NEWS FROM THE ELECTROWEAK SM FIT AND CONSTRAINTS ON SM EXTENSIONS

Dörthe Kennedy (DESY/University of Hamburg)
for the Gfitter Group*

LoopFest XI, Pittsburgh
May 11th 2012

* M. Baak, M. Goebel, J. Haller, A. Höcker, D. K., K. Möning, M. Schott, J. Stelzer
**INTRODUCTION TO Gfitter**

1. **Goal**
   - provide state-of-the-art model testing tool for LHC era

2. **Input to Gfitter**
   - electroweak precision measurements from LEP, SLD, Tevatron and LHC
   - theoretical predictions

3. **The Gfitter Package**
   - C++, ROOT, xml
   - Core Package: data handling, fitting and statistics tools
   - full statistics analysis
     - parameter scans
     - p-values
     - toy MC analyses
     - goodness-of-the-fit tests
   - physics libraries

**REFERENCE PAPER:**
EPJ C60, 543-583, 2009 [ARXIV:0811.0009]

**UPDATE & BSM:**
ACCEPTED BY EPJ C, [ARXIV:1107.0975]
HTTP://WWW.CERN.CH/GFITTER

Dörthe Kennedy – EW Fit with Gfitter

Loopfest XI May 2012
**INTRODUCTION TO GFITTER**

4. SM: global electroweak Fit
- constraints on $M_H$
- constraints on $M_W, m_t$
- determination of $\alpha_s, \sin^2\theta_{\text{eff}}$
- pull-values of electroweak observables

5. BSM physics models – STU Parameter
- introduce oblique parameters
- ew fit - sensitive to BSM physics through oblique corrections
- SM vs. BSM physics

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Dörthe Kennedy – EW Fit with Gfitter

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THE ELECTROWEAK FIT WITH GFITTER
The Electroweak Fit: Experimental Input I

- **Z-pole observables** including their correlations: LEP/SLD experiments
  
  \[ M_W = 80.385 \pm 0.015 \text{GeV} \]
  
  [ADLO+SLD, Phys. Rept. 427, 257 (2006)]

- **new W mass measurements** from D0 and CDF combined with LEP result:
  
  \[ M_W = 80.385 \pm 0.015 \text{GeV} \]
  
  [ADLO, hep-ex/0612034][D0,arXiv:1203.0293]
  [CDF,arXiv:1203.0275][LEPEWWG]

- **Γ_W**: LEP/Tevatron
  
  [ADLO, hep-ex/0612034][CDF& D0, arXiv:0908.1374]

- **m_c, m_b**: world averages
  

- **m_t**: Tevatron using 5.8 fb\(^{-1}\)
  
  [D0& CDF, arXiv:1107.5255]

- **Δα^{(5)}_{had} (M_Z^2)**: including a_s dependency
  
  [Davier et al. EPJ C71 (2011)]

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<thead>
<tr>
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</tr>
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<tbody>
<tr>
<td>$M_Z$ [GeV]</td>
<td>91.1875 ± 0.0021</td>
<td>yes</td>
</tr>
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<td>$Γ_Z$ [GeV]</td>
<td>2.4952 ± 0.0023</td>
<td>–</td>
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<tr>
<td>$σ_{had}^0$ [nb]</td>
<td>41.540 ± 0.037</td>
<td>–</td>
</tr>
<tr>
<td>$R_0^0$</td>
<td>20.767 ± 0.025</td>
<td>–</td>
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<td>$M_H$ [GeV](^{(0)})</td>
<td>95.32 ± 0.06</td>
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<td>173.2 ± 0.9</td>
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<td>$Δα_{\text{had}} (M_Z^2)$(^{(12)})</td>
<td>2757 ± 10</td>
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<td>$α_s (M_Z^2)$</td>
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- Dörthe Kennedy – EW Fit with Gfitter
The Electroweak Fit: Experimental Input II

• **direct Higgs mass exclusions (at 95% CL):**
  
  o **LEP:** $M_H > 114$ GeV  
  
  o **Tevatron:** **100-119 GeV** and **141-184 GeV**  
  
  o **ATLAS:** **110-117.5 GeV**, **118.5-122.5 GeV**, and **129-539 GeV**  
    [ATLAS-CONF-2012-019]
  
  o **CMS:** **127.5-600 GeV**  
    [CMS-PAS-HIG-12-008]
  
  o **LHC+Tevatron:** excess at 125 GeV

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**Allowed Regions**

- **117.5 – 118.5 GeV**
- **122.5 – 127.5 GeV**

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**$M_H$ [GeV] (°)**

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**δ_{tH}, M_W [MeV]**

| –4.4 | yes |

**δ_{tH} sin^2θ_{eff}(t)**

| –4.7, 4.7 | yes |

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* Dörthe Kennedy – EW Fit with Gfitter
The Electroweak Fit: Theoretical Input I

- Electroweak precision observables expressed as functions of the free SM parameters:

\[ M_Z, M_H, m_t, \Delta \alpha^{(5)}_{\text{had}}(M_Z^2), \alpha_s(M_Z^2), m_c, m_b \]

- Most important predictions for constraining the Higgs mass:
  - \( M_W \) and \( \sin^2\theta^f_{\text{eff}} \): full two-loop + leading beyond-two-loop correction
  - Theoretical uncertainties (due to e.g. truncation of higher QCD orders):
    - \( M_W \) (\( \delta M_W = 4 \text{ MeV} \)) and \( \sin^2\theta^f_{\text{eff}} \) (\( \delta \sin^2\theta^f_{\text{eff}} = 4.7 \cdot 10^{-5} \))
    - \( \sin^2\theta^f_{\text{eff}} \) defines asymmetry parameter and forward-backward asymmetry

- Width of W boson not crucial for fit due to large experimental uncertainty
  - [Hagiwara et al., arXiv:1104.1769]
The Electroweak Fit: Theoretical Input II

- partial Z widths (or ratio of them)
  - important for determination of $\alpha_s$
  - Z couplings implemented by parametrization
    - one-loop, partly at two-loop level for $O(\alpha\alpha_s)$
      [Hagiwara et al., arXiv:1104.1769)][more information in DESY-THESIS-2011-029]
  - Correction applied for large Higgs masses ($M_H>500$ GeV)
    - accounting for difference between ZFitter and parametrization
      [Bardin et al, CPC 133,299(2001)][Arbuzov et al., CPC 174,728(2006)]
  - radiator functions describe final QCD and QED radiation
- including N3LO to hadronic Z decay

- Include new $R_b$ calculation
  [Freitas and Huang, arxiv:1205.0299]
The Electroweak Fit: Constraints on Higgs mass

- $M_H$ from fit including all data except results from direct Higgs searches at LEP, Tevatron, LHC
  - value at minimum $\pm 1\sigma$: $M_H = 94^{+25}_{-22}$ GeV
- 95% (99%) upper bound: 152 GeV (176 GeV)
The Electroweak Fit: New $M_W$

- new $M_W$ measurement improves the 95% and 99% CL limits
The Electroweak Fit: SM Fit Results

- **goodness-of-the fit:**
  - excl. (incl.) direct Higgs searches:
    - $\chi^2_{\text{min}} = 20.3 \ (21.8)$
    - $\text{Prob}(\chi^2_{\text{min}}, 13(14)) = 0.09 \ (0.08)$
    - reduced by new $R_b$ calculation
  - values before 2011:
    - $\chi^2_{\text{min}} = 16.6 \ (17.8)$
    - $\text{Prob}(\chi^2_{\text{min}}, 13(14)) = 0.21 \ (0.23)$

- **pull values (incl. direct Higgs searches)**
  - increased pull-value of $R_b$: -0.8 $\rightarrow$ -2.3
  - $A_0^{0,b\text{FB}}$ largest contributor to $\chi^2_{\text{min}}$
  - no individual pull exceeds $3\sigma$
  - small contributions from $M_Z, \Delta \alpha^{(5)}_{\text{had}}(M_Z^2)$, $m_c$, $m_b$
    - input accuracies exceed fit requirements

- **good agreement between data and SM**
The Electroweak Fit: Determination of $m_t$

- direct top mass measurement is not included
  - fit excluding (including) direct Higgs searches
  - fit with fixed Higgs mass
- fit results in agreement with direct measurements

![Graph showing $\Delta \chi^2$ vs. $m_t$ with different fits and measurements.](image)

**w/o direct Higgs searches**
- $171.1^{+6.8}_{-5.2}$ GeV

**with direct Higgs searches**
- $175.1^{+3.3}_{-2.4}$ GeV
The Electroweak Fit: Determination of $M_W$

- direct $W$ mass measurement is not included
  - fit excluding (including) direct Higgs searches
  - fit with fixed Higgs mass
- fit results in agreement with direct measurements
- indirect determination higher precision than world average

- $80.363 \pm 0.028 \text{ GeV}$
- $80.361 \pm 0.013 \text{ GeV}$
The Electroweak Fit: Scan of $m_t$ and $M_W$

- green bands: world average, agree with indirect constraints
- direct Higgs searches constrain both observables significantly
- possible to probe SM or BSM physics models

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CONSTRAINTS ON NEW PHYSICS MODELS

68%, 95%, 99% CL fit contours
\( M_H = 120 \text{ GeV}, m_t = 173 \text{ GeV}, U = 0 \)

\( M_H \in [117.5, 127.5] \text{ GeV} \)
\( m_t = 173.2 \pm 0.9 \text{ GeV} \)
"Oblique" Parameters


1. **assumption:** high-scale BSM physics appears only through vacuum polarisation corrections (cf. rad. corr. from mt, MH in SM)

2. **ew fit sensitive to BSM physics through these oblique corrections**

3. **oblique corrections** from New Physics described through **STU parametrization**

\[ O = O_{SM;ref} (M_H; m_t) + c_S S + c_T T + c_U U \]

4. **STU measure deviations** from electroweak radiative correction expected in SM_{ref}

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**S:** new physics contribution to **neutral current processes**

**U:** (+S) new physics contribution to **charged current processes**

- U only sensitive to \( M_W \) and \( \Gamma_W \)
- usually very small in new physics models (often: \( U=0 \))

**T:** difference between neutral and charged current processes

- sensitive to weak isospin violation
• S, T, U derived from fit to electroweak observables
  o $\text{SM}_{\text{ref}}$: $m_t = 173$ GeV, $M_H = 120$ GeV

• results for STU:
  o $S = 0.04 \pm 0.10$, $T = 0.05 \pm 0.11$, $U = 0.08 \pm 0.11$

• gray area: SM prediction
  o for $\text{SM}_{\text{ref}}$: $S = T = U = 0$
  o $S$, $T$: logarithmically dependent on $M_H$
  o small $M_H$ compatible with data

• BSM physics models
  o large S-T area allowed due to unconstrained model parameters
  o heavy Higgs masses due to compensation

• status of recent publication
  o update is in progress
  o new $m_t$, $M_H$ partially included
  o no new $M_W$, $R_b$, N3LO to hadronic Z decay

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models with a fourth generation
  - SM: no explanation for n=3 generations
  - introduction of new states for leptons and quarks
    \[ \Psi_L = (\Psi_1^L, \Psi_2^L), \Psi_1^R, \Psi_2^R \]

free parameters:
  - masses of new quarks and leptons
    \[ m_{\nu 4}, m_{d 4}, m_{e 4} \]
  - assuming: no mixing of extra fermions
  - model-independent

contribution to STU from new fermions

sensitivity to mass difference between up-type and down-type fields, rather than absolute mass scale

results:
  - with appropriate mass differences: 4th fermion model consistent with data
  - large MH is allowed
  - data prefer a heavier charged lepton

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Sequential Fourth Generation

[Hubisz et al., JHEP 0601:135 (2006)]

- models with a fourth generation
  - SM: no explanation for n=3 generations
  - introduction of new states for leptons and quarks
    \[ \Psi_L = (\Psi_{1,2}, \Psi_{1,R}, \Psi_{2,R}) \]

- free parameters:
  - masses of new quarks and leptons
    \[ mu_4, \; md_4, \; me_4 \; m_4 \]
  - assuming: no mixing of extra fermions
  - model-independent

- contribution to STU from new fermions

- sensitivity to mass difference between up-type and down-type fields, rather than absolute mass scale

- results:
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**Warped Extra Dimension**


- extra dimension (ED) confined by two branes for solving hierarchy problem
- generation of weak scale on IR brane from UV brane: introduction of warp factor (exp. func. of compactification radius of ED)
- originally: ED only accessible to gravity
- here: SM fermions, gauge bosons propagate into bulk, Higgs does not
- free parameters
  - MKK : KK scale (heavy KK modes)
  - L: log of warp factor
- results:
  - large L requires large MKK
  - compensation if MH is large

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Warped Extra Dimension


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Two-Higgs Doublet Model I


- different 2HDM types:
  - Type-I: only one doublet couples to fermion sector
  - Type-II: one doublet couples to up-type fermions, one to down-type fermions, resembles Higgs sector of MSSM
  - type distinction irrelevant for study of oblique corrections
  - defined according to Yukawa couplings, do not enter oblique corrections at one-loop order

- free parameters:
  - Higgs masses $M_{h0}, M_{H0}, M_{A0}, M_H$
    - LEP limit: $M_H > 78.6$ GeV
  - ratio of the vev of the two doublets, $\tan\beta = v_2/v_1$ (mixing of charged and neutral fields)
  - angle $\alpha$ (mixing of the neutral CP-even Higgs fields)

- introduce one additional $SU(2)_L \times U(1)_Y$ Higgs doublet with hypercharge $Y = 1$
- 2 Higgs doublets $\rightarrow$ 5 physical Higgs boson states
- FCNC can be suppressed with appropriate choice of the Higgs-to-fermion couplings
Two-Higgs Doublet Model II

[111x495]

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- parameter constraints only dependent of other parameters
- for light $M_{h0}$:
  - similar values of the heavy Higgs masses preferred
Many More Models

- Littlest Higgs Model
- Inert Doublet Model
- Warped Extra Dimension with Custodial Symmetry
- One Universal Extra Dimension
- Large Extra Dimensions

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**Conclusion**

**Standard Model**
- global fit of the electroweak SM
- good compatibility of the SM and the electroweak precision data
- inclusion of latest direct Higgs searches
  - Higgs mass strongly constrained
  - light Higgs preferred by SM
- inclusion of the latest $R_b$ calculations

**BSM physics models**
- test compatibility of various BSM models with electroweak precision data via the oblique parameters
- set constraints on BSM model parameters
- heavier Higgs boson allowed in various BSM models
THANK YOU FOR YOUR ATTENTION!

REFERENCE PAPER: EPJC60, 543-583, 2009 [ARXIV:0811.0009]
UPDATE & BSM: ACCEPTED BY EPJC, [ARXIV:1107.0975]
HTTP://WWW.CERN.CH/GFITTER
**Statistical Interpretation of Direct Higgs Searches**

- **Statistical interpretation**
  - Experiments measure test statistic
  - Transformed by experiments into 1-sided upper limit (CLS=CLS+B/CLB) using pseudo experiments
  - We transform 1-sided CLS+B into 2-sided CL2sS+B
    - SM is null hypothesis. We measure both down- and upward deviations from SM!
  - $\chi^2$ contribution calculated via inverse error function:
    $$d\chi^2 = \text{Erf}^{-1}(1-\text{CL2sS+B})$$

- **Alternative treatment, followed here:**
  - $\chi^2$ contribution is: -2lnQ
  - Lacks statistical information from experiments.
  - No 2-sided interpretation
  - ATLAS CLS+B not public

- **Note about combination of ATLAS and CMS H→WW results**
  - Ignores correlations between x-section theory and luminosity uncertainties!
  - Tevatron/LHC combination procedure needed

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**Graph:**
- Direct Searches at LEP
- Direct Searches at Tevatron
- Direct Searches at ATLAS
- Direct Searches at CMS

**Legend:**
- LEP, Tevatron, LHC combined

**Axes:**
- $M_H$ [GeV]
- $\delta\chi^2$

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