Two Higgs doublet models and electroweak precision observables

Stephan Hessenberger

Max Planck Institute for Physics

27th IMPRS Workshop

11th November 2013

Outline

1. Introduction
2. THDM Higgs sector
   - Higgs potential
   - Higgs boson interaction with gauge bosons and fermions
3. The W boson mass
   - Calculation of M_W by the μ decay
   - Results in the THDM
4. Z resonance observables
   - Effective couplings
   - Electroweak mixing angle
   - Results in the THDM
5. Summary

Introduction

- July 2012: discovery of a candidate Higgs boson at LHC
  - $\Rightarrow$ SM Higgs or part of an extended Higgs sector?
- Two Higgs doublet model: interesting candidate for an extended scalar sector of the SM
  - $\Rightarrow$ simple extension of SM
  - $\Rightarrow$ adds new phenomena like physical charged Higgs bosons
  - $\Rightarrow$ MSSM is a SUSY-version of a THDM
- Analysis of electroweak precision observables in the THDM provides information on the free parameters

Higgs potential

- two complex $SU(2)_L$ doublet scalar fields Φ_1 and Φ_2
- most general, CP conserving potential ($\lambda_i \in \mathbb{R}$)

$$
\begin{aligned}
V(\Phi_1, \Phi_2) =& \lambda_1 \left(\Phi_1^\dagger \Phi_1 - v_1^2\right)^2 + \lambda_2 \left(\Phi_2^\dagger \Phi_2 - v_2^2\right)^2 \\
&+ \lambda_3 \left[\left(\Phi_1^\dagger \Phi_1 - v_1^2\right) + \left(\Phi_2^\dagger \Phi_2 - v_2^2\right)\right]^2 \\
&+ \lambda_4 \left[\left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) - \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right)\right] \\
&+ \lambda_5 \left[\mathrm{Re}\left(\Phi_1^\dagger \Phi_2\right) - v_1 v_2\right]^2 + \lambda_6 \left[\mathrm{Im}\left(\Phi_1^\dagger \Phi_2\right)\right]^2
\end{aligned}
$$

- minimum of the potential for $\lambda_i \geq 0$

$$
\langle \Phi_1 \rangle = \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \qquad \langle \Phi_2 \rangle = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}
$$

- parametrization of the Higgs fields ($\eta_i, \chi_i \in \mathbb{R}$)

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}\left(v_1 + \eta_1 + i\chi_1\right) \end{pmatrix} \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}\left(v_2 + \eta_2 + i\chi_2\right) \end{pmatrix}$$

- quadratic terms in the potential

$$V_{\text{mass}} = \begin{pmatrix} \phi_1^- & \phi_2^- \end{pmatrix} \underbrace{\begin{pmatrix} \lambda_4 v_2^2 & -\lambda_4 v_1 v_2 \\ -\lambda_4 v_1 v_2 & \lambda_4 v_1^2 \end{pmatrix}}_{\mathcal{M}^A} \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix}$$

$$+ \begin{pmatrix} \chi_1 & \chi_2 \end{pmatrix} \underbrace{\frac{1}{2} \begin{pmatrix} \lambda_6 v_2^2 & -\lambda_6 v_1 v_2 \\ -\lambda_6 v_1 v_2 & \lambda_6 v_1^2 \end{pmatrix}}_{\mathcal{M}^B} \begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix}$$

$$+ \begin{pmatrix} \eta_1 & \eta_2 \end{pmatrix} \underbrace{\frac{1}{2} \begin{pmatrix} 4v_1\left(\lambda_1 + \lambda_3\right) + v_2^2 \lambda_5 & \left(4\lambda_3 + \lambda_5\right) v_1 v_2 \\ \left(4\lambda_3 + \lambda_5\right) v_1 v_2 & 4v_2\left(\lambda_2 + \lambda_3\right) + v_1^2 \lambda_5 \end{pmatrix}}_{\mathcal{M}^C} \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix}$$

- diagonalization of $\mathcal{M}^A$ and $\mathcal{M}^B$ leads to physical Higgs states $H^\pm$, A^0 (CP-odd) and Goldstone bosons $G^\pm$, G^0

$$\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix}; \quad \begin{pmatrix} G^0 \\ A^0 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix}$$

$$\tan\beta = \frac{v_2}{v_1}$$

- diagonalization of $\mathcal{M}^C$ leads to two physical, CP-even Higgs states h^0 and H^0

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix}$$

$\Rightarrow$ free parameters: $m_{H^\pm}$, m_{H^0}, m_{h^0}, m_{A^0}, $\tan\beta$, α, λ_5

Higgs boson interaction with gauge bosons and fermions

Higgs boson interaction with gauge bosons

$$\mathcal{L}_{\text{kin}} = \sum_{i=1,2} (D_\mu \Phi_i)^\dagger (D^\mu \Phi_i) \xrightarrow[\Phi_i \to \begin{pmatrix} 0 \\ v_i \end{pmatrix}]{} M_W^2 W_\mu^- W^{+\mu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu$$

covariant derivative $D_\mu = \partial_\mu + \frac{1}{2} i g I^a W_\mu^a + \frac{1}{2} i g' Y B_\mu$; $(Y_{\Phi_i} = 1)$

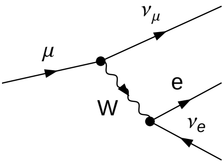
$$M_W^2 = \frac{g^2(v_1^2 + v_2^2)}{2} \qquad M_Z^2 = \frac{(g^2 + g'^2)(v_1^2 + v_2^2)}{2}$$

Higgs boson interaction with fermions (Type II)

$$\mathcal{L}_{\text{Yukawa}} = -\left(y_e \overline{L_L} \cdot \Phi_1 e_R + h.c.\right) - \left(y_d \overline{Q_L} \cdot \Phi_1 d_R + h.c.\right) - \left(y_u \overline{Q_L} \cdot \widetilde{\Phi_2} u_R + h.c.\right)$$

$$L_L = \begin{pmatrix} \nu_e \\ e_L \end{pmatrix} \qquad Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad \widetilde{\Phi_2} = i\sigma_2 \Phi_2^*$$

Calculation of M_W by the μ decay



- μ decay at tree level yields relation between M_W and the Fermi constant G_μ

$$\frac{G_\mu}{\sqrt{2}} = \frac{e^2}{8 s_W^2 M_W^2} = \frac{\pi\alpha}{2M_W^2\left(1 - \frac{M_W^2}{M_Z^2}\right)}$$

- G_μ: effective 4-fermion coupling constant in the Fermi model, defined by the muon lifetime

$$G_\mu = 1.1663787(6) \cdot 10^{-5}\ \text{GeV}^{-2}$$

- higher order corrections: loop diagrams and renormalization of masses and couplings (on-shell scheme)

$$\frac{G_\mu}{\sqrt{2}} = \frac{\pi\alpha}{2M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)}\left[1+\Delta r\right], \quad \Delta r = \Delta r\left(M_Z, M_W, m_t, m_H\right)$$

$\Rightarrow$ M_W can be calculated by M_Z, α, G_μ and Δr for a given input M_Z, m_t, m_H

- calculation has to be done iteratively since Δr depends on M_W
- predicted value can be compared with the measured value

$$M_W^{\text{exp}} = 80.385 \pm 0.015 \text{ GeV}$$

Δr in the SM:

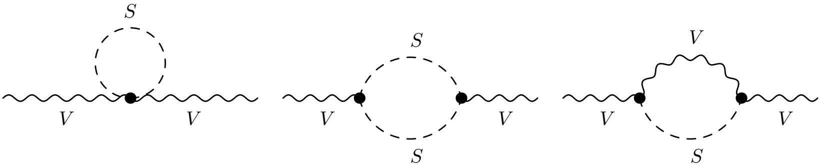
- precise calculation in the SM: complete at two-loop with leading higher-order terms
- Result of M_W for a SM Higgs of 126 GeV and $m_t = 173.2 \pm 0.9$ GeV

$$M_W^{\text{SM}} = 80.361 \pm 0.006 \pm 0.004 \text{ GeV}$$

non standard contribution Δr_{NS} from the THDM

- vertex and box corrections can be neglected due to small Yukawa couplings

⇒ Δr_{NS} is given in terms of the scalar contributions to the gauge boson self energies



Results in the THDM

- results obtained with the programs FeynArts, FormCalc and LoopTools

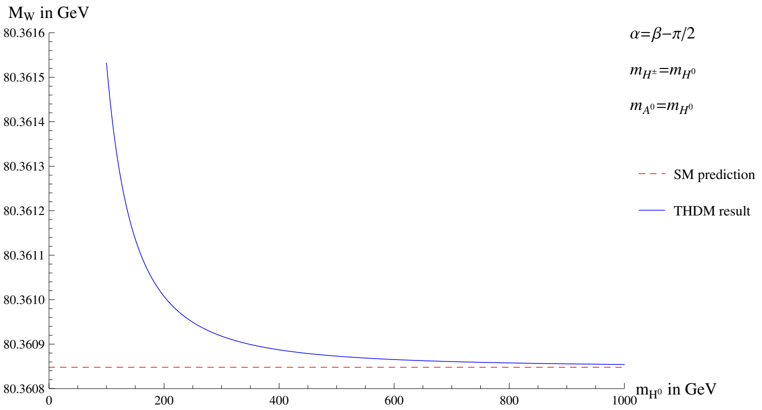
Assumptions:

- one of the CP-even Higgs states can be identified with the resonance found at ATLAS/CMS
  - without loss of generality select h^0

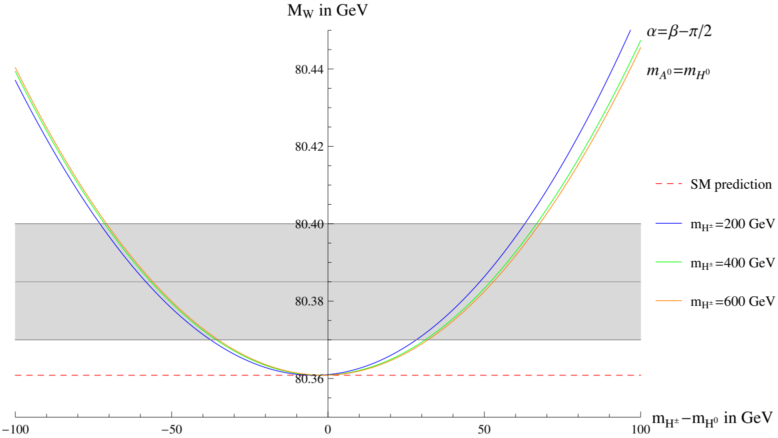
  $\Rightarrow$ $m_{h^0} = 126$ GeV
- couplings of h^0 should be SM-like (indicated by the experiments)

  $\Rightarrow$ $\alpha = \beta - \frac{\pi}{2}$

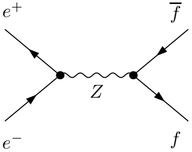
- result for equal masses of H^0, A^0, $H^\pm$
- for large masses the result in the THDM approaches the SM prediction ⇒ decoupling limit



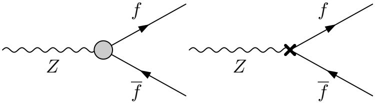
- influence of a mass splitting between charged and neutral Higgs states
- grey area represents the measured value of M_W and its 1σ experimental limit



Effective couplings



- properties of the Z boson investigated at LEP and SLC experiments with high accuracy
- precise knowledge of Z resonance observables like the width of the Z boson, asymmetries or mixing angles at the Z peak
  - $\Rightarrow$ well-suited for comparision between theory and experiment
- $g^f_{V,A}$: effective vector and axial vector couplings between Z and $\overline{f}f$, include self energies, vertex corrections, counterterms



Electroweak mixing angle

effective leptonic mixing angle

$$\sin^2\theta_{\text{eff}}^{\text{lept}} = \frac{1}{4}\left(1 - \mathrm{Re}\,\frac{g_V^e}{g_A^e}\right)$$

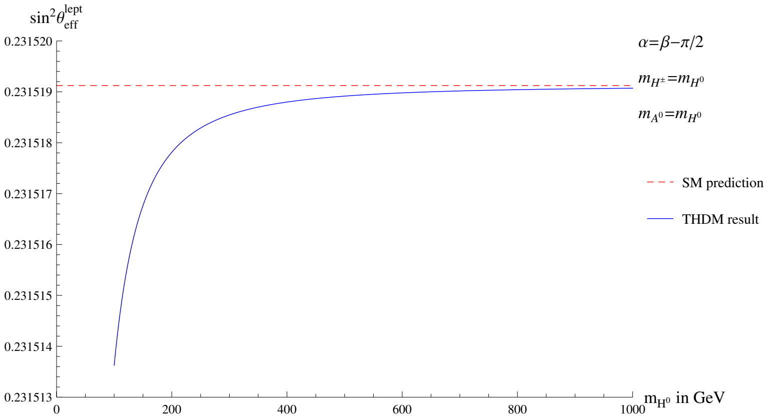
- experimental value: $\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.23153 \pm 0.00016$
- $\sin^2\theta_{\text{eff}}^{\text{lept}}$ calculated in the SM at the same level of accuracy as Δr

$\Rightarrow$ result for a SM Higgs mass of 126 GeV and $m_t = 173.2 \pm 0.9$

$$\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.23152 \pm 0.00005 \pm 0.00005$$

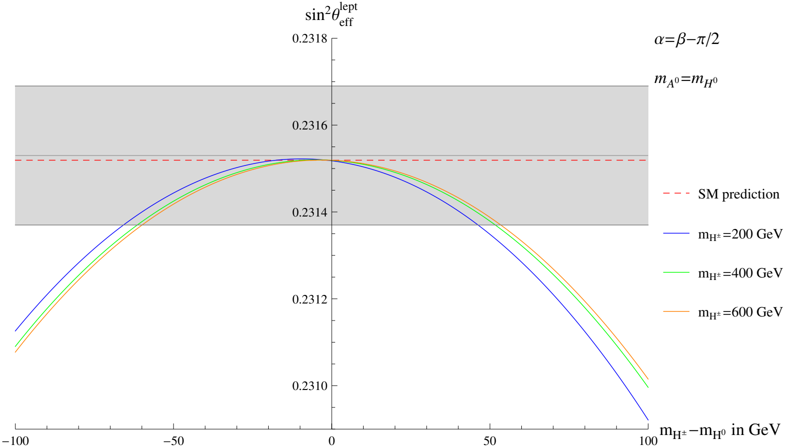
Results in the THDM

- Prediction for $\sin^2\theta_{\text{eff}}^{\text{lept}}$ in the THDM for $\alpha = \beta - \frac{\pi}{2}$ and $m_{h^0} = 126$ GeV
- result for equal masses of H^0, A^0, $H^{\pm}$



Results in the THDM

- influence of a mass splitting between the charged and neutral Higgs states
- grey area represents the experimental value of $\sin^2\theta_{\text{eff}}^{\text{lept}}$ and its 1σ experimental limit

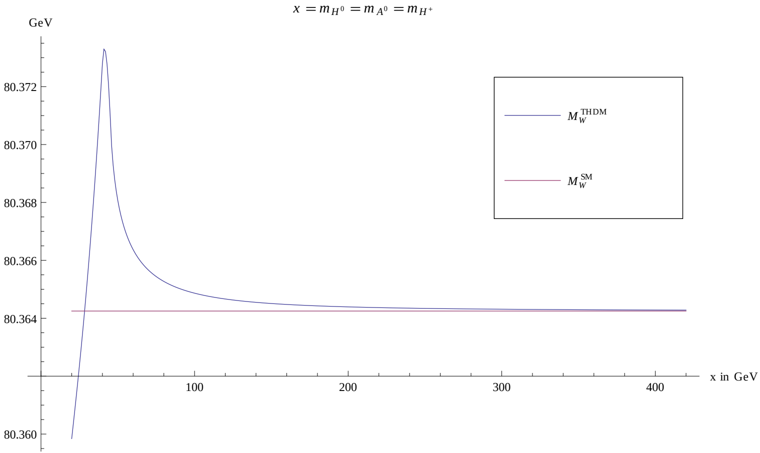


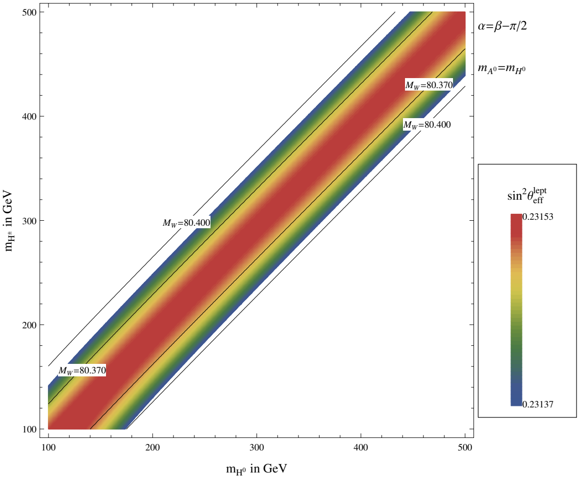
Summary

- Higgs potential of the THDM and the Higgs boson interaction with gauge bosons and fermions were described
- calculation of M_W by the μ decay
- $\sin^2\theta_{\text{eff}}^{\text{lept}}$ as an example for a Z resonance observable
- non standard corrections to the mass of the W boson and the effective leptonic mixing angle
  - $\Rightarrow$ for large non-standard Higgs masses the calculations approach the SM prediction (decoupling)
  - $\Rightarrow$ mass splitting between the charged and neutral Higgs states lead to large contributions
  - $\Rightarrow$ significant constraints on mass spectrum
- other Z resonance observables were studied also

Outlook:

- calculation of higher order (two-loop) non-standard terms of the precision observables
- analyse higher order effects on Higgs physics for LHC results


$x = m_{H^0} = m_{A^0} = m_{H^+}$
GeV
80.372
80.370
80.368
80.366
80.364
80.360
100
200
300
400
x in GeV
M_W^{THDM}
M_W^{SM}



500
400
300
200
100
100
200
300
400
500
$m_{H^\pm}$ in GeV
m_{H^0} in GeV
M_W=80.400
M_W=80.370
M_W=80.370
M_W=80.400
$\alpha=\beta-\pi/2$
$m_{A^0}=m_{H^0}$
$\sin^2\theta_{eff}^{lept}$
0.23153
0.23137