News From The Global Electroweak Fit

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University of Hamburg
for the Gfitter group

Higgs Hunting
LAL, August 1st, 2015

The Gfitter group: M. Baak (CERN), J. Cúth (Univ. of Mainz), J. Haller (Univ. Hamburg), A. Hoecker (CERN), R. K. (Univ. Hamburg), K. Mönig (DESY), T. Peiffer (Univ. Hamburg), M. Schott (Univ. of Mainz), J. Stelzer (Univ. of Michigan)
State of the Standard Model

68% and 95% CL contours
- direct $M_W$ and $\sin^2(\theta^f_{\text{eff}})$ measurements
- fit w/o $M_W$, $\sin^2(\theta^f_{\text{eff}})$ and Z widths measurements
- fit w/o $M_W$, $\sin^2(\theta^f_{\text{eff}})$ and $M_H$ measurements
- fit w/o $M_W$, $\sin^2(\theta^f_{\text{eff}})$, $M_H$ and Z widths measurements

$M_W$ world comb. $\pm 1\sigma$

$\sin^2(\theta^f_{\text{eff}})$ LEP+SLC $\pm 1\sigma$

(see also talk by Tongguang Cheng)
Prediction of Top Quark Mass

What precision is needed to see significant deviations between measurements and predictions?

- $m_t$ predictions from loop effects since 1990
- official LEPEWWG fit since 1993
- the fits have always been able to predict $m_t$ correctly!
Prediction of Higgs Mass

- $M_H$ predictions from loop effects since the discovery of the top quark 1995
- weaker constraints than for $m_t$ because of logarithmic dependence
- still, the fits have always predicted $M_H$ correctly!

Again: what precision should we strive for? What are the major challenges?
Fit is overconstrained

- all free parameters measured ($\alpha_s(M_Z)$) unconstrained in fit
  - most input from $e^+e^-$ colliders
    - $M_Z : 2 \cdot 10^{-5}$
  - but crucial input from hadron colliders:
    - $m_t : 4 \cdot 10^{-3}$
    - $M_H : 2 \cdot 10^{-3}$
    - $M_W : 2 \cdot 10^{-4}$
  - remarkable precision (<1%)
- require precision calculations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_H$ [GeV]</td>
<td>125.14 ± 0.24</td>
</tr>
<tr>
<td>$M_W$ [GeV]</td>
<td>80.385 ± 0.015</td>
</tr>
<tr>
<td>$\Gamma_W$ [GeV]</td>
<td>2.085 ± 0.042</td>
</tr>
<tr>
<td>$M_Z$ [GeV]</td>
<td>91.1875 ± 0.0021</td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>2.4952 ± 0.0023</td>
</tr>
<tr>
<td>$\sigma_{\text{had}}$ [nb]</td>
<td>41.540 ± 0.037</td>
</tr>
<tr>
<td>$R_\ell^0$</td>
<td>20.767 ± 0.025</td>
</tr>
<tr>
<td>$A_{FB}^0,\ell$</td>
<td>0.0171 ± 0.0010</td>
</tr>
<tr>
<td>$A_{FB}^\ell$</td>
<td>0.1499 ± 0.0018</td>
</tr>
<tr>
<td>$\sin^2\theta_{\text{eff}}(Q_{FB})$</td>
<td>0.2324 ± 0.0012</td>
</tr>
<tr>
<td>$A_c$</td>
<td>0.670 ± 0.027</td>
</tr>
<tr>
<td>$A_b$</td>
<td>0.923 ± 0.020</td>
</tr>
<tr>
<td>$A_{FB}^0,\ell$</td>
<td>0.0707 ± 0.0035</td>
</tr>
<tr>
<td>$A_{FB}^\ell$</td>
<td>0.0992 ± 0.0016</td>
</tr>
<tr>
<td>$R_c^0$</td>
<td>0.1721 ± 0.0030</td>
</tr>
<tr>
<td>$R_b^0$</td>
<td>0.21629 ± 0.00066</td>
</tr>
<tr>
<td>$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$</td>
<td>2757 ± 10</td>
</tr>
<tr>
<td>$\bar{m}_c$ [GeV]</td>
<td>1.27^{+0.07}_{-0.11}</td>
</tr>
<tr>
<td>$\bar{m}_b$ [GeV]</td>
<td>4.20^{+0.17}_{-0.07}</td>
</tr>
<tr>
<td>$m_t$ [GeV]</td>
<td>173.34 ± 0.76</td>
</tr>
</tbody>
</table>
Calculations

All observables calculated at 2-loop level

- $M_W$: full EW one- and two-loop calculation of fermionic and bosonic contributions
  [M Awramik et al., PRD 69, 053006 (2004), PRL 89, 241801 (2002)]
  + 4-loop QCD correction [Chetyrkin et al., PRL 97, 102003 (2006)]

- $\sin^2 \theta_{\text{eff}}$: same order as $M_W$, calculations for leptons and all quark flavours

- partial widths $\Gamma_f$: fermionic corrections in two-loop for all flavours (includes predictions for $\sigma^0_{\text{had}}$) [A. Freitas, JHEP04, 070 (2014)]

- Radiator functions: QCD corrections at $N^3$LO
  [Baikov et al., PRL 108, 222003 (2012)]

- $\Gamma_W$: only one-loop EW corrections available, negligible impact on fit
  [Cho et al, JHEP 1111, 068 (2011)]

- all calculations: one- and two-loop QCD corrections and leading terms of higher order corrections
Theoretical Uncertainties

- estimated using a geometric series \((a_n = a \cdot r^n)\), example: 
  \[ O(\alpha^2 \alpha_s) = \frac{O(\alpha^2)}{O(\alpha)} O(\alpha \alpha_s) \]
  - similar results from scale variations
- reasonable estimates for all observables
- exception: \(m_t\)!

\[ M_{exp}^2 = \left( \sum_{i=1,\ldots,n} p_i \right)^2 \]

[A. Hoang arXiv:1412.3649, M. Mangano]

- MC definition, relation to \(m_{\text{pole}}\) unknown
- uncertainties from colour structure, hadronisation and \(m_{\text{pole}} \rightarrow m_t(m_t)\) smaller

- 10 additional free parameters, Gaussian likelihood
- important missing higher order terms:
  - \(O(\alpha^2 \alpha_s), O(\alpha \alpha_s^2), O(\alpha^2_{\text{bos}})\) (in some cases), \(O(\alpha^3), O(\alpha_s^5)\) (rad. functions)

<table>
<thead>
<tr>
<th>Observable</th>
<th>Exp. error</th>
<th>Theo. error</th>
</tr>
</thead>
<tbody>
<tr>
<td>(M_W)</td>
<td>15 MeV</td>
<td>4 MeV</td>
</tr>
<tr>
<td>(\sin^2\theta_{\text{eff}})</td>
<td>1.6 (\times) 10^{-4}</td>
<td>0.5 (\times) 10^{-4}</td>
</tr>
<tr>
<td>(\Gamma_Z)</td>
<td>2.3 MeV</td>
<td>0.5 MeV</td>
</tr>
<tr>
<td>(\sigma_{\text{had}}^0)</td>
<td>37 pb</td>
<td>6 pb</td>
</tr>
<tr>
<td>(R_b^0)</td>
<td>6.6 (\times) 10^{-4}</td>
<td>1.5 (\times) 10^{-4}</td>
</tr>
<tr>
<td>(m_t)</td>
<td>0.76 GeV</td>
<td>0.5 GeV</td>
</tr>
</tbody>
</table>

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News from the global electroweak fit
Theoretical uncertainty on $m_t$

Impact of variation in $\delta_{\text{theo}} m_t$ between 0 and 1.5 GeV

- Better assessment of uncertainty on $m_t$ important for the fit
- Uncertainty of 0.5 GeV small impact on result
Future Improvements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Present</th>
<th>LHC</th>
<th>ILC/GigaZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_H$ [GeV]</td>
<td>0.2</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>$M_W$ [MeV]</td>
<td>15</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>$M_Z$ [MeV]</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>$m_t$ [GeV]</td>
<td>0.8</td>
<td>0.6</td>
<td>0.1</td>
</tr>
<tr>
<td>$\sin^2 \theta_{\text{eff}} [10^{-5}]$</td>
<td>16</td>
<td>16</td>
<td>1.3</td>
</tr>
<tr>
<td>$\Delta \alpha^5_{\text{had}}(M^2_Z) [10^{-5}]$</td>
<td>10</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>$R_l^0 [10^{-3}]$</td>
<td>25</td>
<td>25</td>
<td>4</td>
</tr>
<tr>
<td>$\kappa_V (\lambda = 3 \text{ TeV})$</td>
<td>0.05</td>
<td>0.03</td>
<td>0.01</td>
</tr>
</tbody>
</table>

- theoretical uncertainties reduced by a factor of 4 (esp. $M_W$ and $\sin^2 \theta_{\text{eff}}$)
  - implies three-loop calculations!
  - exception: $\delta_{\text{theo}} m_t$ (LHC) = 0.25 GeV (factor 2)
- central values of input measurements adjusted to $M_H = 125$ GeV

-LHC = LHC with 300 fb$^{-1}$
- ILC/GigaZ = future $e^+e^-$ collider, option to run on Z-pole (w polarized beams)

[Baak et al, arXiv:1310.6708]
SM Fit Results

black: direct measurement (data)
orange: full fit
light-blue: fit excluding input from row

- goodness of fit, p-value:
  \[ \chi^2_{\text{min}} = 17.8 \quad \text{Prob}(\chi^2_{\text{min}}, 14) = 21\% \]
  Pseudo experiments: 21 ± 2 (theo)%
  - \[ \chi^2_{\text{min}}(\Gamma_i \text{ in } 1\text{-loop}) = 18.0 \]
  - \[ \chi^2_{\text{min}}(\text{no theory uncertainties}) = 18.2 \]
- no individual value exceeds 3\(\sigma\)
- largest deviations in b-sector:
  - \[ A^{0,b}_{\text{FB}} \text{ with } 2.5\sigma \]
    \[ \to \text{largest contribution to } \chi^2 \]
- small pulls for \(M_H, M_Z\)
  - input accuracies exceed fit requirements
Present Results: Higgs

Determination of $M_H$

- grey band: fit without $M_H$ measurement
  - $M_H = 93^{+25}_{-21}$ GeV
  - consistent with measurement at $1.3\sigma$
- blue line: full SM fit

Impact of most sensitive observables

- determination of $M_H$, removing all sensitive observables except the given one
- known tension ($3\sigma$) between $A_l$(SLD), $A_{0,b}^F_B$, and $M_W$ clearly visible

$\Delta \chi^2$ vs $M_H$ [GeV]

- Fit w/o $M_H$
- LHC average

Present Results:

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**Future: Higgs Mass**

- Logarithmic dependency on $M_H \to$ cannot compete with direct $M_H$ meas.
  - no theory uncertainty: $M_H = 125 \pm 7$ GeV
  - future theory uncertainty (Rfit): $M_H = 125^{+10}_{-9}$ GeV
  - present day theory uncertainty: $M_H = 125^{+20}_{-17}$ GeV
- If EWPO central values unchanged (94 GeV), $\sim 5\sigma$ discrepancy with measured Higgs mass
Future: Higgs Mass

- Logarithmic dependency on $M_H \rightarrow$ cannot compete with direct $M_H$ meas.
  - no theory uncertainty: $M_H = 125 \pm 7$ GeV
  - future theory uncertainty (Rfit): $M_H = 125^{+10}_{-9}$ GeV
  - present day theory uncertainty: $M_H = 125^{+20}_{-17}$ GeV

- If EWPO central values unchanged (94 GeV), $\sim 5\sigma$ discrepancy with measured Higgs mass compromised by present theory uncertainty!
Indirect determination of $W$ mass

- also shown: SM fit with minimal input: $M_Z, G_F, \Delta \alpha_{\text{had}}^{(5)}(M_Z), \alpha_s(M_Z), M_H$, and fermion masses
  - good consistency
- $M_H$ measurement allows for precise constraint on $M_W$
  - agreement at $1.4\sigma$
- fit result for indirect determination of $M_W$ (full fit w/o $M_W$):

  $$M_W = 80.3584 \pm 0.0046_{m_t} \pm 0.0030\delta_{\text{theo}m_t} \pm 0.0026_{M_Z} \pm 0.0018\Delta\alpha_{\text{had}}$$
  $$\pm 0.0020_{\alpha_S} \pm 0.0001_{M_H} \pm 0.0040\delta_{\text{theo}M_W} \text{ GeV}$$
  $$= 80.358 \pm 0.008_{\text{tot}} \text{ GeV}$$

  more precise than direct measurement (15 MeV)
Indirect determination of $W$ mass

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\]
\[
\pm 0.0020_{\alpha_S} \pm 0.0001_{M_H} \pm 0.0040_{M_W} \text{ GeV}
\]
\[
= 80.358 \pm 0.008_{\text{tot}} \text{ GeV} \quad (\delta m_t (1 \text{ GeV}): \pm 9 \text{ MeV}, \text{Rfit: } \pm 13 \text{ MeV})
\]

more precise than direct measurement (15 MeV)
**Future: $M_W$**

**LHC-300 Scenario**
- moderate improvement (~30%) of indirect constraint
  - theoretical uncertainties already important

**ILC Scenario**
- improvement of factor 3 possible, similar to direct measurement

**Fit Results:**

$$
\delta M_W = 1.7 M_Z + 0.1 m_t + 1.2 \sin^2 \theta^f_{\text{eff}} + 0.6 \Delta \alpha_{\text{had}} + 0.3 \alpha_s \text{ MeV}
$$

$$
\delta M_W = 1.3_{\text{theo}} + 1.9_{\text{exp}} \text{ MeV} = 2.3_{\text{tot}} \text{ MeV}
$$

Measurement uncertainty for ILC: **5 MeV**
Indirect determination of $m_t$

- determination of $m_t$ from Z-pole data (fully obtained from radiative corrections $\sim m_t^2$)
- alternative to direct measurements
- $M_H$ allows for significantly more precise determination of $m_t$

$$m_t = 177.0 \pm 2.3 M_W \sin^2 \theta^f_{\text{eff}} \pm 0.6 \alpha_s \pm 0.5 \Delta \alpha_{\text{had}} \pm 0.4 M_Z \text{ GeV}$$

$$= 177.0 \pm 2.4_{\text{exp}} \pm 0.5_{\text{theo}} \text{ GeV}$$

- similar precision as determination from $\sigma_{tt\bar{t}}$, good agreement
- dominated by experimental precision
Future: Top Quark Mass

LHC-300 Scenario
- improvement due to improved precision on $M_W$

ILC Scenario
- Comparable precision due to $M_W$ and $\sin^2 \theta^l_{\text{eff}}$ measurements
  ($M_W$: $\delta m_t = 1$ GeV
  $\sin^2 \theta^l_{\text{eff}}$: $\delta m_t = 0.9$ GeV)

Fit Results:

$$\delta m_t = 0.6 M_W \oplus 0.5 M_Z \oplus 0.3 \sin^2 \theta^f_{\text{eff}} \oplus 0.4 \Delta \alpha_{\text{had}} \oplus 0.2 \alpha_s \text{ GeV}$$

$$\delta m_t = 0.2_{\text{theo}} \oplus 0.7_{\text{exp}} \text{ GeV} = 0.8_{\text{tot}} \text{ GeV}$$

- similar precision as present world average of $m_t^{\text{kin}}$ from hadron colliders
- still dominated by experimental precision
Present: Effective Weak Mixing Angle

- all measurements directly sensitive to $\sin^2 \theta^l_{\text{eff}}$
  - removed from fit (asymmetries, partial widths)
  - good agreement with minimal input
- $M_H$ measurement allows for precise constraint

- fit result for indirect determination of $\sin^2 \theta^l_{\text{eff}}$:

\[
\sin^2 \theta^l_{\text{eff}} = 0.231488 \pm 0.000024_{m_t} \pm 0.000016_{\delta_{\text{theo}} m_t} \pm 0.000015_{M_Z} \pm 0.000035_{\Delta \alpha_{\text{had}}} \\
\quad \pm 0.000010_{\alpha_S} \pm 0.000001_{M_H} \pm 0.000047_{\delta_{\text{theo}} \sin^2 \theta^l_{\text{eff}}} \\
= 0.23149 \pm 0.00007_{\text{tot}}
\]

more precise than determination from LEP/SLD ($1.6 \times 10^{-4}$)
Future: Effective Weak Mixing Angle

LHC-300 Scenario
- large improvement of indirect constraint
  - compromised by today’s theoretical uncertainties

ILC Scenario
- Indirect constraint and direct measurement comparable precision

Fit Results:

$$\delta \sin^2 \theta^f_{\text{eff}} = \left(1.7 M_W \oplus 1.2 M_Z \oplus 0.1 m_t \oplus 1.5 \Delta \alpha_{\text{had}} \oplus 0.1 \alpha_s\right) \cdot 10^{-5}$$

$$\delta \sin^2 \theta^f_{\text{eff}} = \left(1.0_{\text{theo}} \oplus 2.0_{\text{exp}}\right) \cdot 10^{-5} = \left(2.3_{\text{tot}}\right) \cdot 10^{-5}$$

Measurement uncertainty for ILC: $1.3 \cdot 10^{-5}$
Coupling Constraints from EWPO

- consider specific model in $\kappa$ parametrisation:
  - scaling of Higgs-vector boson ($K_V$) and Higgs-fermion couplings ($K_F$), with no invisible/undetectable widths
- main effect on EWPD due to modified Higgs coupling to gauge bosons ($K_V$) [Espinosa et al. arXiv:1202.3697, Falkowski et al. arXiv:1303.1812], etc

\[
S = \frac{1}{12\pi} \left(1 - \kappa_V^2\right) \ln \frac{\Lambda^2}{M^2_H} \\
T = -\frac{3}{16\pi \cos^2\theta^\ell_{\text{eff}}} \left(1 - \kappa_V^2\right) \ln \frac{\Lambda^2}{M^2_H} \\
\Lambda = \frac{\lambda}{\sqrt{1 - \kappa_V^2}}
\]

- correlation between $\kappa_V$ and $M_W$
  - slightly smaller values of $M_W$ preferred

![Diagram showing correlation between $\kappa_V$ and $M_W$]
Higgs Coupling Results

Higgs coupling measurements:

- $\kappa_V = 0.99 \pm 0.08$
- $\kappa_F = 1.01 \pm 0.17$

Combined result:

- $\kappa_V = 1.03 \pm 0.02$  
  ($\lambda = 3$ TeV)
- implies NP-scale of  
  $\Lambda \geq 13$ TeV

- some dependency for $\kappa_V$ in central value [1.02-1.04] and error [0.02-0.03] on cut-off scale $\lambda$ [1-10 TeV]
  - EW fit sofar more precise result for $\kappa_V$ than current LHC experiments
  - EW fit has positive deviation of $\kappa_V$ from 1.0
    - many BSM models: $\kappa_V < 1$
Prospects of EW Fit

- competitive results between EW fit and Higgs coupling measurements!
  - precision of about 1%
- ILC/GigaZ offers fantastic possibilities to test the SM and constrain NP
Summary of Indirect Predictions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Experimental input [$\pm 1\sigma_{\text{exp}}$]</th>
<th>Indirect determination [$\pm 1\sigma_{\text{exp}}, \pm 1\sigma_{\text{theo}}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Present</td>
<td>LHC</td>
</tr>
<tr>
<td>$M_H$ [GeV]</td>
<td>0.2</td>
<td>&lt; 0.1</td>
</tr>
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<td>$M_W$ [MeV]</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td>$M_Z$ [MeV]</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>$m_t$ [GeV]</td>
<td>0.8</td>
<td>0.6</td>
</tr>
<tr>
<td>$\sin^2\theta^\ell_{\text{eff}}$ [10^{-5}]</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>$\Delta\alpha^5_{\text{had}}(M^2_Z)$ [10^{-5}]</td>
<td>10</td>
<td>4.7</td>
</tr>
<tr>
<td>$R^0_l$ [10^{-3}]</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>$\alpha_S(M^2_Z)$ [10^{-4}]</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$S</td>
<td>U=0$</td>
<td>–</td>
</tr>
<tr>
<td>$T</td>
<td>U=0$</td>
<td>–</td>
</tr>
<tr>
<td>$\kappa_V$ ($\lambda = 3\text{TeV}$)</td>
<td>0.05</td>
<td>0.03</td>
</tr>
</tbody>
</table>

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Fits of EWPO in the SM
### Summary of Indirect Predictions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Experimental input $[\pm 1\sigma_{\text{exp}}]$</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$M_H$ [GeV]</td>
<td>Present 0.2, LHC &lt; 0.1, ILC/GigaZ &lt; 0.1</td>
<td>Present $+31$, LHC $+10$, ILC/GigaZ $-26$, $-8$</td>
</tr>
<tr>
<td>$M_W$ [MeV]</td>
<td>15, 8, 5</td>
<td>LHC $6.0$, ILC/GigaZ $5.0$</td>
</tr>
<tr>
<td>$M_Z$ [MeV]</td>
<td>2.1, 2.1</td>
<td>LHC $11$, ILC/GigaZ $4$</td>
</tr>
<tr>
<td>$m_t$ [GeV]</td>
<td>0.8, 0.6, 0.1</td>
<td>LHC $2.4$, ILC/GigaZ $0.6$</td>
</tr>
<tr>
<td>$\sin^2 \theta^\ell_{\text{eff}} [10^{-5}]$</td>
<td>16, 16, 1.3</td>
<td>LHC $4.5$, ILC/GigaZ $4.9$</td>
</tr>
<tr>
<td>$\Delta \alpha^5_{\text{had}}(M^2_Z) [10^{-5}]$</td>
<td>10, 4.7, 4.7</td>
<td>LHC $42$, ILC/GigaZ $13$</td>
</tr>
<tr>
<td>$R^0_l [10^{-3}]$</td>
<td>25, 25, 4</td>
<td>LHC $36$, ILC/GigaZ $6$</td>
</tr>
<tr>
<td>$\alpha_S(M^2_Z) [10^{-4}]$</td>
<td>–, –, –</td>
<td>LHC $39$, ILC/GigaZ $7$</td>
</tr>
<tr>
<td>$S</td>
<td>_{U=0}$</td>
<td>–, –, –</td>
</tr>
<tr>
<td>$T</td>
<td>_{U=0}$</td>
<td>–, –, –</td>
</tr>
<tr>
<td>$\kappa_V (\lambda = 3 \text{TeV})$</td>
<td>0.05, 0.03, 0.01</td>
<td>LHC $0.02$, ILC/GigaZ $0.02$</td>
</tr>
</tbody>
</table>

- Theory uncertainty needs to be reduced if we want to achieve the ultimate precision with the LHC!
- Future $e^+e^-$ collider: fantastic possibilities for consistency tests of the SM on loop level and NP constraints
Summary

Uncertainties on $M_W$

<table>
<thead>
<tr>
<th></th>
<th>Today</th>
<th>LHC-300</th>
<th>ILC/GigaZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_{\text{meas}}$</td>
<td>15 MeV</td>
<td>8 MeV</td>
<td>5 MeV</td>
</tr>
<tr>
<td>$\delta_{\text{fit}}$</td>
<td>8 MeV</td>
<td>6 MeV</td>
<td>2 MeV</td>
</tr>
<tr>
<td>$\delta_{\text{fit , theo}}$</td>
<td>5 MeV</td>
<td>2 MeV</td>
<td>1 MeV</td>
</tr>
</tbody>
</table>

Impact of individual uncertainties on $\delta M_W$ in fit (numbers in MeV)

Improved theoretical precision needed already for the LHC-300!
Additional Material
Two Higgs Doublet Models

- extend the scalar sector by another doublet
- studies of $Z_2$ Type-I and Type-II 2HDMs
  - difference in the coupling to down-type quarks
  - Type-II related to MSSM, but less constrained

<table>
<thead>
<tr>
<th>Higgs</th>
<th>$C_V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h$</td>
<td>$\sin(\beta - \alpha)$</td>
</tr>
<tr>
<td>$H$</td>
<td>$\cos(\beta - \alpha)$</td>
</tr>
<tr>
<td>$A$</td>
<td>0</td>
</tr>
</tbody>
</table>

- constraints derived from EWPD using S,T,U formalism
- lightest scalar $M_h = 125.1$ GeV
- weak constraints on masses, since $\tan\beta$ and $\cos(\beta-\alpha)$ are unconstrained

(see talk by M. Beckingham)
2HDM and H Coupling Measurements

- coupling measurements place important constraints on 2HDMs
- predictions of BRs using 2HDMC \cite{Eriksson:2010}\[D. Eriksson et al., CPC 181, 189 (2010)\]
- 7 additional, unconstraint parameters (4 masses, 2 angles, soft breaking scale): importance sampling with MultiNest \cite{Feroz:2013}\[F. Feroz et al., arXiv:1306.2144\]

\[\tan \beta > 1\]

- additional constraints from flavour data
  - \(B \rightarrow X_s \gamma\): \(\tan \beta > 1\)
  - \(B_s \rightarrow \mu \mu\): constraints depending on \(M_H\) and \(M_{H^\pm}\)
Global Fit to 2HDM of Type-2

- for given $M_{H^\pm}$ tight constraints from H coupling measurements and EWPD
- expect improvement from direct searches at the LHC