The Next-Two-Higgs-Doublet Model confronts the Naturalness Problem

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Based on: Eur.Phys.J.C 84 (2024) 8, 799

The International Symposium of High Energy Physics (ISHEP-2024)
October 20, 2024

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1. Introduction
2. Motivation and Objectives
3. N2HDM framework
4. Constraints
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6. Conclusion

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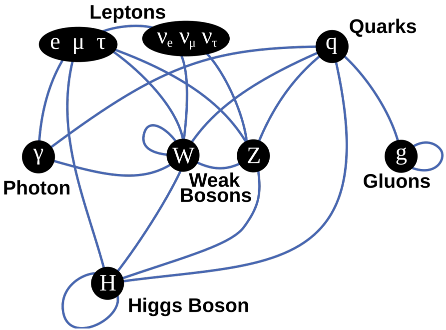

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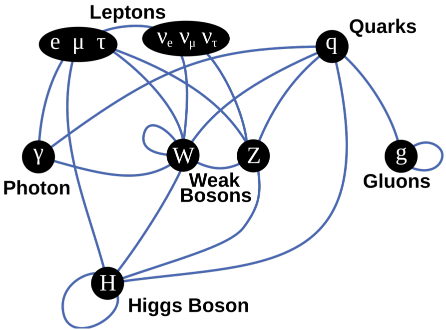

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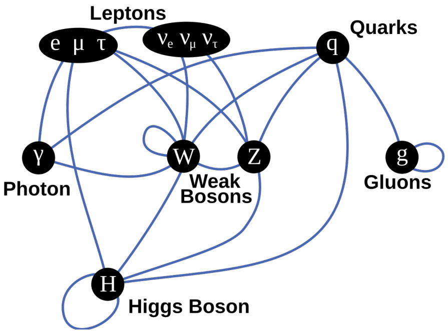
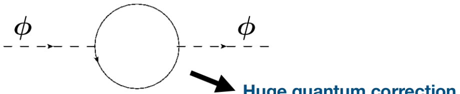
- **Key Points:**
  - The mass of the Higgs boson is **unnaturally fine-tuned**, leading to what is known as the **naturalness problem**.
  - Radiative corrections to the Higgs mass introduce large quadratic divergences, which suggest that new physics beyond the SM is necessary to stabilize the Higgs boson mass.





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Objectives:

- Investigate the naturalness problem in the context of the **Next-Two-Higgs Doublet Model (N2HDM)** as an extension of the SM with an extra Higgs doublet and a singlet scalar.
- Explore how the **Veltman Condition** can be imposed to cancel quadratic divergences and constrain the model's parameter space.

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N2HDM Parametrization

The scalar sector of N2HDM consists of two weak isospin doublets H_i (i = 1,2), with hypercharge $Y = 1$ and a real singlet field with hypercharge $Y = 0$ which are given by

$$H_i = \begin{pmatrix} \phi_i^{\pm} \\ \frac{1}{\sqrt{2}}(v_i + \phi_i + i\chi_i) \end{pmatrix} \text{ and } S = v_s + \phi_s. \quad (1)$$

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Implementation of the extra doublet and the singlet in the Standard Model. The lagrangian is,

$$\mathscr{L} = (D_\mu H_1)^\dagger (D^\mu H_1) + (D_\mu H_2)^\dagger (D^\mu H_2) + (\partial_\mu S)^\dagger (\partial^\mu S) - V(H_1, H_2, S) \tag{2}$$

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The most general renormalizable scalar potential for the N2HDM that respect $SU(2)_L \otimes U(1)_Y$ gauge symmetry has the following form:

$$\begin{aligned} V(H_1, H_2, S) &= m_{11}^2 H_1^\dagger H_1 + m_{22}^2 H_2^\dagger H_2 - \mu_{12}^2 \left(H_1^\dagger H_2 + h.c\right) + \frac{\lambda_1}{2}\left(H_1^\dagger H_1\right)^2 + \frac{\lambda_2}{2}\left(H_2^\dagger H_2\right)^2 \\ &+ \lambda_3 \left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) + \lambda_4 \left(H_1^\dagger H_2\right)\left(H_2^\dagger H_1\right) + \frac{\lambda_5}{2}\left[\left(H_1^\dagger H_2\right)^2 + h.c\right] \\ &+ \frac{1}{2} m_S^2 S^2 + \frac{\lambda_6}{8} S^4 + \frac{1}{2}\left[\lambda_7 H_1^\dagger H_1 + \lambda_8 H_2^\dagger H_2\right] S^2 \end{aligned} \qquad (3)$$

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+ \; & \lambda_3 \left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) + \lambda_4 \left(H_1^\dagger H_2\right)\left(H_2^\dagger H_1\right) + \frac{\lambda_5}{2}\left[\left(H_1^\dagger H_2\right)^2 + h.c\right] \\
+ \; & \frac{1}{2} m_S^2 S^2 + \frac{\lambda_6}{8} S^4 + \frac{1}{2}\left[\lambda_7 H_1^\dagger H_1 + \lambda_8 H_2^\dagger H_2\right] S^2 \qquad (3)
\end{aligned}
$$

- All scalar couplings $\lambda_i (i = 1,2,3,4,5,6,7,8)$ and μ_{12}^2 are assumed to be real parameters.
- This potential is obtained by imposing two $\mathbb{Z}_2$ symmetries on the scalar potential:

$$
\begin{aligned}
H_1 \to H_1, \quad H_2 \to -H_2, \quad S \to S. \\
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\end{aligned}
$$

N2HDM Parametrization

- Mixing in the CP-even scalar sector

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \mathscr{R}_{\alpha_{1,2,3}} \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_s \end{pmatrix}, \qquad \mathscr{R}_{\alpha_{1,2,3}} = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -c_1 s_2 s_3 - s_1 c_3 & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -c_1 s_3 - s_1 s_2 c_3 & c_2 c_3 \end{pmatrix}$$

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- "Physical" input free parameters:

$$m_{h_{1,2,3}} \;,\; m_A \;,\; m_{H^\pm} \;,\; v \;,\; v_S \;,\; \tan\beta = v_2/v_1 \;,\; \alpha_{1,2,3} \;,\; \mu_{12}^2$$

Higgs bosons couplings

- Extension of the $\mathbb{Z}_2$ symmetry to fermions determines four types:

	u-type	*d-type*	*leptons*
type I	Φ_2	Φ_2	Φ_2
type II	Φ_2	Φ_1	Φ_1
lepton-specific	Φ_2	Φ_2	Φ_1
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- N2HDM type-II Higgs bosons couplings to quarks and gauge bosons:

	$\chi_t^{h_i}$	$\chi_d^{h_i}$	$\chi_V^{h_i}$
h_1	$(c_{\alpha_2} s_{\alpha_1})/s_\beta$	$(c_{\alpha_1} c_{\alpha_2})/c_\beta$	$c_{\beta-\alpha_1} c_{\alpha_2}$
h_2	$(c_{\alpha_1} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3})/s_\beta$	$-(c_{\alpha_3} s_{\alpha_1} + c_{\alpha_1} s_{\alpha_2} s_{\alpha_3})/c_\beta$	$-c_{\beta-\alpha_1} s_{\alpha_2} s_{\alpha_3} + c_{\alpha_3} s_{\beta-\alpha_1}$
h_3	$-(c_{\alpha_1} s_{\alpha_3} + c_{\alpha_3} s_{\alpha_1} s_{\alpha_2})/s_\beta$	$(s_{\alpha_1} s_{\alpha_3} - c_{\alpha_1} c_{\alpha_3} s_{\alpha_2})/c_\beta$	$-c_{\beta-\alpha_1} s_{\alpha_2} c_{\alpha_3} - s_{\alpha_3} s_{\beta-\alpha_1}$

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Theoretical and Experimental Constraints

The parameter space of the N2HDM must satisfy several theoretical and experimental constraints:

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- the mass of the charged Higgs boson is restricted to be at least approximately 580 GeV [arXiv:2207.09959 [hep-ph]].

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Modified Veltman Conditions

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- Assuming that the vacuum is CP-even, one needs to calculate the quadratic divergences that show up in the tadpoles for the three CP-even neutral Higgs of our model.

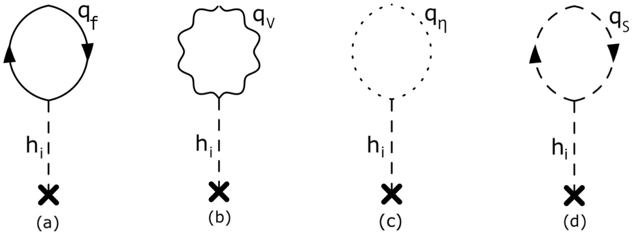

Figure 1: Higgs bosons $h_i\,(i=1,2,3)$ tadpole diagrams showing the contribution at one loop of: fermions (f): straight line; vector bosons ($V = W^{\pm}, Z$): wiggly line; scalars ($S = h_1, h_2, h_3, A, H^{\pm}$): short dashed line; and ghosts ($\eta = \eta^0, \eta^{\pm}$): long-dashed line.

Modified Veltman Conditions

- For each Higgs particle h_k $(k=1,2,3)$, one obtains:

$$T_{h_k} = \sum_{i=1}^{9} c_i^{h_k} s_i^{h_k} t_i^{h_k} - \sum_{i=U}^{D} c_i^{h_k} s_i^{h_k} t_i^{h_k} - \sum_{i=10}^{11} c_i^{h_k} s_i^{h_k} t_i^{h_k} \quad (4)$$

where the couplings $c_i^{h_k}$, the symmetry factors $s_i^{h_k}$, and the propagator loops $t_i^{h_k}$ for each CP-even neutral Higgs boson h_k

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- The linear combination of the fermionic coupling constants

$$\mathcal{R}_{i1}^{-1} c_{f\bar{f}}^{h_1} + \mathcal{R}_{i2}^{-1} c_{f\bar{f}}^{h_2} + \mathcal{R}_{i3}^{-1} c_{f\bar{f}}^{h_3} = 0 \quad \forall\, i = 1,2,3; \tag{5}$$

which it turns out that

$$\mathcal{R}_{i1}^{-1} T_{h_1} + \mathcal{R}_{i2}^{-1} T_{h_2} + \mathcal{R}_{i3}^{-1} T_{h_3} = 0 \quad \forall\, i = 1,2,3 \tag{6}$$

- Using Dimensional Regularization approach, and by assuming the Feynman-'t Hooft gauge-invariant, the type-II N2HDM one-loop tadpoles can be expressed as:

$$T_{h_1} = \left[-\frac{12m_b^2}{v^2 c_\beta^2} + \left(3\lambda_1 + 2\lambda_3 + \lambda_4 + \frac{\lambda_7}{4}\right) + \frac{3m_W^2}{v^2}\left(2 + \frac{1}{c_W^2}\right)\right] \leq \epsilon \quad (7)$$

$$T_{h_2} = \left[-\frac{12m_t^2}{v^2 s_\beta^2} + \left(3\lambda_2 + 2\lambda_3 + \lambda_4 + \frac{\lambda_8}{4}\right) + \frac{3m_W^2}{v^2}\left(2 + \frac{1}{c_W^2}\right)\right] \leq \epsilon \quad (8)$$

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- The 2HDM limit $\Longleftrightarrow \lambda_7 = \lambda_8 = 0$ [Nucl. Phys. B 926, 167 (2018), arXiv:1709.07219 [hep-ph]]

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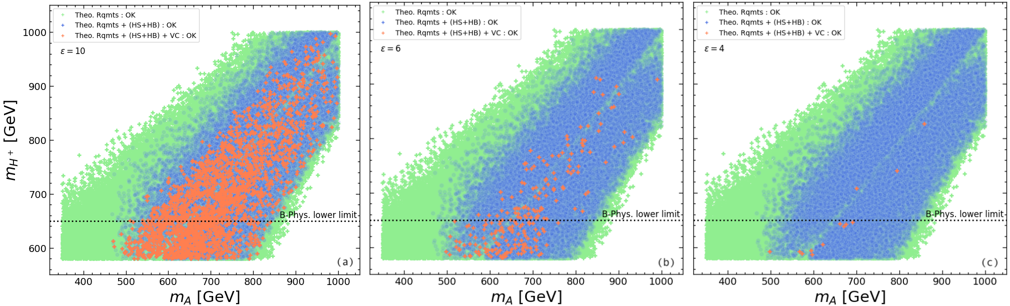
Parameter scan

⇒ we perform a random scan over the parameter space of the N2HDM type-II, by applying all the theoretical and experimental constraints and we keep only the points in the parameter space that fits within the definition of VC (as the parameter ϵ must be controllably small, we consider the cases $\epsilon = 4, 6, 10$).

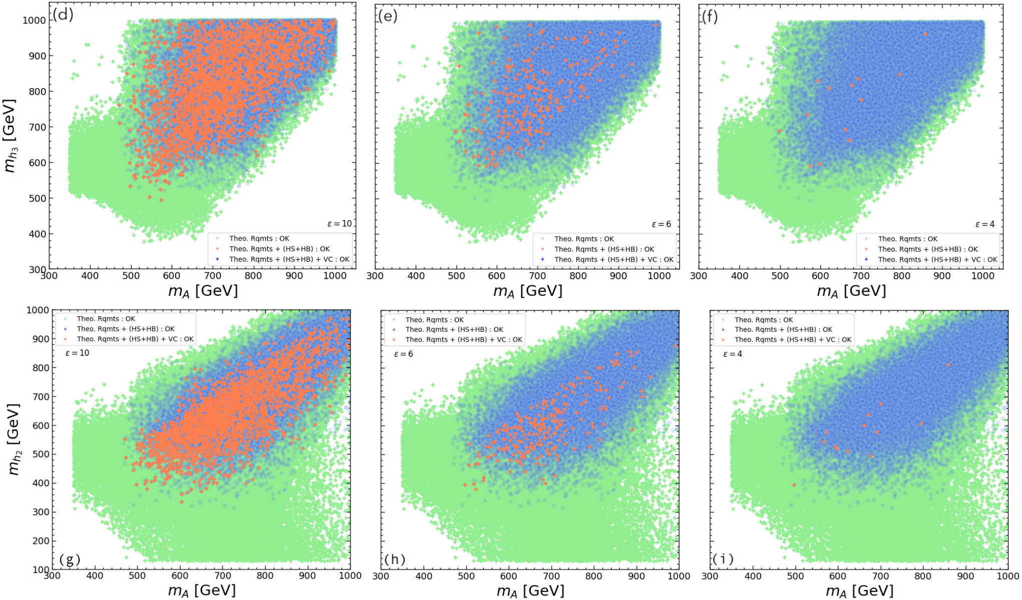
m_{h_1}	$m_{h_{2,3}}$	m_A	$m_{H^\pm}$	$\tan\beta$	$\alpha_{1,2,3}$	μ_{12}^2	v_s
125.09	[130; 1000]	[200; 1000]	[580; 1000]	[0.5; 12]	$[-\frac{\pi}{2}; \frac{\pi}{2}]$	$[0; 10^6]$	[100; 1000]

Table 1: Scan ranges of the Type-II input parameters. Masses, μ_{12}^2, and v_S are given in GeV.

Numerical Results



- for $\epsilon = 4$ and taking into account limit from B-physics - most of the orange points falling within the range of m_A (resp. $m_{H^\pm}$), from 700 GeV to 858 GeV (resp. from 706 GeV to 824 GeV).


(d)
(e)
(f)
(g)
(h)
(i)
m_{h_3} [GeV]
m_{h_2} [GeV]
m_A [GeV]
$\varepsilon = 10$
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$\varepsilon = 4$
Theo. Rqmts : OK
Theo. Rqmts + (HS+HB) : OK
Theo. Rqmts + (HS+HB) + VC : OK

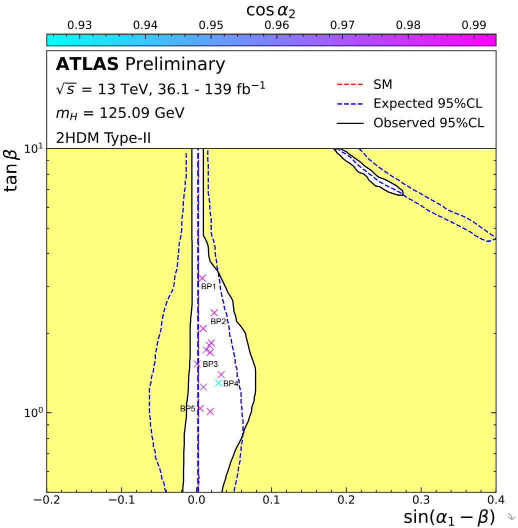
Numerical Results

- For h_2 (resp. h_3), the excluded Higgs mass region is significantly extended with lower bounds around 604 GeV (resp. 776 GeV) and upper bounds reaching 809 GeV (resp. 962 GeV).

Numerical Results

Fig: Projection of the surviving samples of the type-II N2HDM, while respecting the Veltman conditions for $\epsilon = 4$, in the $\left[\sin(\alpha_1 - \beta), \tan\beta\right]$ plane. Such a projection is overlaid on the expected exclusion limits at 2σ in the type-II 2HDM hypothesis, according to to the measured rates of Higgs boson production and decays by ATLAS [ATLAS-CONF-2021-053 (2021)].

$\Rightarrow$ The model outcome falls squarely within the observed range at 2σ, fully reflecting the consistency of N2HDM with the experimental measurements, together with the VC.



Benchmark datasets

BPs	t_β	c_{α_2}	$s_{\beta-\alpha_1}$	$c_{\beta-\alpha_1}$	m_{h_1}	m_{h_2}	m_{h_3}	m_A	$m_{H^\pm}$	μ	v_S
BP1	3.23	0.9927	-0.0076	0.999971	125.09	676.714	779.429	700.329	708.470	363	379
BP2	2.39	0.9908	-0.023606	0.999721	125.09	811.969	966.002	858.407	826.424	500.70	379.55
BP3	1.53	0.9778	-0.000842	1.0	125.09	606.698	851.301	794.755	740.410	503.47	379.55
BP4	1.29	0.9249	-0.02957	0.999563	125.09	394.440	691.753	497.419	592.647	358.012	379.55
BP5	1.03	0.9835	-0.005086	0.999987	125.09	601.137	696.009	661.480	643.149	459.600	379.55

Table 2: Higgs bosons masses, μ-parameter and singlet's *vev* v_S (in GeV) are shown in the scenario of h1 is the SM-like Higgs boson for various values of angles α's and β.

Benchmark datasets

BPs	$\chi_t^{h_1}$	$\chi_b^{h_1}$	$\chi_V^{h_1}$	$R_{\gamma\gamma}^{h_1}$	$R_{Z\gamma}^{h_1}$	$\frac{\Gamma_{h_1}^{tot}}{\Gamma_h^{tot}(\mathrm{SM})}$	S	T	U
exp	$1.02^{+0.19}_{-0.15}$	$0.91^{+0.17}_{-0.16}$	$1.035^{+0.031}_{-0.031}$	$1.04^{+0.1}_{-0.09}$	$2.2^{+0.7}_{-0.7}$	$0.98^{+0.31}_{-0.25}$	$-0.02^{+0.1}_{-0.1}$	$0.03^{+0.12}_{-0.12}$	$0.01^{+0.11}_{-0.11}$
BP1	0.995	0.968	0.992	1.032	1.027	0.955	0.000502	0.000621	-0.000058
BP2	1.000	0.934	0.990	1.076	1.081	0.913	0.001837	0.003784	-0.000074
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BP5	0.988	0.978	0.983	0.980	0.982	0.962	0.004677	-0.003014	-0.000128

Table 3: The h_1 SM-like relative couplings, decays rates and S, T and U parameters.

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Table 3: The h_1 SM-like relative couplings, decays rates and S, T and U parameters.

$\Rightarrow$ In view of the upcoming HL-LHC, for small $\tan\beta$ solutions (below 3.5), lead to a consistent agreement of $R_{\gamma\gamma}^{\text{HL-LHC}} = 1 \pm 0.04$ and $R_{Z\gamma}^{\text{HL-LHC}} = 1 \pm 0.23$ with the expected experimental results.

1 Introduction

2 Motivation and Objectives

3 N2HDM framework

4 Constraints

5 Results

6 Conclusion

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Thank You