Two Higgs doublet models and electroweak precision obervables

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Outline

Higgs Mechanism in the SM

Electroweak standard model (SM):

- gauge theory based on the symmetry group $SU(2)_L \times U(1)_Y$
- spontaneous symmetry breaking introduces masses of $W^\pm$, Z

$$SU(2) \times U(1) \to U(1)_{\text{em}}$$

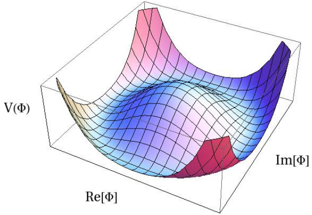
$\Rightarrow$ single complex scalar doublet

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}\left(v + H_{\text{SM}} + i\chi\right) \end{pmatrix}$$

Higgs field H_{SM}: neutral, scalar particle with mass M_H

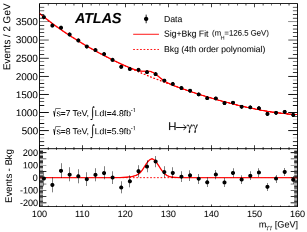
Higgs potential

$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \frac{\lambda}{4}(\Phi^\dagger \Phi)^2$$
$$\Rightarrow v = \frac{2\mu}{\sqrt{\lambda}};\ M_H = \mu\sqrt{2}$$

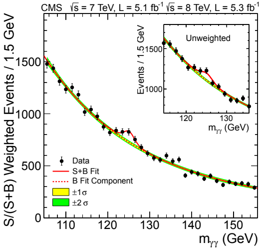


- non-vanishing vacuum expectation value v introduces gauge boson masses M_W, M_Z
- fermion masses induced by Yukawa couplings
- M_H free parameter $\Rightarrow$ measurement
- July 2012: announcement of the discovery of a new boson by the ATLAS and CMS collaborations

$\Rightarrow$ SM Higgs or part of an extended Higgs sector?



arXiv:1207.7214



arXiv:1207.7235

THDM Higgs sector

- Two Higgs doublet model: interesting candidate for an extended scalar sector of the SM
  - ⇒ one of the simplest extensions of the SM
  - ⇒ introduces only few additional parameters
  - ⇒ adds new phenomena like physical charged Higgs bosons
  - ⇒ MSSM is a SUSY-version of the THDM
- Analysis of electroweak precision observables in the THDM provides information on the free parameters

- two complex $SU(2)_L$ doublet scalar fields Φ_1 and Φ_2

most general, CP conserving potential ($\lambda_i \in \mathbb{R}$)

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

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

$$
\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \qquad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \end{pmatrix}
$$

- field excitations around v_i $(\eta_i, \chi_i \in \mathbb{R})$

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

$\Rightarrow$ quadratic terms in the potential

$\Rightarrow$ diagonalization leads to five massive scalar particles

- two CP even Higgs states $(m_{h^0} \leq m_{H^0})$

$$h^0 = -\sin\alpha \cdot \eta_1 + \cos\alpha \cdot \eta_2$$
$$H^0 = \cos\alpha \cdot \eta_1 + \sin\alpha \cdot \eta_2$$

- a CP odd Higgs state

$$A^0 = -\sin\beta \cdot \chi_1 + \cos\beta \cdot \chi_2$$

- a pair of charged Higgs bosons

$$H^\pm = -\sin\beta \cdot \phi_1^\pm + \cos\beta \cdot \phi_2^\pm$$

- $v^2 = v_1^2 + v_2^2$ related to the gauge boson masses and the electric charge e

$$v^2 = \frac{4M_W^2 s_W^2}{e^2}$$

(electroweak mixing angle: $s_W^2 = \sin^2\theta_W$; $c_W^2 = \cos^2\theta_W = \frac{M_W^2}{M_Z^2}$)

$\Rightarrow$ 7 free parameters:

- Higgs masses m_{h^0}, m_{H^0}, m_{A^0} and $m_{H^\pm}$
- ratio of the vacuum expectation values $\tan\beta = \frac{v_2}{v_1}$
- CP-even mixing angle α
- λ_5

Calculation of precision observables in the THDM

Assumptions:

- one of the CP-even Higgs states can be identified with the resonance found at the LHC
  $\Rightarrow$ $m_{h^0} = 126$ GeV
- couplings of h^0 should be SM-like (indicated by the experiments)
  $\Rightarrow$ $\alpha = \beta - \frac{\pi}{2}$

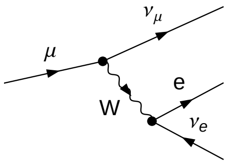
Analysis of two scenarios:

- decoupling region:

$$m_{H^0} = m_{A^0} = m_{H^\pm} \gg m_{h^0}$$

  $\Rightarrow$ results approach the SM results
- large mass differences between the charged and neutral Higgs states
  $\Rightarrow$ large corrections to the SM results

Calculation of M_W by the μ decay

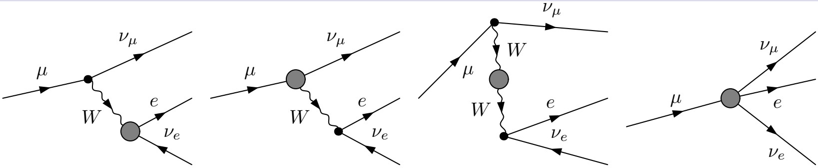


- μ decay at tree level: relation between M_W and G_μ

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

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

$$G_\mu = 1.663787(6) \cdot 10^{-5}\ \text{GeV}^{-2}$$



vertex corrections | vertex corrections | W self energy | box diagrams

Higher order corrections:

- loop diagrams and renormalization of masses and couplings (on-shell scheme)

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

$\Rightarrow$ 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

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 $m_t = 173.2 \pm 0.9$

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

- predicted value can be compared with the measured value

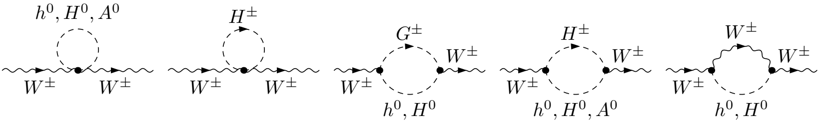
$$M_W^{\text{exp}} = 80.385 \pm 0.015 \text{ GeV}$$

Non standard contribution Δr_{NS}

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

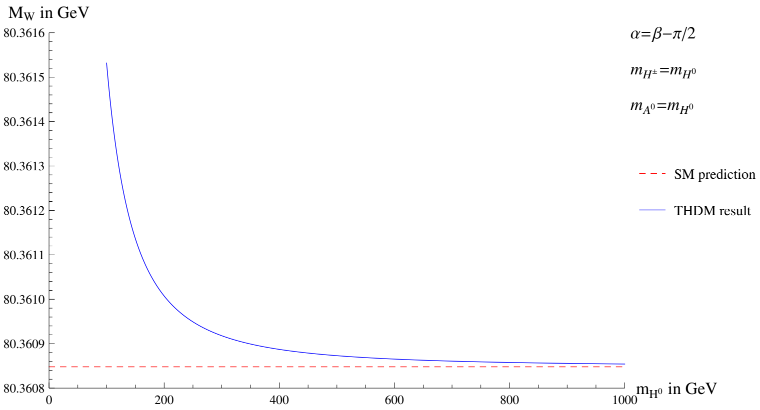
⇒ Δr_{NS} is given in terms of the scalar contributions to the gauge boson self energies

⇒ calculated with the help of the programs FeynArts, FormCalc and LoopTools

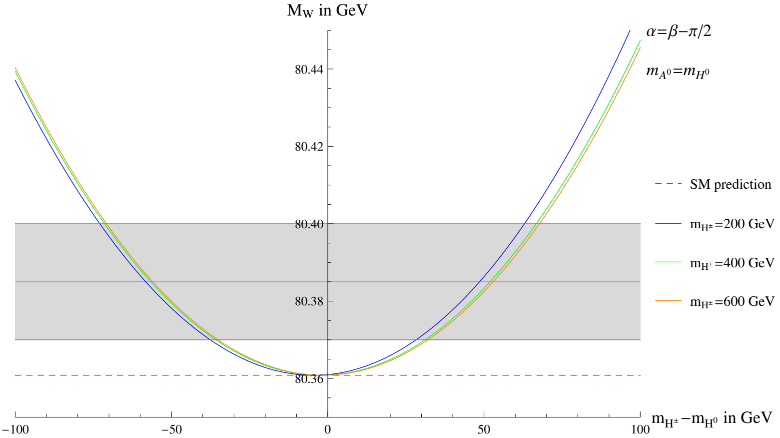


Results in the THDM

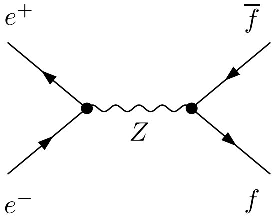
- result in the THDM for equal masses m_{H^0}, m_{A^0}, $m_{H^\pm}$
  $\Rightarrow$ approaches the SM prediction for large masses (decoupling)



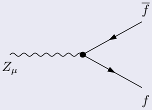
- influence of a mass difference between the charged and neutral Higgs states
- grey area represents the measured value of M_W and its 1σ experimental limit



Z resonance



$Z\overline{f}f$ coupling



$$= \frac{-ie}{2c_W s_W}\gamma_\mu \left(v_f - a_f\gamma_5\right)$$

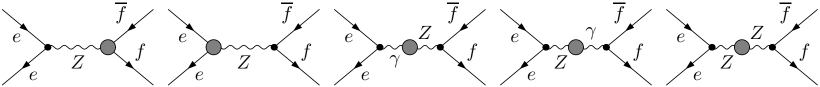
v_f: vector coupling

a_f: axial vector coupling

$$\frac{v_f}{a_f} = 1 - 4\left|Q_f\right| s_W$$

- properties of the Z boson investigated at LEP and SLC with high accuracy
- precise knowledge of Z resonance observables:
  - the width of the Z boson
  - asymmetries
  - mixing angles at the Z peak

$\Rightarrow$ well-suited for comparison between theory and experiment



Higher order corrections near the Z pole:

- include self energies, vertex corrections and counterterms
- external fermion self energies are contained in the wave function renormalization
- box diagrams can be neglected

effective vector and axial vector couplings

$$v_f \to g_V^f = v_f + \Delta g_V^f$$
$$a_f \to g_A^f = a_f + \Delta g_A^f$$

Corrections to the effective mixing angle

effective leptonic mixing angle

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

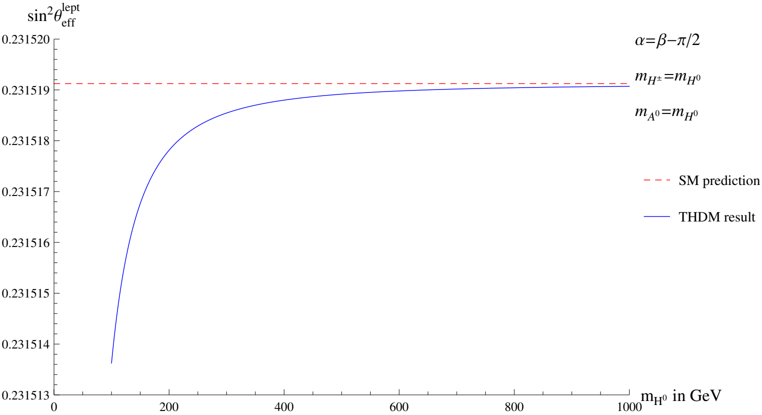
- experimental value: $\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.23153 \pm 0.00016$
- $\sin^2\theta_{\text{eff}}^{\text{lept}}$ calculated in the SM at the same level of accuracy as Δr
  - ⇒ result for $M_H = 126$ GeV and $m_t = 173.2 \pm 0.09$ GeV

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

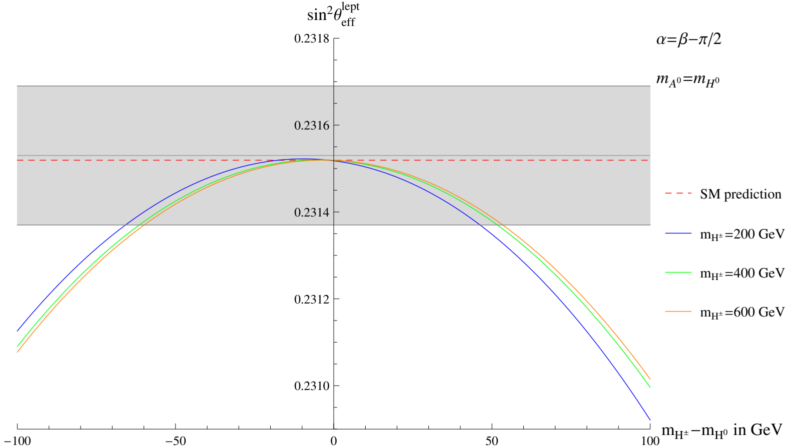
- non-standard corrections from the THDM
  - ⇒ scalar corrections to the vertex and the external fermions can be neglected
  - ⇒ depend only on the counterterms of the gauge boson sector

Results in the THDM

- result for equal masses m_{H^0}, m_{A^0}, $m_{H^\pm}$ between 100 and 1000 GeV



- influence of a mass difference 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 and outlook

Summary

- Higgs potential of the THDM
- 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)
  - $\Rightarrow$ large mass differences between the charged and neutral Higgs states lead to large contributions

Outlook

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