PROCEEDINGS OF SCIENCE

The global electroweak fit in the SM and SMEFT

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We present results from the global electroweak fit to precision measurements of the Standard Model (SM). The fit uses the latest experimental results as well as up-to-date theoretical calculations for observables on the Z pole and the W boson mass, yielding precise SM predictions for the effective weak mixing angle and the masses of the W and Higgs bosons, as well as the top quark. We report constraints on coefficients of the SM effective field theory (SMEFT), obtained from electroweak precision data. We present correlations between the SMEFT coefficients, evaluated at next-to-leading order for the precision observables entering the fit, and the free parameters of the SM.

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1. Introduction

Electroweak (EW) precision data from LEP and SLD [1, 2], together with precise measurements at low energy [3], and direct measurements of the parameters of the Standard Model (SM) by the Tevatron and LHC experiments, can be used to test the internal consistency of the theory. With all particles predicted by the SM discovered, the EW sector of the SM is complete and the fit is overconstrained. This allows for consistency checks with unprecedented precision. With the full two-loop EW contributions for Z boson production calculated [4, 5], the theoretical uncertainties are now smaller than the experimental ones in all observables entering the EW fit. Furthermore, comparisons between measured values and predictions of key observables such as the mass of the W boson M_W allow for concise validation of the SM and can indicate shortcomings of the theory.

Besides the probing the SM, the implementation of BSM parameters into the fit allows for a direct search for new physics. A broad, model-independent search for new physics can be achieved by adding coefficients of a SM effective field theory (SMEFT) to the EW fit.

In this contribution we update our previous results [6, 7] with a new measurement of M_W [8], recent luminosity corrections on the measurement of the Z pole observables by LEP [9] and the above mentioned full two loop EW calculations [4, 5]. In addition, we present limits on different SMEFT coefficients in various fitting scenarios.

2. Measurements and calculations

Since our previous results [7], a new measurement of M_W has been performed by the ATLAS Collaboration [8]. The reported value of 80360 ± 16 MeV is in agreement with the LEP average [2] of 80376 ± 33 MeV. For the fitting procedure, an average of the new ATLAS measurement, the LEP average and the newest LHCb result [10] is used. The resulting average is $M_W = 80369 \pm 16$ MeV with a χ^2 of 0.25 for 2 degrees of freedom (dof).

For m_t, we use the same combination of ATLAS and CMS measurements as in our previous fit [7], which results in $m_t = 172.47 \pm 0.46$ GeV. We add an uncertainty of 0.5 GeV in m_t to account for a potential ambiguity when translating the measured value into the top quark pole mass.

For $\sin^2\theta^\ell_{\text{eff}}$, we include the direct measurement by the LEP Collaborations [1] and a combination from measurements at hadron colliders. The combination is made from the measurements by ATLAS [11], CMS [12], LHCb [13], and the combined value from CDF and D0 [14]. We correlate the PDF uncertainties fully between the ATLAS and CMS measurements, and we assume a correlation of 50% between the Tevatron and ATLAS/CMS PDF uncertainties, as well as between LHCb and ATLAS/CMS. In addition, we use a correlation of 30% between the Tevatron and LHCb PDF uncertainties. The resulting value is $\sin^2\theta^\ell_{\text{eff}} = 0.23141 \pm 0.00026$. The combination shows good compatibility of the individual measurements with $\chi^2/\text{dof} = 0.74/3$, resulting in a p value of 0.86. Besides electroweak precision data from LEP and SLD [1], other experimental inputs to the fit are the hadronic contribution to the electromagnetic coupling strength [3], M_H [15] and the masses of the c and b quarks [16].

An integral part of the EW fit are precise calculations. The theoretical higher-order calculations used here are the same as in our previous publication [7]. Most notably, we included the latest two-loop EW calculations of bosonic contributions [5] to the Z boson production and decay. For

$\sin^2\theta^f_{\text{eff}}$, we use the parametrisation of Ref. [4], and the prediction of M_W is obtained from Ref. [17]. The width of the W boson is known up to one-loop order in the EW interaction, where we use the parametrisation given in Ref. [18]. Theoretical uncertainties reflect the size of unknown higher order contributions. Since these are difficult to estimate, a reliable consistency test of the SM is only obtained if the theoretical uncertainties are small compared to the experimental uncertainties. We introduce a free parameter for each theoretical uncertainty in the EW fit, and find that the impact of these parameters is small.

3. Results of the electroweak fit

The fit converges on a minimum χ^2 value of 13.78 for 15 dof, corresponding to a p value of 0.55. This is the highest p value we have observed so far, further increasing the already high value from our last result [7]. The individual deviations of the input values from the predictions given in units of the measurement uncertainty (pull values), are shown in Figure 1. The largest contribution to the χ^2 originates from the forward-backward asymmetry from b quarks, A^b_{FB}, which shows a deviation of 2.4σ from its SM prediction. The leptonic left-right asymmetry A_ℓ from SLD has a deviation of -2.1σ. These two effects are unchanged with respect to our previous results. The best-fit value of the strong coupling strength at the mass of the Z boson, $\alpha_S(M_Z^2)$, is 0.1196 ± 0.0029. In Figure 1, this is compared to the PDG value of 0.1179 ± 0.0009 [16], which does not enter the fit, resulting in a pull value of 2.0σ.

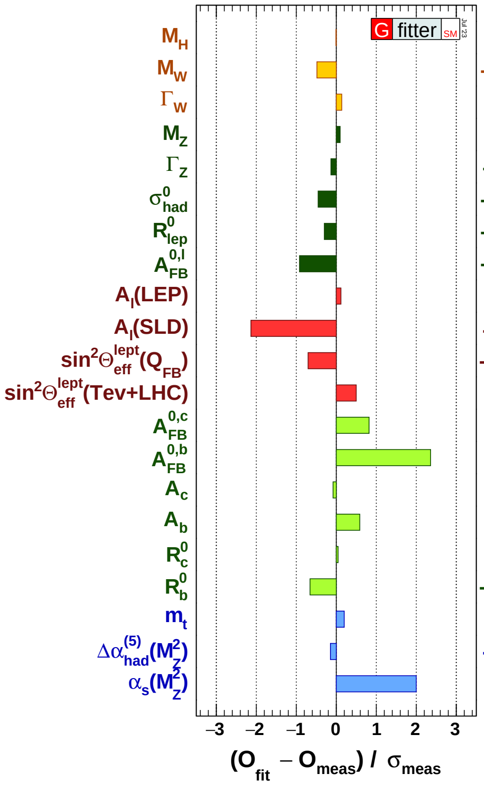

Figure 1: Pull values of the fit, defined as deviations between measurements and predictions evaluated at the best-fit point, divided by the experimental uncertainties.

A significantly smaller pull can be observed for the hadronic cross section at the Z peak σ^0_{had} and the leptonic partial width R^0_{lep}. Their pull values are now -0.5σ and -0.3σ respectively compared to 1.6σ and 0.9σ in our previous result. The pull of M_W has also decreased with respect to out last result, namely from -0.8σ to -0.5σ. When not including M_W in our fit, we obtain a value of 80.354 ± 0.007 GeV.

In Figure 2 comparisons are shown between the direct measurements of M_W, m_{t} and $\sin^2\theta^\ell_{\text{eff}}$ and their fitted values. The direct measurements are indicated by a green 1σ band. The differently coloured ellipses indicate the fitting results. The blue ellipses indicate the full fit only omitting the direct measurements shown in the plot. The other ellipses show the result of the fit omitting even more measurements. Generally

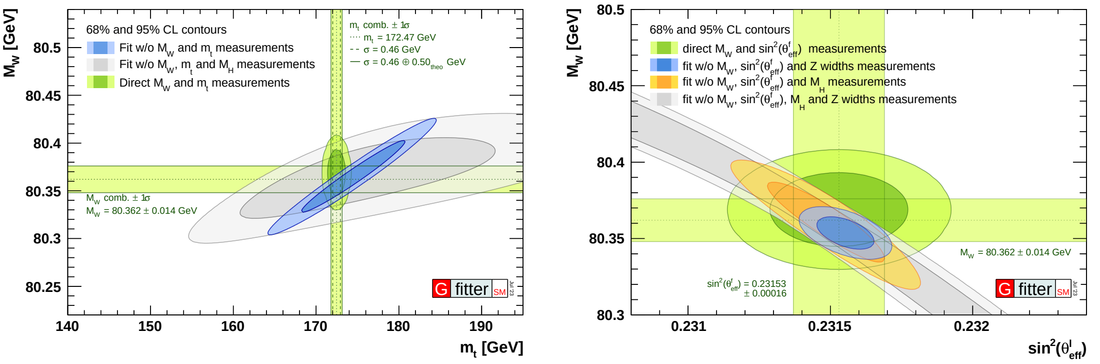

Figure 2: Comparison between direct measurements and different fitting scenarios for M_W vs. m_t (left) and M_W vs $\sin^2\theta^\ell_\mathrm{eff}$ (right)

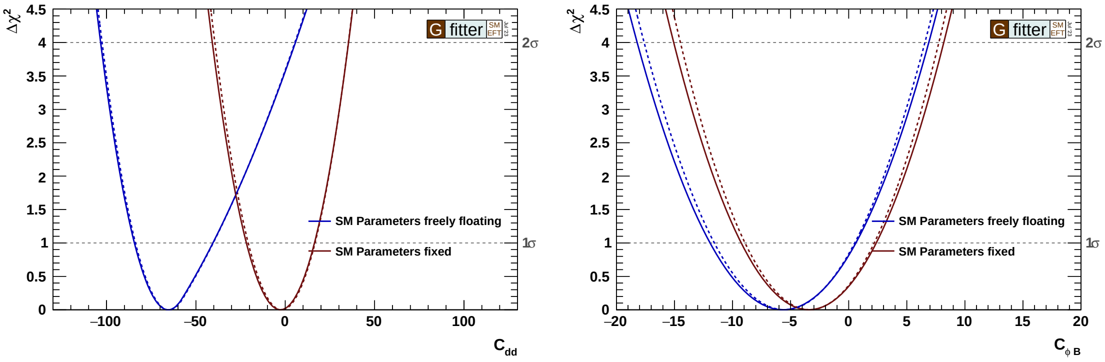

Figure 3: Fit of two SMEFT operators ($C_{\phi B}$ left, C_{dd} right) with fixed and freely floating SM parameters.

a good agreement between the direct measurements and the different sets of fits can be observed. The plots highlight the importance of a precise measurement of especially M_W and m_t.

4. Constraints on SMEFT

As an example of a search for physics beyond the Standard Model we study SMEFT effects on the EW fit. These effects have been calculated to the one-loop level [19], including all terms $O(v^2/\Lambda^2)$, where v is the vacuum expectation value and Λ the scale of new physics. We include all 32 relevant operators at dimension six, and observe that each corresponding Wilson coefficient (WC) is compatible with 0 at 95% confidence level when fitting them individually. We obtain numerically excellent agreement with the results of Ref. [19].

As a next step, we include theoretical uncertainties as additional parameters and allow the SM parameters to vary in the fit. We observe that the limits on the SMEFT WCs become weaker for some operators, as shown in Figure 3. However, for most operators the effect of leaving the SM parameters free in the fit has an effect of a few percent only. We observe that fermionic operators are more affected than bosonic ones, and that leaving α_S unconstrained accounts for the largest part of this effect.

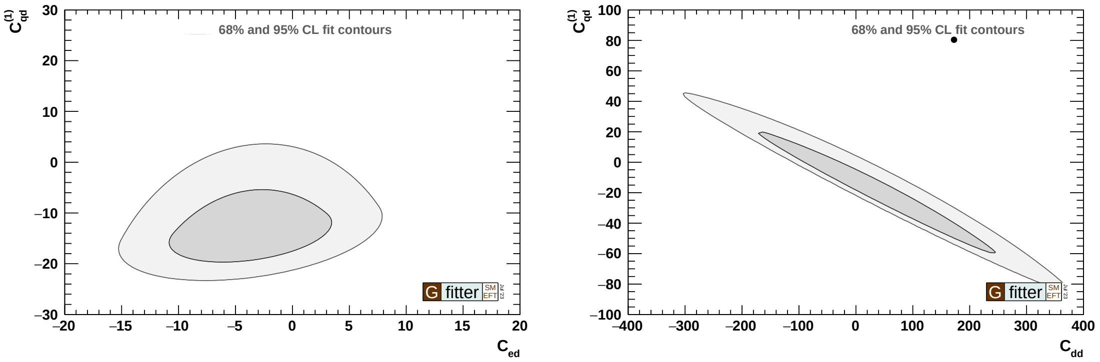

Figure 4: Simulanous fit of two pairs of SMEFT operators (C^1_{qd} vs. C_{ed} left,C^1_{qd} vs C_{dd} right)

In addition, we calculated constraints for various pairs of operators simultaneously. The resulting 68 and 95% confidence interval contour regions are shown in Figure 4 for two example combinations. In these cases, we again observe that some bounds on WCs become weaker, depending on the choice of combination. For some pairings of operators we observe "flat" directions in the fit, where the effects of two operators cancel, resulting in very weak constraints (Figure 4 right). When fitting larger sets of operators simultaneously, similar effects appear resulting in weak limits. Knowledge of the flat directions in the fits is hence needed for determining the multidimensional constrains on EW SMEFT operators. Additional data will help to lift these flat directions. In the era of precision full fits are necessary in order to determine exact exclusion limits.

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