \pm 0.70$ GeV [11] and $m_H = 125.09 \pm 0.24$ GeV [12], and to the combined values of m_W measured at LEP [13] and at the Tevatron collider [14]. Figure taken from [3].

To face the new data taking conditions, experimental innovations will also be developed, e.g. new pile-up mitigation techniques. More and more ancillary measurements like W p_T or polarisation can also be performed, helping to reduce the uncertainties.

Finally, combinations with existing measurements (e.g Tevatron) and potentially future ones at other LHC experiments (e.g. CMS) should help to achieve a result with an uncertainty converging to the 10 MeV level.

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