The global electroweak fit and constraints on new physics

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Content
- Introduction to Gfitter
- Update on the electroweak fit
- Oblique Parameters
- Constrains on new physics
- Conclusion and Outlook
A Gfitter package for the global EW fit of the SM
- State of the art implementation of SM predictions of EW precision observables
- Based on huge amount of pioneering work by many people
- Radiative corrections are important (Logarithmic dependence on $M_H$ through virtual corrections)

Gfitter/GSM sub-package used in the global EW fit of the SM

In particular:
- $M_W$: full two-loop + leading beyond-two-loop corrections
- $\sin^2\theta^\prime_{\text{eff}}$: full two-loop + leading beyond-two-loop corrections
  [M. Awramik et al., JHEP 11, 048 (2006) and refs.] (Theoretical uncertainties: $\Delta \sin^2\theta_{\text{eff}} = 4.7 \times 10^{-5}$)
- Partial and total widths of $Z$ and $W$: integrated from ZFITTER
  See also: http://zfitter.desy.de

Including up to two-loop electroweak and all known QCD corrections

• Free fit parameters
  - $M_Z$, $M_H$, $m_t$, $D_{\text{had}}^{(5)}(M_Z^2)$, $a_S(M_Z^2)$, $m_c$, $m_b$
  - Scale parameters for theoretical uncertainties on $M_W$, $\sin^2\theta_{\text{eff}}^f$ (and the EW form factors $r_Z^f$, $k_Z^f$)

• Latest experimental input
  - $Z$-pole observables: LEP / SLC results
    [ADLO+SLD, Phys. Rept. 427, 257 (2006)]
  - $M_W$ and $G_W$ latest from LEP/Tevatron (03/2010)
    [ADLO, CDF+D0: arXiv:0908.1374v1]
  - $m_{\text{top}}$: latest Tevatron average (07/2010)
    [CDF&D0: new combination ICHEP’10]
  - $m_c$, $m_b$ world averages [PDG, J. Phys. G33,1 (2006)]
  - $\Delta a_{\text{had}}^{(5)}(M_Z^2)$ including $a_S$ dependency (10/2010)
    [Davier et al., arXiv:1010.4180]
  - Not considered: $\sin^2\theta_{\text{eff}}^f$ results from NuTeV. APV and polarized Möller scattering

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Input value</th>
<th>Free in fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_Z$ [GeV]</td>
<td>$91.1875 \pm 0.0021$</td>
<td>yes</td>
</tr>
<tr>
<td>$T_Z$ [GeV]</td>
<td>$2.4952 \pm 0.0023$</td>
<td>–</td>
</tr>
<tr>
<td>$\sigma_{\text{had}}^{(5)}$ [nb]</td>
<td>$41.540 \pm 0.037$</td>
<td>–</td>
</tr>
<tr>
<td>$R_Z^{(5)}$</td>
<td>$20.767 \pm 0.025$</td>
<td>–</td>
</tr>
<tr>
<td>$A_{FB}^{0.5}$</td>
<td>$0.0171 \pm 0.0010$</td>
<td>–</td>
</tr>
<tr>
<td>$A_e^{(\times)}$</td>
<td>$0.1499 \pm 0.0018$</td>
<td>–</td>
</tr>
<tr>
<td>$A_c$</td>
<td>$0.670 \pm 0.027$</td>
<td>–</td>
</tr>
<tr>
<td>$A_b$</td>
<td>$0.923 \pm 0.020$</td>
<td>–</td>
</tr>
<tr>
<td>$A_{V,b}^{(5)}$</td>
<td>$0.0707 \pm 0.0035$</td>
<td>–</td>
</tr>
<tr>
<td>$A_{FB}^{0,5}$</td>
<td>$0.0992 \pm 0.0016$</td>
<td>–</td>
</tr>
<tr>
<td>$R_Z^{0}$</td>
<td>$0.1721 \pm 0.0030$</td>
<td>–</td>
</tr>
<tr>
<td>$\sin^2\theta_{\text{eff}}^f(Q_{FB})$</td>
<td>$0.2324 \pm 0.0012$</td>
<td>–</td>
</tr>
<tr>
<td>$M_W$ [GeV]</td>
<td>$80.399 \pm 0.023$</td>
<td>–</td>
</tr>
<tr>
<td>$G_W$ [GeV]</td>
<td>$2.085 \pm 0.042$</td>
<td>–</td>
</tr>
<tr>
<td>$m_c$ [GeV]</td>
<td>$1.27_{-0.90}^{+1.07}$</td>
<td>yes</td>
</tr>
<tr>
<td>$m_b$ [GeV]</td>
<td>$4.20_{-0.07}^{+0.17}$</td>
<td>yes</td>
</tr>
<tr>
<td>$m_t$ [GeV]</td>
<td>$173.3 \pm 1.1$</td>
<td>yes</td>
</tr>
<tr>
<td>$\Delta a_{\text{had}}^{(5)}(M_Z^2)$ (±Δ)</td>
<td>$2749 \pm 10$</td>
<td>yes</td>
</tr>
<tr>
<td>$a_S(M_Z^2)$</td>
<td>–</td>
<td>yes</td>
</tr>
<tr>
<td>$\delta_{\text{th}} M_W$ [MeV]</td>
<td>$[-4, 4]_{\text{theo}}$</td>
<td>yes</td>
</tr>
<tr>
<td>$\delta_{\text{th}} \sin^2\theta^f_{\text{eff}}$ (+)</td>
<td>$[-4.7, 4.7]_{\text{theo}}$</td>
<td>yes</td>
</tr>
<tr>
<td>$\delta_{\text{th}} \rho_Z^{(5)}$ (+)</td>
<td>$[-2, 2]_{\text{theo}}$</td>
<td>yes</td>
</tr>
<tr>
<td>$\delta_{\text{th}} \kappa_Z^{(5)}$ (+)</td>
<td>$[-2, 2]_{\text{theo}}$</td>
<td>yes</td>
</tr>
</tbody>
</table>
• Include Results from the 2010 LHC run
  - ATLAS (combining six different final states)
  - CMS (H →WW → lνlν)

• Assume SM to be true to test compatibility with the data
  - Transform the one-sided confidence level, \( CL_{s+b} \) into a two-sided confidence level, \( CL_{2\text{-sided}}^{s+b} \).
  - reduces the statistical constraint from the direct searches compared to one-sided \( CL_{s+b} \)

• The contribution to the \( \chi^2 \) estimator minimized in the fit is obtained from
  \[
  \delta \chi^2 = 2 \cdot [\text{Erf}^{-1}(1 - CL_{s+b}^{2\text{-sided}})]^2
  \]
  - No correlations are taken into account among LEP, Tevatron and LHC results
Standard Model Fit Results

- Standard Fit Results
  - $\chi^2_{\text{min}} = 16.7$
  - 13 degrees of freedom
  - $\text{Prob}(\chi^2_{\text{min}}, 13) = 0.21$

- Complete Fit Results
  - $\chi^2_{\text{min}} = 17.6$
  - 14 degrees of freedom
  - $\text{Prob}(\chi^2_{\text{min}}, 14) = 0.23$

- Probabilities confirmed by pseudo Monte Carlo experiments

- Improvement in the p-value of the complete fit due to increased best-fit value of the Higgs mass in the standard fit

- new result reduces the tension with the direct Higgs boson searches
SM Higgs Results

- $\Delta \chi^2$ estimator for the standard and complete fits versus $M_H$

\[
M_H = \begin{cases} 
96^{+31}_{-24} \text{ GeV} & \text{(standard fit)} \\
120^{+12}_{-5} \text{ GeV} & \text{(complete fit)} 
\end{cases}
\]

- with the 95\% (99\%) upper bounds of
  - 169 GeV (200 GeV) for the standard fit
  - 143 GeV (149 GeV) for the complete fit

- The errors and limits include the various theory uncertainties that taken together amount to approximately 8 GeV on $M_H$.

- The standard fit value for $M_H$ has moved by $+12$ GeV as a consequence of the new $\Delta \alpha^{(5)}_{\text{had}}(M_Z^2)$

- Using the preliminary result $\Delta \alpha^{(5)}_{\text{had}}(M_Z^2)$ of K. Hagiwara, R. Liao, A. D. Martin, D. Nomura and T. Teubner, 1105.3149, we find

\[
M_H = 88^{+29}_{-23} \text{ GeV}
\]
Indirect Determination of $m_t$ and $m_W$

- Indirect Determinations
  - Perform (complete) fit for each parameter or observable, obtained by scanning the profile likelihood without using the corresponding experimental or phenomenological constraint in the fit.

- W mass is 1.6$\sigma$ below and exceeds in precision the experimental world average
  $$M_W = 80.359^{+0.017}_{-0.010} \text{ GeV}$$

- Allowed 1$\sigma$ regions are found from the indirect constraint of the top quark pole mass in the complete fit
  $$m_t = [173.5, 181.1] \text{ GeV} \quad \text{and} \quad [184.3, 190.3] \text{ GeV}$$

- $N^3LO$ $\alpha_s$ from fit
  $$\alpha_s(M_W^2) = 0.1193 \pm 0.0028$$
  - Negligible theoretical uncertainty
  - Excellent agreement with result $N^3LO$ from $\tau$-decays
Oblique Corrections

- Gfitter Beyond Standard Model Package
  - At low energies, BSM physics appears dominantly through vacuum polarization corrections
  - Called: oblique corrections

- Oblique corrections reabsorbed into electroweak parameters
  - $\Delta \rho, \Delta \kappa, \Delta \Gamma$ parameters, appearing in
    - $M_W^2, \sin^2 \theta_{\text{eff}}, G_F, \alpha,$ etc
  - Electroweak fit sensitive to BSM physics through oblique corrections

- In direct competition with sensitivity to Higgs loop corrections

- Also implemented: correction to $Z \rightarrow \text{bb}$ coupling, extended parameters (VWX)

- Oblique corrections from New Physics described through STU parametrization

- $O_{\text{meas}} = O_{\text{SM,REF}}(m_H, m_t) + c_S + c_T + c_U$

- **S-Parameter**: New Physics contributions to neutral currents
- (S+U) Parameter describes new physics processes to charged current processes

- **T-Parameter**: Difference between neutral and charged current processes – sensitive to weak isospin violation

- **U-Parameter**: (+S) New Physics contributions to charged currents. $U$ only sensitive to $W$ mass and width, usually very small in BSM models (often: $U=0$)
• S, T, U obtained from fit to EW observables

• Results for STU:
  - $S = 0.04 \pm 0.10$
  - $T = 0.05 \pm 0.11$
  - $U = 0.08 \pm 0.11$

• SM prediction
  - $\text{SM}_{\text{ref}}$ chosen at: $M_H = 120$ GeV and $m_t = 173.1$ GeV
  - This defines $(S, T, U) = (0, 0, 0)$
  - $S, T$: logarithmically dependent on $M_H$

• Comparison of EW data w/ SM prediction:
  - Preference for small $M_H$
  - No indication for new physics

• Many BSM models also compatible with the EW data:
  - Variation of model parameters often allows for large area in ST-plane
  - Tested: UED, 4th fermion generation, Littlest Higgs, SUSY, Two-Higgs-Doublet Model, Inert HDM, etc.
**Well Known Example: Extended Technicolor**

- **Basic Idea of Technicolor**
  - Dynamical explanation for electroweak symmetry breaking
  - Introduce a new QCD-like gauge interaction that is asymptotically free at high energies but confining at the electroweak scale
  - Gauge interaction is to be based on a SU(NTC) gauge group GTC, where NTC
  - “Scaled up” version of QCD

- **Well known result for all QCD-like technicolor models**
  - Full incompatibility with electroweak precision data
  - One reason for the “death” of extended technicolor theories
  - Possible solution: “Walking” technicolor
• Basic Concept of IDM:
  - Introduction of extra Higgs doublet to help solve hierarchy problem
  - Does not couple to fermions ("inert"). Does not acquire a VEV.

• Three new Higgses
  - Two neutral ($M_{H^0}, M_A$), one charged ($M_{H^+}$)
  - Lightest inert particle ("LIP") is stable ($M_L$), assumed neutral.
  - Natural dark matter candidate

• Contributions to:
  - T: isospin violation between neutral and charged Higgses.
  - S: $H^+H^-$ and HA loop corrections to self energy of Z-photon propagator

• Results: large SM Higgs mass allowed

[Barbieri et al., hep-ph/0603188v2 (2006)]
• Basic Concept of UED
  - All SM particles can propagate into ED
  - Compactification → KK excitations
  - Conservation of KK parity
    o Phenomenology similar to SUSY
    o Lightest stable KK state: DM candidate
  - Model parameters
    o $d_{ED}$: number of ED (fixed to $d_{ED} = 1$)
    o $R^{-1}$: compactification scale ($m_{KK} \sim n/R$)

• Contribution to vac. polarisation (STU):
  - From KK-top/bottom and KK-Higgs loops
  - Dependent on $R^{-1}$, $M_H$ (and $m_t$)

• Results:
  - Large $R^{-1}$: UED approaches SM (exp.)
    - Only small $M_H$ allowed
  - Small $R^{-1}$: large UED contribution can be compensated by large $M_H$
  - Excluded: $R^{-1} < 300$ GeV and $M_H > 800$ GeV

• Basic Concept of WED
  - Introduction of one extra dimension (ED) to help solve the hierarchy problem
  - RS model characterized by one warped ED, confined by two three-branes
  - Higgs localized on “IR” brane
  - Gauge and matter fields allowed to propagate in bulk region
  - SM particles accompanied by towers of heavy KK modes.

• Model parameters:
  - $L$: inverse warp factor, function of compactification radius, explains hierarchy between EW an Pl scale
  - $M_{KK}$: KK mass scale

• Results
  - Large values of $T$ possible
  - Large $L$ forces large $M_{KK}$ (several TeVs)
  - Some compensation if $M_H$ is large

• Models with a fourth generation
  - No explanation for \( n=3 \) generations
  - Intr. new states for leptons and quarks
    - Free parameters:
      - masses of new quarks and leptons
      - assume: no mixing of extra fermions

• Contrib. to STU from new fermions
  - Discrete shift in S from extra generation
  - Sensitive to mass difference between up- and down-type fields. (not to absolute mass scale)

• CDF+D0 & CMS: SM4G Higgs partially excluded:
  - CDF+D0: \( 131 > M_H > 204 \text{ GeV} \) @ 95% CL
  - CMD: \( 144 > M_H > 207 \text{ GeV} \) @ 95% CL

• Fit-Results:
  - With appropriate mass differences: 4\(^{th}\) fermion model consistent with EW data (large \( M_H \) is allowed)
  - 5+ generations disfavored
  - Data prefer a heavier charged lepton / up-type quark (which both reduce size of S)
• Unfortunately we didn’t receive the latest CLS+B values from the experiments
• Hopefully an Update will be available during the next week, maybe even during the conference
  - In the latter case: We will update this slide with the latest exclusion limits
  - Otherwise: Look at Gfitter’s contribution during the Higgs-Hunter Workshop

• In the meanwhile:
  - P-value versus MH of the standard electroweak fit as obtained from pseudo-MC simulation.
  - The error band represents the statistical error from the MC sampling size
Conclusion & Prospects

• Gfitter is a powerful framework for HEP model fits.
  - Latest results/updates and new results always available at: http://cern.ch/Gfitter

• Results shown
  - New & updated global fit of the electroweak SM
  - Very happy to see first LHC Higgs results included in EW fit!
  - SM Higgs mass strongly constrained. Light Higgs very much preferred by SM.
  - Oblique parameters (still!) a powerful method to constrain BSM theories
  - Presented constraints on various BSM theories
  - Heavy Higgs boson allowed in many BSM models!

• The future
  - Maintain and extend existing fits.
  - Update with latest Tevatron and LHC results
  - 2011: SUSY results

Much more and detailed information to be found in our recent publication: http://arxiv.org/abs/1107.0975