The $\mathbb{W}$ Boson Mass Anomaly within the inversed scenario of the Two-Higgs Doublet Model

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17 Jun 2023

- A scalar particle with a mass of approximately 125 GeV was discovered in 2012[1],[2] by ATLAS and CMS that is so far compatible with SM Higgs boson ...

1. Phys. Lett B 716 (2012) 1-29
2. Phys. Lett B 716 (2012) 30

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- A scalar particle with a mass of approximately 125 GeV was discovered in 2012 [1], [2] by ATLAS and CMS that is so far compatible with SM Higgs boson ...
- λ_{hhh}, λ_{hhhh} and $\mathrm{H} \to \mathrm{Z}\gamma$ are still not reached at the LHC.
- The need of new physics is motivated by : Dark matter, baryon asymmetry, neutrino masses, among other.

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Two Higgs Doublet Model

Motivation

Motivation

- Larger scalar sector than SM
- Rich collider phenomenology gauge symmetry.

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Two Higgs Doublet Model

General potential

The Higgs potential

$$\begin{aligned} V_{\mathrm{THDM}} = & m_1^2 \left|\Phi_1^2\right| + m_2^2 \left|\Phi_2^2\right| - m_{12}^2(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1) + \frac{\lambda_1}{2} |\Phi_1|^4 + \frac{\lambda_2}{2} |\Phi_2|^4 \\ & + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 \left|\Phi_1^+ \Phi_2\right|^2 + \frac{\lambda_5}{2} \left\{(\Phi_1^+ \Phi_2)^2 + (\Phi_2^+ \Phi_1)^2\right\} \\ & + \left\{\left[\lambda_6(\Phi_1^+ \Phi_1) + \lambda_7(\Phi_2^+ \Phi_2)\right] \Phi_1^+ \Phi_2 + \mathrm{h.c.}\right\} \end{aligned} \quad (1)$$

- Higgs 5 Bosons : H^+, H^-, 2 CP-even h^0, H^0 et 1 CP-odd A^0.
- 9 free parameters :
  $m_A, m_h, m_H, m_{H^\pm}, \alpha, \tan(\beta), \lambda_6, \lambda_7$ and m_{12}^2
- No additional symmetry required.
- FCNC at the three level.

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Two Higgs Doublet Model

Different types

2HDM Types

The yukawa Lagrangian can be given as :

$$\mathcal{L}^{\mathrm{2HDM}}_{\mathrm{YUKAWA}} = \bar{\mathrm{Q}}^{0}_{\mathrm{L}} \mathrm{Y}^{0}_{\mathrm{u}} \widetilde{\Phi}_2 \mathrm{u}^{0}_{\mathrm{R}} + \bar{\mathrm{Q}}^{0}_{\mathrm{L}} \mathrm{Y}^{0}_{\mathrm{d}} \Phi_{\mathrm{d}} \mathrm{d}^{0}_{\mathrm{R}} + \bar{\mathrm{L}}^{0}_{\mathrm{L}} \mathrm{Y}^{0}_{\ell} \widetilde{\Phi}_{\ell} \ell^{0}_{\mathrm{R}} + \mathrm{h.c} \tag{2}$$

Type	u	d	l
I	Φ_2	Φ_2	Φ_2
II	Φ_2	Φ_1	Φ_1
X	Φ_2	Φ_1	Φ_2
Y	Φ_2	Φ_2	Φ_1

The scalar Potential

$$
\begin{aligned}
V_{THDM} = & m_1^2 \left|\Phi_1^2\right| + m_2^2 \left|\Phi_2^2\right| - m_{12}^2(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1) \\
& + \frac{\lambda_1}{2} \left|\Phi_1\right|^4 + \frac{\lambda_2}{2} \left|\Phi_2\right|^4 + \lambda_3 \left|\Phi_1\right|^2 \left|\Phi_2\right|^2 \\
& + \lambda_4 \left|\Phi_1^+ \Phi_2\right|^2 + \frac{\lambda_5}{2} \left\{(\Phi_1^+ \Phi_2)^2 + (\Phi_2^+ \Phi_1)^2\right\}
\end{aligned} \tag{3}
$$

- The $\lambda_i, i = 1 \cdots 4$ parameters are all real.
- 5 Higgs bosons : 2 CP-even h^0 and H^0, CP-odd A^0, 2 charged H^+ and H^-.
- 7 free parameters :
  $m_A, m_h, m_H, m_{H^\pm}, \alpha, \tan(\beta)$ and m_{12}^2
- Additional symmetry Z_2 .

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Investigating the $\mathrm{M_W}$ Anomaly in the 2HDM

Motivation

- New CDF-II measurement of the W bosons mass

$$\mathrm{M_W^{CDF}} = 80.4435 \pm 0.0094$$

- Deviation from $\mathrm{M_W^{SM}}$ with a 7σ of significance.

$$\mathrm{M_W^{SM}} = 80.357 \pm 0.006$$

- Possibility of New Physics.

Investigating the $\mathrm{M_W}$ Anomaly in the 2HDM

Theoretical prediction of $\mathrm{M_W}$

1. Theoretical prediction for $\mathrm{M_W}$:

$$\mathrm{M_W^2}\left(1-\frac{\mathrm{M_W^2}}{\mathrm{M_Z^2}}\right)=\frac{\pi\alpha}{\sqrt{2}\mathrm{G}_\mu}(1-\underbrace{\Delta\mathrm{r}}_{\text{loop corrections}}), \tag{4}$$

with Δr is the shift in the fine structure constant arising from the charge renormalization which contains the contributions from light fermions.

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Theoretical prediction of $\mathrm{M_W}$

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with $\Delta\mathrm{r}$ is the shift in the fine structure constant arising from the charge renormalization which contains the contributions from light fermions.

2. Approximation for the 2HDM

$$\Delta\mathrm{M_W^2}=\frac{\alpha_0\mathrm{c_W^2M_Z^2}}{\mathrm{c_W^2-s_W^2}}\left[-\frac{1}{2}\mathrm{S}+\mathrm{c_W^2T}+\frac{\mathrm{c_W^2-s_W^2}}{4\mathrm{s_W^2}}\mathrm{U}\right], \tag{5}$$

where $\Delta\mathrm{M_W^2}=(\mathrm{M_W^{2HDM}})^2-(\mathrm{M_W^{SM}})^2$.

3. The 2HDM contribution to the effective weak mixing angle

$$\Delta\sin^2\theta_{\text{eff}}=\frac{\alpha_0}{\mathrm{c_W^2-s_W^2}}\left[\frac{1}{4}\mathrm{S}-\mathrm{s_W^2c_W^2T}\right]. \tag{6}$$

Investigating the $\mathrm{M_W}$ Anomaly in the 2HDM

Scan strategy

- 2HDM type-I and type-X.
- Systematic scan using the public program `2HDMC-1.8.0` Eriksson :2009.
- Heavy Higgs is the SM-like Higgs boson $\mathrm{m_H} = \mathrm{m_h^{SM}} = 125.09$ GeV.
- The parameter scan are :

$$\begin{aligned}
&\mathrm{M_h} \in [15, 120]\ \mathrm{GeV}, \quad \mathrm{M_A} \in [15, 700]\ \mathrm{GeV}, \\
&\mathrm{M_{H^\pm}} \in [80, 700]\ \mathrm{GeV}, \quad \sin(\beta - \alpha) \in [-0.5, 0.5], \\
&\tan\beta \in [2, 25], \quad \mathrm{m_{12}^2} \in [0, \mathrm{M_h^2} \sin\beta \cos\beta]\ \mathrm{GeV}^2.
\end{aligned} \tag{7}$$

Investigating the $\mathrm{M_W}$ Anomaly in the 2HDM

Constraints

During the scan, the following theoretical and experimental constraints are fulfilled :

- Theoretical limit are imposed via `2HDMC`.
- The experimental collider limits are examinated using `HiggsBounds-5.9.0` and `HiggsSignals-2.6.0` Bechtle :2020.
- Constraints from flavor physics are enforced using the result given in Ref. Haller :2018.
  Related observables are calculated using the program `SuperIso v4.1` Mahmoudi :2008.
- Compatibility with the Z width measurement from LEP. ALEPH :2005

We apply then the $\chi^2_{\mathrm{M_W^{CDF}}}$ within 2σ of the new CDF measurement :

$$\chi^2_{\mathrm{M_W^{CDF}}} = \frac{(\mathrm{M_W^{2HDM}} - \mathrm{M_W^{CDF}})^2}{(\Delta \mathrm{M_W^{CDF}})^2}. \quad (8)$$

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Results

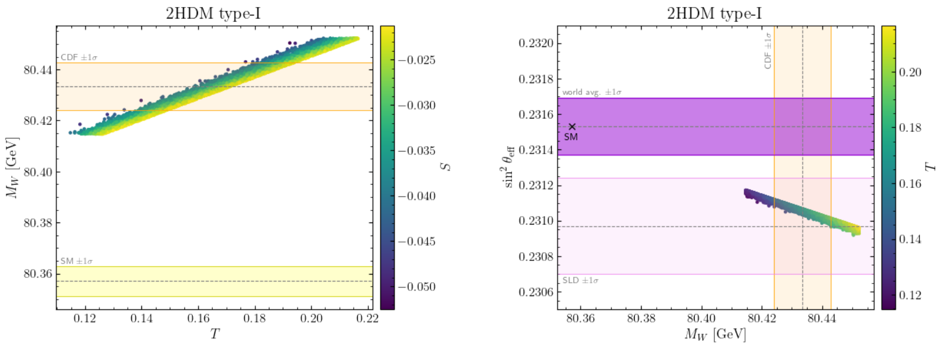

Figure – Left : The 2HDM prediction for the W boson mass as a function of T, with the color bar showing the size of S. The light orange band indicates the new CDF measurement and the associated 1σ uncertainty. The SM prediction for $\mathrm{M_W}$ showing in light yellow region within $\pm1\sigma$

Investigating the $\mathrm{M_W}$ Anomaly in the 2HDM

Results

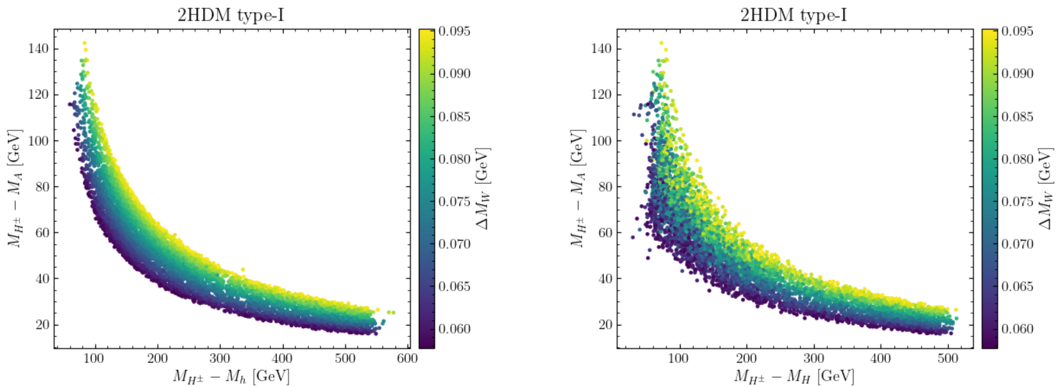

Figure – Points from the scan in the $(\mathrm{M_{H^\pm} - M_h, M_{H^\pm} - M_A})$ plane (left) and $(\mathrm{M_{H^\pm} - M_H, M_{H^\pm} - M_A})$ plane (right) planes in 2HDM type-I. The color code indicates the shift from the SM prediction for $\mathrm{M_W}$.

Conclusion

- SM is the most sophisticate and precise theory but not an ultimate model of fundamental physics.
- 2HDM can explain the new CDF results on the M_W as well as SLD measurment on $\sin^2\theta_{\text{eff}}$.

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Thank you !