Global Fits of the electroweak Standard Model and beyond with Gfitter

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In the global fit of the Standard Model using Gfitter, electroweak precision observables as well as constraints from direct Higgs searches have been compared with state-of-the-art electroweak predictions. We use the most recent results for direct Higgs searches at LEP and Tevatron and the latest measurements of m_t and M_W. Example results are an estimation of the mass of the Higgs boson ($M_H = 116.3^{+15.6}_{-1.3}$ GeV) and a forth-order result for the strong coupling constant ($\alpha_S(M_Z^2) = 0.1193 \pm 0.0028(\mathrm{exp}) \pm 0.0001(\mathrm{theo})$). A fit of the oblique parameters (STU) to the electroweak data is performed, in order to constrain physics beyond the Standard Model. For instance, the parameter space of the Littlest Higgs Model with T-parity can be restricted via the oblique parameters. In addition, fit results for a model with an extended Higgs sector (2HDM) using mainly observables from the B and K physics are presented.

1 Introduction

Precision measurements allow us to probe physics at much higher energy scales than the masses of the particles directly involved in experimental reactions by exploiting contributions from quantum loops. Prominent examples are the electroweak precision measurements, which are used in conjunction with the Standard Model (SM) to predict via multidimensional parameter fits unmeasured quantities like the Higgs mass.

Several theoretical libraries within and beyond the SM have been developed in the past containing the pertubative calculations of the SM and new physics models for the electroweak observables. However, most of these programs are relatively old, were implemented in outdated programming languages, and are difficult to maintain with respect to the theoretical and experimental progress expected during the forthcoming era of the LHC. These considerations led to development of the generic fitting package *Gfitter* [1], designed to provide a modular framework for complex fitting tasks in high-energy physics. *Gfitter* is implemented in C++ and relies on ROOT functionality. The package allows a consistent treatment of statistical, systematic and theoretical errors, possible correlations and inter-parameter dependencies.

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In this paper we present *Gfitter* results of the global SM fit to the electroweak observables as well as an estimate of the oblique parameters, which can be also used to constrain the parameter space of the Littlest Higgs Model (LHM). In addition, a fit of a Two Higgs Doublets Model (2HDM) is performed using B and K physics observables.

2 The Global SM Fit

In the global electroweak fit the state-of-the-art calculations of the electroweak precision observables are compared with the most recent experimental data to constrain the free parameters of the fit and to test the goodness-of-fit. The free parameters of the SM relevant for the global electroweak analysis are the coupling constant of the electromagnetic, weak, and strong interactions, as well as the masses of the elementary fermions and bosons. Due to electroweak unification and simplifications arising from fixing parameters with insignificant uncertainties compared to the sensitivity of the fit, the number of free fit parameters can be reduced. The remaining floating parameters in the fit are the coupling parameters $\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$ and $\alpha_S(M_Z^2)$, the masses M_Z, $\overline{m}_c$, $\overline{m}_b$, $m_{\rm top}$, and M_H.

In *Gfitter* a complete new library of the electroweak precision observables as measured by the LEP, SLC, and Tevatron experiments has been implemented. State-of-the-art predictions in the one-mass-shell scheme are used. In particular, the full two-loop and leading beyond two-loop corrections are available for the predictions of M_W [2] and $\sin^2\theta^l_{\rm eff}$ [3,4]. The implementation of the NNNLO pertubative calculation of the massless QCD Adler function [5], contributing to the vector and axial radiator functions in the prediction of the Z hadronic width, allows to fit the strong coupling constant with a unique theoretical accuracy. Wherever possible the calculations have been cross-checked against the ZFITTER package [6]. More details on the theoretical computations in *Gfitter* can be found in [1].

The following experimental measurements are used: The mass and width of the Z boson, the hadronic pole cross section $\sigma^0_{\rm had}$, the partial widths ratio R^0_l, and the forward-backward asymmetries for leptons $A^{0,l}_{\rm FB}$, have been determined by fits to the Z line-shape measured precisely at LEP (see [7] and references therein). Measurements of the τ polarization at LEP [7] and the left-right asymmetry at SLC [7] have been used to determine the lepton asymmetry parameter A_l. The corresponding c and b-quark asymmetry parameters $A_{c(b)}$, the forward-backward asymmetries $A^{0,c(b)}_{\rm FB}$, and the widths ratios R^0_c and R^0_b, have been measured at LEP and SLC [7]. In addition, the forward-backward charge asymmetry measurement in inclusive hadronic events at LEP was used to directly determine $\sin^2\theta^l_{\rm eff}$ [7]. For the running quark masses $\overline{m}_c$ and $\overline{m}_b$ the world average values are used. For $\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$ we take the phenomenological result [8]. For the W width we use the official combined LEP and Tevatron result, while for the W mass we take also into account the recent D0 measurement [9] leading to our private preliminary combined value of $M_W = (80.399 \pm 0.023)$ GeV. In case of the top mass the latest combined result [10] $m_t = (173.1 \pm 1.3)$ GeV is used. The direct searches for the SM Higgs Boson at LEP [11] and the most recent results from the Tevatron [12], leading to a 95% confidence level (CL) exclusion for $M_H < 114.4$ GeV and at $M_H = [160, 170]$ GeV respectively, are included using a Gaussian approach that quantifies the difference between the observed test statistics (the log-likelihood ratios) and the expected values for the s+b hypothesis using the values of the respective confidence level ($\rm CL_{S+B}$). A contribution to the χ^2 estimator of the fit is derived for each Higgs mass. More details of the procedure can be found in [1]. We perform global fits in two versions: the *standard ("blue-band") fit* makes use of all the available information except for the direct Higgs searches and the *complete fit* uses also the constraints from the direct Higgs searches.

The *standard* (*complete*) *fit* converges at the global minimum value $\chi^2_{\rm min} = 16.4$ ($\chi^2_{\rm min} =$ 7.9) for 13 (14) degrees of freedom, corresponding to a p-value of $0.228 \pm 0.004_{-0.002}$ (0.204 +

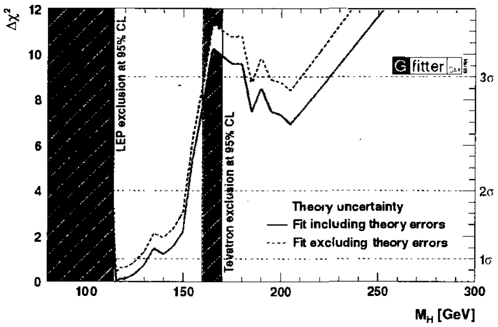

Fig. 1: $\Delta\chi^2$ as a function of M_H for the *complete fit*.

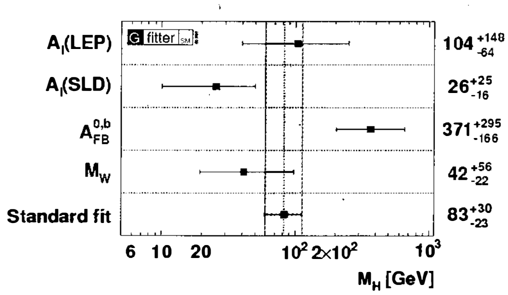

Fig. 2: Determination of M_H excluding all the sensitive observables from the *standard fit*, except for the one given.

$0.004_{-0.002}$) derived from MC toy experiments. The estimation for M_H from the *standard fit*, *i.e.*, without the direct Higgs searches is $M_H = 83^{+30}_{-23}$ GeV and the 2σ and 3σ intervals are respectively [42, 158] GeV and [28, 211] GeV. The *complete fit* represents the most accurate estimation of M_H considering all available data. The resulting $\Delta\chi^2$ curve versus M_H is shown in Figure 1. The shaded band indicates the influence of theoretical uncertainties, which are included in the fit with a flat likelihood within the allowed ranges. The inclusion of the direct Higgs search results from LEP leads to a strong rise of the $\Delta\chi^2$ curve below $M_H = 115$ GeV. The data points from the searches at the Tevatron, available in the range 110 GeV $< M_H <$ 200 GeV increases the $\Delta\chi^2$ estimator for Higgs masses above 150 GeV beyond that obtained from the *standard fit*. The estimation for M_H from the *complete fit* results in $M_H = 116.3^{+15.6}_{-1.3}$ GeV and the 2σ interval is reduced to [114, 145] GeV.

In figure 2 only the observable indicated in a given row of the plot is included in the fit. Only for the four observables providing the strongest constraint on M_H, namely A_ℓ(LEP), A_ℓ(SLD), $A_{\rm FB}^{0,b}$ and M_W, the Higgs mass is determined. The compatibility among these measurements can be estimated by repeating the global fit where the least compatible of the measurements (here $A_{\rm FB}^{0,b}$) is removed, and by comparing the $\chi^2_{\rm min}$ estimator obtained in that fit to the one of the full fit (here the *standard fit*). To assign a probability to the observation, the $\Delta\chi^2_{\rm min}$ obtained this way must be gauged with toy MC experiments to take into account the "look-elsewhere" effect introduced by the explicit selection of the pull outlier. We find that in (1.4 ± 0.1)% ("2.5σ") of the toy experiments, the $\Delta\chi^2_{\rm min}$ found exceeds the $\Delta\chi^2_{\rm min} = 8.0$ observed in current data.

The strong coupling at the Z-mass scale is determined by the *complete fit* to $\alpha_S(M_Z^2) = 0.1193 \pm 0.0028 \pm 0.0001$ where the first error is experimental and the second due to the truncation of the pertubative QCD series.

Figure 3 compares the direct measurements of M_W and m_t, shown by the shaded/green 1σ bands, with the 68%, 95%, and 99% CL obtained for three sets of fits. The largest/blue (narrower/yellow) allowed regions are derived from the *standard fit* (*complete fit*) excluding the measured values in the fits. The inclusion of the LEP and Tevatron Higgs searches significantly impacts the constraints obtained. Figure 3 allows to compare the indirect and direct determination of the M_W and m_t. So far the indirect determinations and the direct measurements are in good agreement. The third set of fits (narrowest/green) results from the *complete fit* including the measured values. Hence, it uses all available information and leads to the narrowest allowed region.

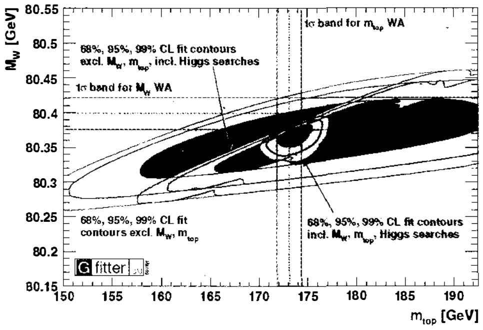

Fig. 3: Contours of 68%, 95%, and 99% CL obtained from scans of fits with fixed variable pairs M_W vs. m_t for three sets of fits. The horizontal bands indicate the 1σ regions of measurements (world averages).

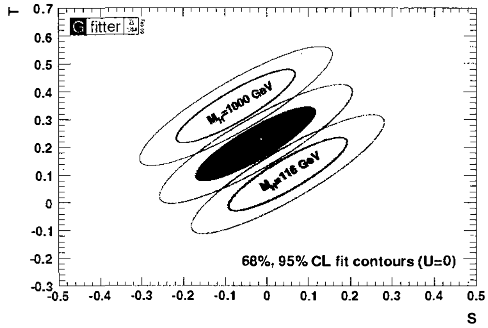

Fig. 4: Allowed contours of 68% and 95% CL in the (T,S)-plane obtained from fits with m_t = 172.4 GeV and M_H=116, 350, and 1000 GeV.

Oblique Parameters

. common approach to constrain physics beyond the SM using the global electroweak fit is ıe introduction of oblique parameters. which assumes that the contributions of new physics ıodels only appear through vacuum polarization. Most of the effects on electroweak precision bservables can be parametrized by three gauge self-energy parameters (S, T, U) introduced by 'eskin and Takeuchi [13]. S ($S+U$) describes new physics contributions to neutral (charged) urrent processes at different energy scales, while T measures the difference between the new hysics contributions of neutral and charged current processes at low energies (*i.e.*, T is sensitive) isospin violation). Further generalizations like additional corrections to Zbb couplings [ ] an be also taken into account.

The constraints on the STU parameters are derived from the fit to the electroweak precision ata, presented in section 2. The STU parameters replace M_H and m_t as free parameters in ıe fit. The following fit results are determined from a fit assuming $\alpha_S(M_Z^2) = 0.1193 \pm 0.0028$, $\imath_t = 172.4$ GeV, and $M_H = 116$ GeV (in parentheses $M_H = 350$ GeV):

$$\begin{aligned} S &= 0.02\ (-0.06)\ \pm\ 0.11 \\ T &= 0.05\ (\ \ 0.15)\ \pm\ 0.12 \\ U &= 0.07\ (\ \ 0.08)\ \pm\ 0.12 \end{aligned} \tag{1}$$

ince U is generally small in new physics models and only constraints by the mass and width of ıe W boson, the STU parameter space is often projected to a two-dimensional parameter space ı which the experimental constraints are easy to visualize. Figure 4 shows the 68%, 95%, and)9% CL allowed contours in the (T,S)-plane for three different assumptions for M_H. In any case ıe oblique parameters are small, *i.e.*, possible new physics models may affect the electroweak)servables only weakly.

Littlest Higgs Model with T-Parity

he fine-tuning problem of the Higgs mass parameter (hierarchy problem) is one of the driving ·guments to consider physics beyond the SM. Besides supersymmetric extensions of the SM, ittle Higgs theories provide a way to tackle the hierarchy problem. The generic structure of

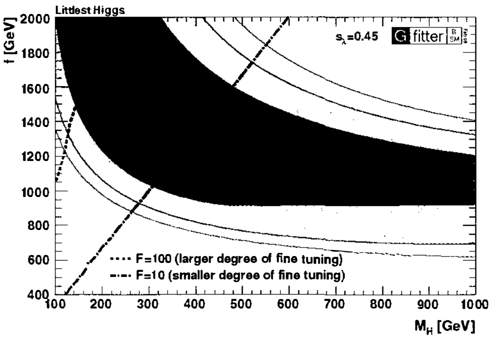

Fig. 5: Allowed contours of 68%, 95%, and 99% CL obtained from scans of fits with fixed variable pairs f and M_H ($s_\lambda = 0.45$). The parameter F is a quantitative measure of fine-tuning (larger values of F correspond to larger degree of fine-tuning).

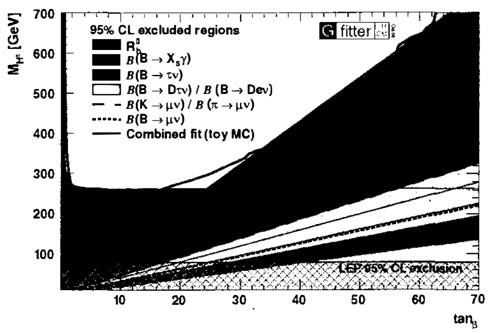

Fig. 6: Simple overlay of the 95% CL exclusion regions in the ($\tan\beta, M_{H^\pm}$)-plane from individual 2HDM constraints and the toy-MC-based result (black solid line) from the combined fit overlaid.

Little Higgs Models is a global symmetry broken at a scale f (around 1 TeV) where new gaug bosons, scalars, and fermions exist canceling the one-loop quadratic divergences to the Higg mass from the SM particles.

The Littlest Higgs Model (LHM) [15] is based on a non-linear 1σ model describing a SU(5)/SO(5) symmetry breaking. T-parity conservation can provide a possible candidate for dark matter WIMP (similar to R-parity conservation in supersymmetry). In addition T-parit forbids tree-level contribution from heavy gauge bosons to the electroweak precision observables The STU parameters of the oblique parameter fit are replaced by the calculations of the cor responding ones in the LHM [16]. The new floating parameters of the fit are: f the symmetr breaking scale, $s_\lambda \approx m_{T-}/m_{T+}$ in leading order the ratio of masses of the T-odd and the T-eve state from the LHM top sector, and δ_c a order one-coefficient, which exact value depends o detail of UV physics. The latter parameter is treated as theory uncertainty in the fit $\delta_c = -5...$

Figure 5 shows the 68%, 95%, and 99% CL allowed contours in the (M_H,f)-plane for a fixe value of $s_\lambda = 0.45$. Contributions of the T-odd partners of light fermions to the T parameter ar neglected. This assumption is justified as long as the T-odd fermions are sufficiently light. Th parameter F is a quantitative measure of fine-tuning, indicated by the black lines. Since large values of F correspond to larger degree of fine-tuning, large values of M_H are more preferred tha small values. Therefore, large Higgs masses are not only allowed by the electroweak precisio data, but they are also favored in terms of fine-tuning.

5 Two Higgs Doublet Model

In the Type-II 2HDM, we constrain the mass of the charged Higgs and the ratio of the vacuu expectation values of the two Higgs doublets using current measurements of observables from th B and K physics sectors and their most recent theoretical 2HDM predictions, namely R_b^0 [7,17 the branching ratio (BR) of $B \to X_s\gamma$ [18,19], the BR of leptonic decays of charged pseudoscala mesons ($B \to \tau\nu$ [20,21], $B \to \mu\nu$ [22,21] and $K \to \mu\nu$ [23]) and the BR of the semileptoni decay $B \to D\tau\nu$ [24,25].

For each observable, individual constraints have been derived in the ($\tan\beta, M_{H^\pm}$) plan Figure 6 displays the resulting 95% excluded regions derived assuming Gaussian behavior of th st statistics, and one degree of freedom. The figure shows that R_b^0 is mainly sensitive to $\tan\beta$ xcluding small values. BR($B \to X_s\gamma$) is only sensitive to $\tan\beta$ for values below $\simeq$1. For larger lues it provides an almost constant exclusion of a charged Higgs lighter than $\simeq$260 GeV. For l leptonic observables the 2HDM contribution can be either positive or negative since signed rms enter the prediction of the BRs resulting in a two-fold ambiguity in the $(\tan\beta, m_{H^\pm})$ pace.

In addition, we have performed a global fit combining the information from all observables. or the CL calculation in the two-dimensional plane we performed toy MC tests in each scan oint which allows to avoid the problem of ambiguities in the effective number of degrees of eedom. The 95% CL excluded region obtained are indicated in Figure 6 by the area below e single solid black line. We can exclude a charged Higgs mass below 240 GeV independently $\tan\beta$. This limit increases towards larger $\tan\beta$, e.g., $M_{H^\pm} < 780$ GeV are excluded for n $\beta = 70$.

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