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Precision measurements of the weak mixing angle and the W boson mass

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Measurements of the weak mixing angle and the *W* boson mass from the LHC experiments are reported and discussed, and the future prospects in this area are considered.

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1. Introduction

At lowest order in the standard model (SM) the electroweak interactions are governed by three parameters, namely the vacuum expectation value of the Higgs field and the U(1) and SU(2) gauge couplings. From these one can derive other parameters such as the fine structure constant α and the masses of the W and Z bosons. At lowest order $\sin^2\theta_W = 1 - m_W^2/m_Z^2$ where θ_W is the weak-mixing (or Weinberg) angle. It is common to work with the effective parameter in leptonic interactions, $\sin^2\theta_{\text{eff}}^{\text{lept}}$. Including higher order corrections predictions[1] of $m_W = 80354.5 \pm 5.7$ MeV and $\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.231511 \pm 0.000058$ can be made within the SM [2]. Contributions from fields beyond those of the SM could mis-align the measurements and predictions of these parameters. Prior to the LHC, the most precise measurements of m_W have been from the Tevatron experiments [3]. Recently a new measurement of m_W was reported by CDF [4], which is in considerable tension with other measurements. The most precise determinations of $\sin^2\theta_{\text{eff}}^{\text{lept}}$ have been from the SLC, LEP and Tevatron collider experiments.

2. Inclusive vector boson production at hadron colliders

Up to non-factorising electroweak corrections, the differential cross-section can be decomposed into the product of an unpolarised cross-section and eight angular coefficients A_i:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_\mathrm{T}\mathrm{d}y\mathrm{d}M\mathrm{d}\cos\theta\mathrm{d}\phi} = \frac{3}{16\pi}\frac{\mathrm{d}\sigma^{\text{unpol.}}}{\mathrm{d}p_\mathrm{T}\mathrm{d}y\mathrm{d}M}\left\{(1+\cos^2\theta) + A_0\frac{1}{2}(1-3\cos^2\theta) + \ldots + A_4\cos\theta + \ldots\right\} \quad (1)$$

where p_T, M and y denote the transverse momentum, mass and rapidity of the dilepton system, respectively. The angles θ and ϕ are often defined in the Collins-Soper frame [5]. Predictions of the cross-section require the folding of partonic subprocess cross-sections with the parton distribution functions. The $A_4\cos\theta$ term, which is related to the forward-backward asymmetry A_{FB}, in the neutral current process is sensitive to $\sin^2\theta_{\text{eff}}^{\text{lept.}}$ because A_4 depends on products of vector and axial-vector couplings of the Z boson to the participating fermions. At the LHC the ambiguity in the positive direction of the z axis is resolved by the sign of the rapidity of the dilepton system and the sensitivity to $\sin^2\theta_{\text{eff}}^{\text{lept.}}$ scales with the magnitude of the rapidity. The value of m_W can be determined from the shapes of three kinematic distributions in leptonic W boson decays at hadron colliders, namely the charged lepton p_T, the missing p_T and the transverse mass. Figure 1 (left) shows how the shape of the charged lepton q/p_T distribution, where q is the lepton charge, varies with m_W. It is extremely challenging to disentangle this subtle change from the uncertainties in the modelling of the underlying shape.

3. Measurements of the weak mixing angle

A first measurement of $\sin^2\theta_{\text{eff}}^{\text{lept.}}$ by the LHCb Collaboration is based on muonic decays in a dataset corresponding to 1 fb^{-1} at $\sqrt{s} = 7$ TeV and 2 fb^{-1} at $\sqrt{s} = 8$ TeV [6]. The values of A_{FB} as a function of mass are corrected for backgrounds and detector effects before being compared to templates with different $\sin^2\theta_{\text{eff}}^{\text{lept.}}$ hypotheses. The dominant experimental systematic uncertainty

[1]Similar predictions are reported in, e.g., Ref. [1].

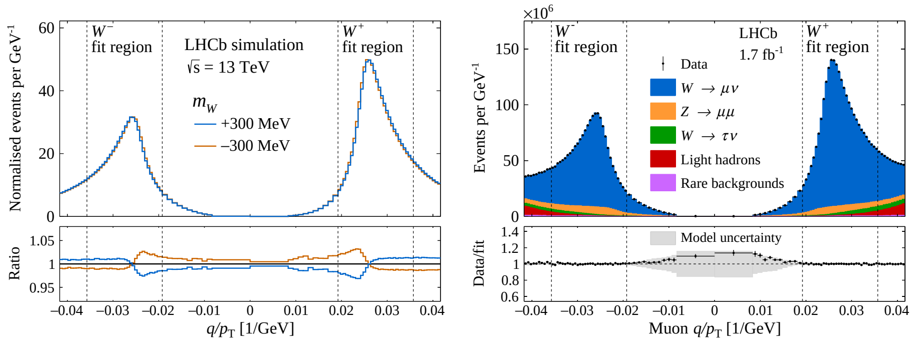

Figure 1: Left: Distribution of q/p_T for two m_W values: Right: q/p_T distribution in the LHCb data.

is due to corrections for curvature biases while the dominant uncertainty in the template fit is attributed to the parton distribution functions. The result is $\sin^2\theta^{\text{lept.}}_{\text{eff}} = 0.23142 \pm 0.00073_{\text{stat}} \pm 0.00052_{\text{syst}} \pm 0.00056_{\text{theory}}$.

A preliminary result from ATLAS [7] is based the 2012 dataset, corresponding to 20 fb^{-1} at $\sqrt{s}$ = 8 TeV. Both electron and muon decay channels are included. The rapidity coverage is extended by a novel use of events with one electron in the central region and one in the forward calorimeter, which is beyond the acceptance of the tracking detectors. Rather than measuring the forward backward asymmetry the value of A_4 is measured as a function of mass. This requires care in the treatment of electroweak corrections when extracting the value of $\sin^2\theta^{\text{lept.}}_{\text{eff}}$ in a template fit. The measured value is $\sin^2\theta^{\text{lept.}}_{\text{eff}} = 0.23140 \pm 0.00021_{\text{stat}} \pm 0.00024_{\text{PDF}} \pm 0.00016_{\text{syst}}$.

A measurement from CMS [8] is based on roughly 20 fb^{-1} at $\sqrt{s}$ = 8 TeV. The forward backward asymmetry is measured in intervals of rapidity and weights are used to further enhance the sensitivity to $\sin^2\theta^{\text{lept.}}_{\text{eff}}$. The PDF uncertainty is reduced with the use of weights that disfavour variations in the PDFs that lead to a poorer consistency with the data. The measured value is $\sin^2\theta^{\text{lept.}}_{\text{eff}} = 0.23101 \pm 0.00036_{\text{stat}} \pm 0.00018_{\text{syst}} \pm 0.00016_{\text{th}} \pm 0.00031_{\text{PDF}}$. Figure 2 (left) shows the current status of measurements of $\sin^2\theta^{\text{lept.}}_{\text{eff}}$. The hadron collider determinations are self consistent and agree well with the SM prediction.

4. Measurements of the W boson mass

The first direct measurement of m_W at the LHC was reported by the ATLAS Collaboration in 2016 [9]. This analysis is based on the 2011 dataset of pp collisions at $\sqrt{s}$ = 7 TeV corresponding to 4.6 fb^{-1}. The modelling of W boson production is based on a combination of exact $O(\alpha_s^2)$ matrix elements for the rapidity distribution and the angular coefficients, and a parton-shower description of the boson p_T distribution. The single dominant source of systematic uncertainty is attributed to the PDFs. The measurement is based on template fits in 28 categories spanning; the electron and muon decay channels, the two W boson charges, intervals in η, and the transverse mass and charged lepton p_T distributions. The data are well described by the fit model and many consistency checks are performed. The result is $m_W = 80370 \pm 7_{\text{stat}} \pm 11_{\text{exp}} \pm 14_{\text{mod}}$ MeV, which agrees well with previous measurements and with the SM prediction.

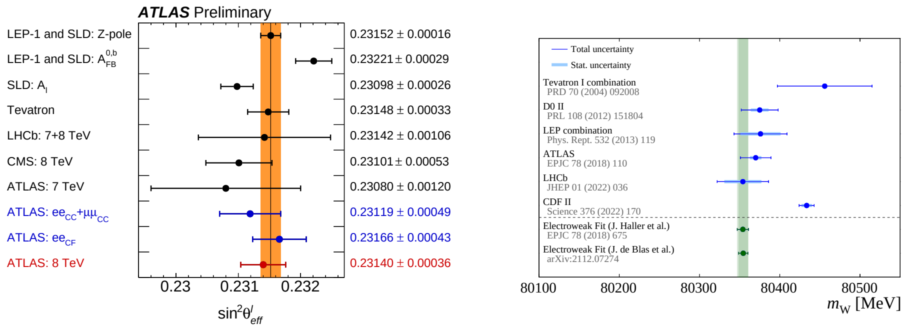

Figure 2: Summary of (left) $\sin^2\theta^{\text{lept.}}_{\text{eff}}$ and (right) [19] m_W measurements and (for m_W) predictions.

In 2021 LHCb reported a first measurement of m_W based on the 2016 dataset of pp collisions at $\sqrt{s}$ = 13 TeV corresponding to 1.7 fb^{-1} [10]. Since LHCb is uniquely instrumented at large pseudorapidities the PDF uncertainties in a m_W measurement are expected to be partially anticorrelated with those in a measurement with the ATLAS and/or CMS experiments [11]. The measurement is based on a fit to the muon q/p_T distribution where q is the muon charge. A single $2.2 < \eta < 4.4$ interval is used but a future measurement may benefit from higher granularity in η [12]. The limited perturbative accuracy of the unpolarised cross-section is mitigated by simultaneously fitting for m_W and tuning the α_s and intrinsic k_T parameters [13]. Charge dependent curvature biases are determined using the pseudomass method [14]. The modelling of the W p_T distribution contributes a systematic uncertainty of 17 MeV, which is the single largest contribution. The q/p_T distribution is shown with the fit model overlaid in Figure 1 (right). Measurements are reported based on three recent global PDF sets at next-to-leading order in the strong coupling. The final result is a simple average of these three, $m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{th}} \pm 9_{\text{PDF}}$ MeV.

The CMS Collaboration report a measurement of the double-differential cross-section for W boson production as a function of the charged lepton p_T and η has been performed on the 2016 dataset of pp collisions at $\sqrt{s}$ = 13 TeV corresponding to 35.9 fb^{-1} [15]. The data are also presented in terms of the helicity cross-sections.

5. Future prospects

In the HL-LHC era the ATLAS and CMS experiments will benefit from extended η coverage while the LHCb experiment will have improved capabilities with high p_T electrons. The prospects for $\sin^2\theta^{\text{lept}}_{\text{eff}}$ determinations in the HL-LHC era are explored for CMS and LHCb in Refs. [16] and [17], respectively. A statistical precision of 5 MeV is projected with the upgraded ATLAS experiment with 1 fb^{-1} of data in special low-pileup runs [18]

6. Conclusions

Precision electroweak observables are sensitive to physics beyond the SM. First measurements of $\sin^2\theta^{\text{lept.}}_{\text{eff}}$ and m_W from the LHC experiments are already challenging the precision of the world averages on these parameters. Thus far the measurements are in good agreement with predictions of the SM. Higher precision measurements are expected in the future.

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