PROCEEDINGS OF SCIENCE

Measurement of the W boson mass at CMS

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In this talk, we shall discuss the measurement of the W boson mass by the CMS experiment, which has recently gone public. The W boson mass has been measured using the proton-proton collision data at $\sqrt{s} = 13$ TeV, which corresponds to an integrated luminosity of 16.8 fb^{-1}, recorded during 2016 by the CMS experiment. The observed mass is $m_W = 80360.2 \pm 9.9$ MeV, which is the most precise result at the LHC. We shall also discuss the novel techniques for achieving such a precise measurement.

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1. Introduction

In the global electroweak fit, the standard model (SM) of particle physics is overconstrained, and the W boson mass, m_W, is constrained by the measurements of the other parameters of the theory, like the mass of the Higgs boson, top mass, Z boson mass, etc. With the observation and mass measurement of the Higgs boson at the CERN LHC, all the parameters in the eletroweak (EW) sector of the SM are now constrained by the experimental measurements. Before the CMS measurement, the experimental average was $m_W = 80369.2 \pm 13.3$ MeV [1]. The W boson mass, derived from the predicted relationships of EW parameters in the SM and independently measured observables, known as a global EW fit, is $m_W = 80353 \pm 6$ MeV [1] and is significantly more precise than the experimental measurements. Hence, measuring the W boson mass with higher precision is a stringent test of the SM and may enhance the sensitivity of physics beyond the SM. Furthermore, the recent W mass measurement of the CDF collaboration, which is the most precise and was not included in the above-mentioned experimental average, reported a value of $m_W = 80433.5 \pm 9.4$ MeV [2]. The strong disagreement between the CDF measurement and the SM expectation and the other measurements [3] represents a significant puzzle in particle physics. Hence, an independent measurement of the W boson mass is paramount. In this talk, we shall report the first measurement of the W boson mass by the CMS experiment [4] with 16.8 fb^{-1} of data recorded in 2016.

2. The CMS Detector

CMS is a hermetic detector comprising an all-silicon tracker, an electromagnetic calorimeter, a hadronic calorimeter and a muon system [5]. The tracker, electromagnetic calorimeter and the hadron calorimeter are placed within a superconducting solenoid, which produces a 3.8 T magnetic field. The muon detectors are embedded inside the steel return yoke for the magnetic field. The Particle Flow [6] algorithm in CMS detector is applied to reconstruct and identify electrons, muons, photons, charged and neutral hadrons and high-level objects like jets and hadronic decays of the tau lepton properly.

3. Analysis Strategy

The CMS measurement of the W boson mass is performed using the $W \to \mu\nu$ decay channel by exploiting a simultaneous maximum likelihood fit to the muon $p_T - \eta$ distribution for positively and negatively charged muons. The muon p_T distribution depends on the p_T of the W boson, which is modelled by the Monte Carlo (MC) generators with considerable systematic uncertainty. The systematic uncertainties are constrained in situ during the fit. The events are selected with a single muon trigger, requiring the presence of a single muon with $p_T > 24$ GeV. Identification and isolation criteria are applied to the selected muon to increase the purity of the signal events. After all the selections, roughly 100M W boson candidates were selected.

Signal W events and Z boson events are generated with MiNNNLO$_{PS}$ [7, 8], interfaced with PYTHIA [9] for the parton shower and hadronization, and with PHOTOS++ [10, 11] for the final state radiation. The MiNNLO$_{PS}$ prediction is modified with two-dimensional binned corrections in the W or Z boson p_T and rapidity obtained with SCETLIB [12–14] and thereby

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achieving N3LL+NNLO accuracy. A phenomenological model defines the uncertainties in the non-perturbative motion of the partons inside the proton [13]. A novel proposal, denoted as "theory nuisance parameters" (TNPs) [15], is used to parametrise the impact of unknown perturbative corrections. Uncertainties for variation in matching scale and missing higher orders in α_s are also considered. The CT18Z PDF set [16], at NNLO accuracy, is used.

In CMS, muons are reconstructed by matching a tracker track with a track in the muon system with some quality criteria. Scale factors are applied to MC events to account for differences in the muon reconstruction and identification efficiency between data and MC. These scale factors are measured using $Z \to \mu\mu$ events with unprecedented fine granularity in $p_T - \eta$. The effect of hadronic recoil from W/Z boson is also considered for isolation and trigger efficiencies. Uncertainties on the scale factors are propagated through an order of 3000 nuisance parameters.

A novel calibration procedure for the W mass analysis was performed, which improves the precision of the standard CMS calibration. The unique calibration chain started with tuning the parameters in the CMS simulation. The calibration procedure's next and most crucial step is to refit the muon tracks with the Continuous Variable Helix or CVH method, a global χ^2 fit that extends the generalized broken-line fit [17, 18]. Improved magnetic field and material treatment is incorporated during this step through Geant4e propagator [19–21]. A global correction for residual biases for the alignment, magnetic field and material is measured at the per-module level using $J/\psi \to \mu\mu$ events. Finally, the residual biases in the muon momentum scale are measured by fitting a parametric model in $J/\psi \to \mu\mu$ events in a fine-grained 4D space of $p_T^+, \eta^+, p_T^-, \eta^-$, where + and - refers to the muon charge. The calibration procedure is validated by applying the measured parametric corrections obtained from J/ψ events to J/ψ, Υ and Z events and repeating the extraction of the corrections. The compatibility between the J/ψ and Z is checked with a χ^2 test, and the statistical uncertainty from the J/ψ events are inflated by a factor of 2.1 to cover the nonclosure of the Z events. The statistical uncertainty from the Z events is also included in the uncertainty model, along with the PDG uncertainty on the Z boson mass.

Though the transverse mass is not directly used in the analysis, it is still used in the event selection and non-prompt background estimation. The Missing Transverse Momentum or MET in the event is reconstructed by the "DeepMET" [22] algorithm, which is a DNN-based algorithm with inputs from the individual particle flow candidate level. Recoil corrections are calibrated using $Z \to \mu\mu$ events.

The non-prompt background is estimated using the extended ABCD method [23]. The regions are separated based on the isolation and transverse mass. The estimation is also validated with the QCD MC events and data in a control region enriched in muons from decays of heavy flavour quarks.

The whole analysis chain has been validated with Z mass extraction, both with the dilepton and "W-like" setup, where one muon is removed from the event and added to the MET. In both cases, the extracted Z mass was found to be compatible with the PDG value [4].

4. Results

The W mass was extracted by the likelihood fit in the muon $p_T - \eta$ distribution for positive and negative charges simultaneously. The measured mass is $m_W = 80360.2 \pm 9.9$ MeV, which agrees

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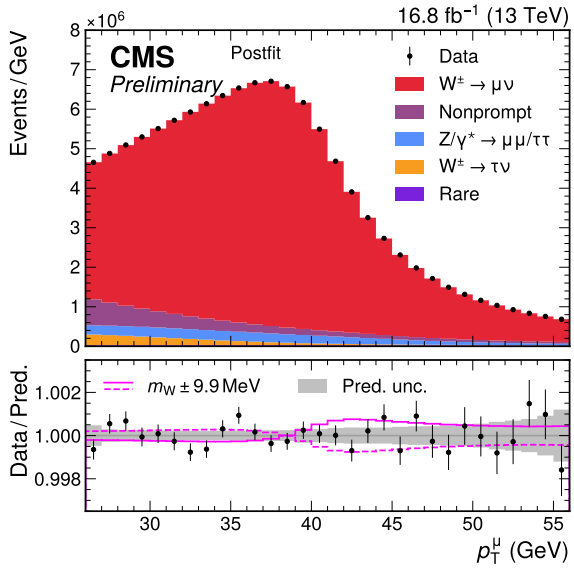

Figure 1: The postfit p_T^μ distribution of data and MC [4]. The solid and dashed pink lines represent an increase and decrease of m_W by 9.9 MeV, respectively. The grey-shaded region represents the postfit uncertainty on the MC prediction.

with the SM prediction [4]. The postfit p_T^μ distribution is shown in Figure 1. In Figure 1, the ± 9.9 MeV variation on the W boson mass is also shown to illustrate the achieved precision. This is the highest achieved precision by the LHC experiments so far. The main source of the uncertainty stems from the calibration of the muon momentum scale, which corresponds to 4.8 MeV. The complete list of systematic uncertainties and their contributions can be found in [4].

5. Summary

Because of disagreement between the W boson mass measured by the CDF experiment and both the SM prediction and other experimental measurements, it was essential to have an independent measurement of the W boson mass. In this talk, we have presented the first CMS measurement of the W boson mass. The measured W boson, $m_W = 80360.2 \pm 9.9$ MeV, mass agrees with the SM, and the achieved 9.9 MeV uncertainty is the best among the LHC experiments and is also competitive with the CDF measurement.

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