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# Electroweak constraints in the Standard Model and beyond

**Max Baak,**[a] **Jakub Cúth,**[b] **Johannes Haller,**[c] **Andreas Hoecker,**[a] **Roman Kogler,**[c]
**Klaus Mönig,**[d] **Thomas Peiffer***,[c] **Matthias Schott,**[b] **Jörg Stelzer**[a]
[a] *CERN, Switzerland*
[b] *Johannes Gutenberg Universität Mainz, Germany*
[c] *Universität Hamburg, Germany*
[d] *Deutsches Elektronen-Synchrotron, Germany*
*E-mail:* `max.baak@cern.ch`, `jakub.cuth@cern.ch`,
`johannes.haller@physik.uni-hamburg.de`, `andreas.hoecker@cern.ch`,
`roman.kogler@desy.de`, `klaus.moenig@desy.de`, `thomas.peiffer@desy.de`,
`mschott@cern.ch`, `stelzer@cern.ch`

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We present an update of the global electroweak fit using electroweak next-to-next-to-leading order (NNLO) calculations for all precision observables that enter the fit. The availability of NNLO corrections allows for the first time the inclusion of realistic estimates of theoretical uncertainties due to missing higher order calculations. The knowledge of the mass of the Higgs boson improves the precision of the predictions in the global electroweak fit considerably and the global fits are used as powerful tools to assess the validity of the Standard Model and to constrain scenarios for new physics. We present updated constraints in a model with modified Higgs couplings to bosons and fermions, and two Higgs doublet models. We show that in many cases the Higgs signal strength measurements give complementary information to constraints obtained from electroweak precison observables. Future measurements at the LHC and an expected electron-positron collider promise to improve the experimental precision of key observables used in the fit. We assess the influence of present and future experimental and theoretical sources of systematic uncertainties on the fit predictions.

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*Speaker.

## 1. The Electroweak Fit

The electroweak sector of the Standard Model of particle physics (SM) is fully determined by three independent parameters. In our analysis, these parameters are chosen to be the electroweak coupling constant $\alpha$, the Fermi constant $G_{\mathrm{F}}$, and the mass of the Z boson, $M_{\mathrm{Z}}$. All other parameters and observables of the electroweak sector of the SM can be calculated as function of these three parameters. The Higgs boson mass $M_{\mathrm{H}}$ as well as the masses of quarks enter the theoretical prediction of observables by radiative corrections. With the discovery of the Higgs boson, all parameters and observables have been determined experimentally. Therefore, a combined fit of all parameters [1] allows for a consistency check of the theory predictions of the SM.

Theoretical predictions used in the fit are known at least up to two-loop level for all relevant observables. We include theoretical calculations of the effective weak mixing angle $\theta_{\mathrm{eff}}^{\ell}$ [2, 3], the mass of the W boson $M_{\mathrm{W}}$ [4], the partial widths of the Z boson [5], and radiator functions to these widths [6]. Electroweak corrections to the width of the W boson are only known to one-loop level [7], but have a negligible impact on the fit with the present precision. Theoretical uncertainties due to unknown higher order effects are estimated using geometric series and are taken into account in the global fit.

The experimental input to the fit contains measurements from the electron-positron colliders LEP and SLC and the hadron colliders Tevatron and LHC. The Z boson properties (mass, partial widths, and forward backward asymmetries) as well as $\sin^2\theta_{\mathrm{eff}}^{\ell}$ have been measured most precisely in lepton collisions. The Tevatron and LHC experiments provide the most accurate determinations of $M_{\mathrm{W}}$, $M_{\mathrm{H}}$, and the top quark mass $m_{\mathrm{t}}$.

The global fit of all electroweak parameters converges in a global minimum with a $\chi^2$ value of 17.8 for 14 degrees of freedom. This result corresponds to a p-value of 0.21. The result of the fit reflects an overall good consistency of the electroweak precision data with the theoretical predictions of the SM. The largest single discrepancy between a single measurement and the prediction of the fit is observed for the forward-backward asymmetry in $\mathrm{Z}\to \mathrm{b}\bar{\mathrm{b}}$ processes ($A_{\mathrm{FB}}^{0,\mathrm{b}}$) and corresponds to a significance of 2.5 $\sigma$.

The electroweak fit is also utilized to indirectly determine certain SM parameters to scrutinize the consistency of the SM. For this purpose, a single measured value of interest is excluded from the fit and the fit is performed to determine the best fit value for this parameter. In case of the indirect determination of $M_{\mathrm{W}}$, the electroweak fit predicts a value of $M_{\mathrm{W}} = 80.358 \pm 0.008$ GeV which is more precise than the combined measured value of $M_{\mathrm{W}} = 80.385 \pm 0.015$ GeV [8].

Indirect determinations of parameters are also performed in two-dimensional scans of parameters sensitive to new physics contributions. In Fig. 1, such two-dimensional scans for $\sin^2\theta_{\mathrm{eff}}^{\ell}$ and $M_{\mathrm{W}}$ (left) as well as $m_{\mathrm{t}}$ and $M_{\mathrm{W}}$ (right) are shown. The blue ellipses indicate the allowed regions for the respective parameters when performing the global fit of all other electroweak observables. The allowed areas from the fit nicely overlap with the green bands that show the direct measured values for the respective observables.

## 2. New Physics Constraints

Besides the overall consistency of the SM predictions with the electroweak precision data, the

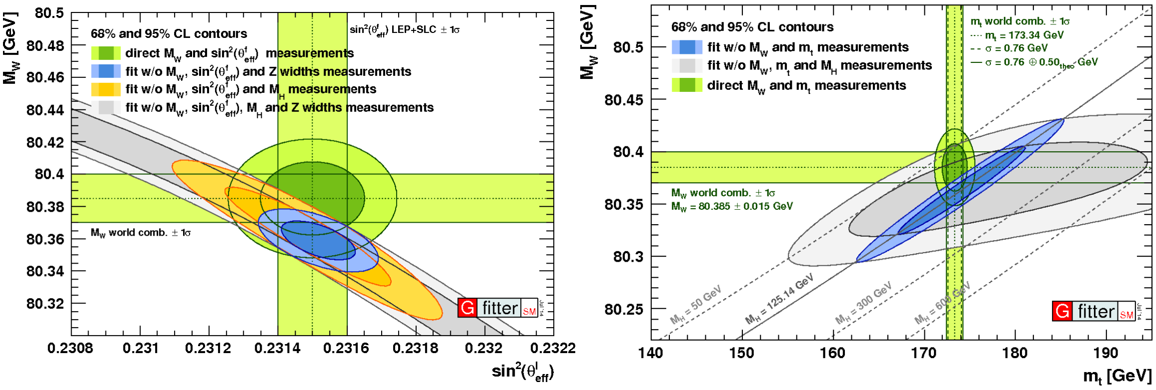

**Figure 1:** Contours of 68% and 95% confidence level obtained from scans of fits with fixed variable pairs, $M_\mathrm{W}$ vs. $\sin^2\theta^\ell_\mathrm{eff}$ (left) and $M_\mathrm{W}$ vs. $m_\mathrm{t}$ (right). The gray bands show the confidence levels obtained when excluding the measurement of $M_\mathrm{H}$. The green bands indicate the $1\sigma$ regions of the direct measurements [1].

global fit allows to constrain models of new physics. A convenient approach to parametrize the impact of new physics to electroweak observables is the usage of the oblique parameters $S$, $T$, and $U$ [9]. The $S$ parameter incorporates changes to neutral currents, $T$ parametrizes changes to the difference between charged and neutral currents, and $U$ takes changes of the W boson width and mass into account. These three parameters are added as additional free parameters to the fit and the fit of the electroweak precision data is used to determine bounds on $S$, $T$, and $U$. The fit yields the values $S = 0.05 \pm 0.11$, $T = 0.09 \pm 0.13$, and $U = 0.01 \pm 0.11$ with large correlations especially between the $S$ and $T$ parameters of 0.9. This result can be used to constrain a variety of new physics models predicting contributions to electroweak currents.

In addition to electroweak precision data, the measured Higgs boson branching ratios provide complementary information and can be used to further constrain new physics models. The computer program HiggsSignals [10] provides a statistical test of any model prediction with the latest measurements of Higgs boson decay rates from Tevatron and LHC. The $\chi^2$ calculated by HiggsSignals is combined with the $\chi^2$ of the global electroweak fit to analyze the constraints to new physics models affecting Higgs and electroweak observables.

In a simple model that affects the Higgs couplings strengths and the oblique parameters, the couplings of the Higgs boson to fermions and vector bosons are scaled with two additional parameters, $\kappa_\mathrm{f}$ and $\kappa_\mathrm{V}$, respectively. The SM is reproduced for $\kappa_\mathrm{f} = \kappa_\mathrm{V} = 1$. The parameter $\kappa_\mathrm{V}$ also contributes to the oblique corrections [11]. The constraints in this model are presented in Fig. 2. Including electroweak data tightens the constraints (blue ellipses) compared to the limits obtained using just the Higgs branching ratio measurements (orange).

Another new physics model that can be constrained by electroweak data and Higgs branching ratio measurements is the Two-Higgs-Doublet model (2HDM) [12]. The 2HDM predicts five physical Higgs bosons, labeled $\mathrm{h}_0$, $\mathrm{H}_0$, $\mathrm{A}_0$, $\mathrm{H}^+$, and $\mathrm{H}^-$. In this analysis, the neutral $\mathrm{h}_0$ is assumed to be the discovered Higgs boson with a mass of 125 GeV. The other Higgs bosons of the 2HDM are assumed to be heavier than the $\mathrm{h}_0$. Besides the masses of the heavy Higgs boson, the 2HDM consist of three further free parameters: $\tan\beta$, the ratio of the vacuum expectation values of the two Higgs doublets, the mixing angle of the neutral, scalar Higgs fields $\alpha$, and the soft breaking scale $M^2_{12}$. These parameters and the masses of the heavy Higgs bosons are added as free parameters to

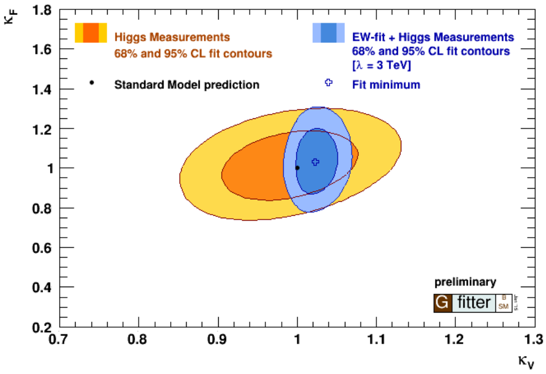

**Figure 2:** Constraints in the parameters $\kappa_f$ and $\kappa_V$ from Higgs branching ratio measurements (orange) and combined Higgs and electroweak data (blue).

the fit.

The influence of the 2HDM to the electroweak precision data is taken into account using the oblique parameters [13, 14, 15]. Theoretical predictions for the Higgs branching ratio measurements are considered using the predictions of the program 2HDMC [16]. Depending on the Yukawa couplings of the two Higgs doublets, four 2HDM types are distinguished with different predictions for the Higgs branching ratio measurements. A multi-dimensional scan of all free parameters of the 2HDM is performed using a nested sampling algorithm [17]. The result of this scan is presented in Fig. 3 for the Type II 2HDM. The Higgs branching ratio measurements constrain mostly the allowed parameter space for $\alpha$ and $\beta$. Allowed parameter points are concentrated in bands around $\beta - \alpha = \pi/2$ or $\beta + \alpha = \pi/2$ (Fig. 3 left). When including also the electroweak precision data and assuming a fixed mass of the charged Higgs bosons $M_{H^\pm}$, either the mass of the heavy scalar $M_{H^0}$ or of the pseudo-scalar Higgs boson $M_{A^0}$ is predicted to be close to $M_{H^\pm}$ (Fig. 3 right). For Type III and IV models, similar constraints are obtained, the constraints in the Type I model are found to be weaker. Limits from direct searches for heavy Higgs bosons and indirect

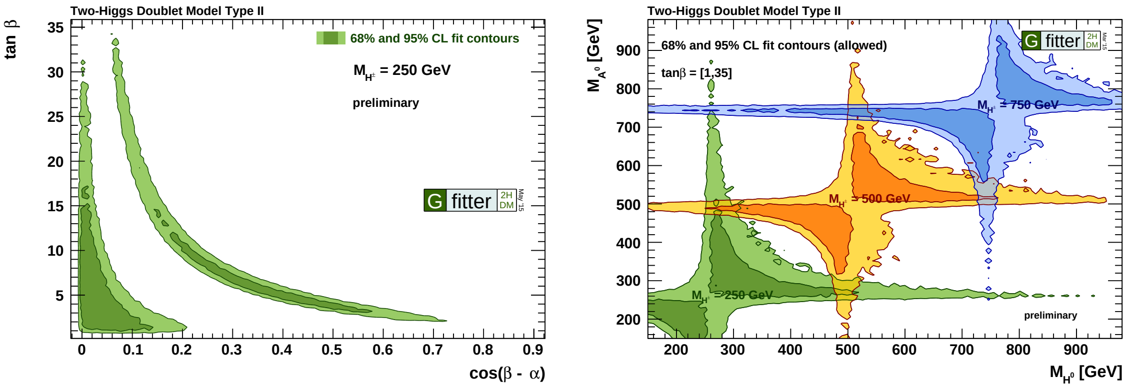

**Figure 3:** Constraints from Higgs branching ratio measurements in the 2HDM parameters $\cos(\beta - \alpha)$ and $\tan\beta$ (left) and the combined constraints from Higgs branching ratio measurements and electroweak precision data in the masses of the neutral Higgs bosons for a given charged Higgs boson mass $M_{H^\pm}$ (right) in the Type II 2HDM.

constraints from flavor physics are not yet included. These can be used to improve the constraints on the 2HDM in the future.

## 3. Future Colliders

Measurements at future collider experiments will improve the precision of several electroweak observables. This will allow for a more accurate consistency check of the SM with the electroweak fit. The LHC is expected to deliver more precise measurements of $m_t$, $M_W$, and $M_H$ in the coming years. For the prospects presented here, an amount of data corresponding to an integrated luminosity of 300 $fb^{-1}$ is assumed to be collected during the LHC Phase-I. A further increase of precision can be reached with an electron-positron collider. The ILC is expected to provide much more precise measurements of $m_t$ and $M_W$ as well as improved determinations of $\sin^2\theta^{\ell}_{\text{eff}}$ and the partial decay widths of the Z boson when running with the Giga-Z option [18, 19]. In Fig. 4, the expected precision of the electroweak fit with input from future colliders is shown for the constraints in the oblique parameters $S$ and $T$. It can be seen, that the expected data taking at the LHC will only slightly improve the precision of the electroweak fit, while an increase in precision by a factor of 4 to 5 can only be obtained with measurements at the ILC.

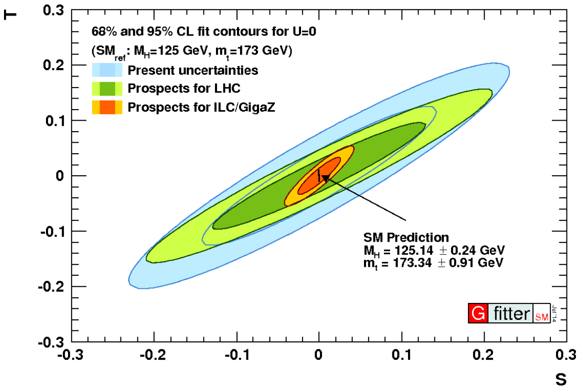

**Figure 4:** Contours of 68% and 95% confidence level in the $S$-$T$ plane with current precision (blue) of the electroweak fit compared to prospects with future measurements from the LHC (green) and ILC (orange). $U$ was fixed to 0 in the fit [1].

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