Light Scalars in Aligned Two Doublet Models

59th Rencontres de Moriond 2025

La Thuile, 28th March 2025

Víctor Miralles

In collaboration with:

Antonio M. Coutinho, Anirban Karan and Antonio Pich

Based on: JHEP 02 (2025) 057

MANCHESTER 1824

The University of Manchester

Motivation

- In this work we extend the SM scalar sector with an additional doublet
- Richer phenomenology helps with the open problems of the SM
- Usually these extensions would introduce FCNC highly suppressed experimentally
- This is usually solved including a Z_2 symmetry
- More general possibility → Imposing alignment in the Yukawa matrices (flavour-align THDM)
  [Look also at M. Valli's talk tomorrow: Charming Higgs]
- In this talk we will study light scalars within the ATHDM
- We also studied the heavy case in [A. Karan, VM, A. Pich, PRD109(2024)3]

The ATHDM model

Scalar potential

- Higgs basis→ Only one scalar acquires VEV$\neq 0$

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\, G^+ \\ v + S_1 + i\, G^0 \end{pmatrix}, \qquad \Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\, H^+ \\ S_2 + i\, S_3 \end{pmatrix}.$$

- Most general Lagrangian

$$V = \mu_1\, \Phi_1^\dagger \Phi_1 + \mu_2\, \Phi_2^\dagger \Phi_2 + \left[\mu_3\, \Phi_1^\dagger \Phi_2 + \mathrm{h.c.}\right] + \frac{\lambda_1}{2}\, (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2}\, (\Phi_2^\dagger \Phi_2)^2 + \lambda_3\, (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4\, (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left[\left(\frac{\lambda_5}{2}\, \Phi_1^\dagger \Phi_2 + \lambda_6\, \Phi_1^\dagger \Phi_1 + \lambda_7\, \Phi_2^\dagger \Phi_2\right)(\Phi_1^\dagger \Phi_2) + \mathrm{h.c.}\right],$$

- Minimisation condition imposes

$$v^2 = -\frac{2\mu_1}{\lambda_1} = -\frac{2\mu_3}{\lambda_6}\,.$$

- 11 d.o.f. from the scalar potential alone: μ_2, v, $\lambda_{1,2,3,4}$, $|\lambda_{5,6,7}|$ and the two relative phases between $\lambda_{5,6,7}$

Scalar potential

- Mass terms

$$V_M = \left(\mu_2 + \frac{1}{2}\lambda_3 v^2\right) H^+ H^- + \frac{1}{2}\begin{pmatrix} S_1 & S_2 & S_3 \end{pmatrix} \mathscr{M} \begin{pmatrix} S_1 \\ S_2 \\ S_3 \end{pmatrix},$$

$$\mathscr{M} = \begin{pmatrix} v^2\lambda_1 & v^2\,\mathrm{Re}(\lambda_6) & -v^2\,\mathrm{Im}(\lambda_6) \\ v^2\,\mathrm{Re}(\lambda_6) & \left(\mu_2 + \frac{1}{2}v^2\lambda_3\right) + \frac{1}{2}v^2\left(\lambda_4 + \mathrm{Re}(\lambda_5)\right) & -\frac{1}{2}v^2\,\mathrm{Im}(\lambda_5) \\ -v^2\,\mathrm{Im}(\lambda_6) & -\frac{1}{2}v^2\,\mathrm{Im}(\lambda_5) & \left(\mu_2 + \frac{1}{2}v^2\lambda_3\right) + \frac{1}{2}v^2\left(\lambda_4 - \mathrm{Re}(\lambda_5)\right) \end{pmatrix}$$

- If CP-conservation in the NP $\rightarrow$ Only the CP-even scalars mix

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\tilde{\alpha} & \sin\tilde{\alpha} \\ -\sin\tilde{\alpha} & \cos\tilde{\alpha} \end{pmatrix} \begin{pmatrix} S_1 \\ S_2 \end{pmatrix}, \quad A = S_3.$$

- We chose to use physical parameters

$$\{v, M_h, M_{H^\pm}, M_H, M_A, \tilde{\alpha}, \lambda_2, \lambda_3, \lambda_7\}$$

Fermionic interaction

- Yukawa interaction

$$-\mathscr{L}_Y = \left(1+\frac{S_1}{v}\right)\left\{\bar{u}_L\, M_u\, u_R + \bar{d}_L\, M_d\, d_R + \bar{l}_L\, M_l\, l_R\right\}$$
$$+\frac{1}{v}\,(S_2+iS_3)\left\{\bar{u}_L\, Y_u\, u_R + \bar{d}_L\, Y_d\, d_R + \bar{l}_L\, Y_l\, l_R\right\}$$
$$+\frac{\sqrt{2}}{v}\,H^+\left\{\bar{u}_L\, V\, Y_d\, d_R - \bar{u}_R\, Y_u^\dagger\, V\, d_L + \bar{\nu}_L\, Y_l\, l_R\right\} + \text{h.c.}\,,$$

- We impose CP-conservation and alignment: $Y_{u,d,l} = \varsigma_{u,d,l}\, M_{u,d,l}$

$$-\mathscr{L}_Y \supset \left(\frac{\sqrt{2}}{v}\right) H^+ \left[\bar{u}\left\{\varsigma_d VM_d\mathscr{P}_R - \varsigma_u M_u^\dagger V\mathscr{P}_L\right\} d + \varsigma_l\,\bar{\nu}\, M_l\mathscr{P}_R l\right] + \text{h.c.}$$
$$+\sum_{i,f}\left(\frac{y_f^{\varphi_i^0}}{v}\right)\varphi_i^0\left[\bar{f}\, M_f\,\mathscr{P}_R f\right],$$

$$y_u^H = -\sin\tilde{\alpha} + \varsigma_u\cos\tilde{\alpha}\,, \qquad y_u^h = \cos\tilde{\alpha} + \varsigma_u\sin\tilde{\alpha}\,, \qquad y_u^A = -i\varsigma_u\,,$$
$$y_{d,l}^H = -\sin\tilde{\alpha} + \varsigma_{d,l}\cos\tilde{\alpha}\,, \qquad y_{d,l}^h = \cos\tilde{\alpha} + \varsigma_{d,l}\sin\tilde{\alpha}\,, \qquad y_{d,l}^A = i\varsigma_{d,l}\,.$$

Theory assumptions

and

Observables

Theoretical considerations

[Ivanov, PRD75(2007)035001]
[Ivanov, Silva, PRD92(2015)055017]

- Bounded from below: $V = -\mathtt{M}_\mu \, \mathtt{r}^\mu + \frac{1}{2} \Lambda^\mu{}_\nu \, \mathtt{r}_\mu \, \mathtt{r}^\nu$

$$\mathtt{M}_\mu = \left[-\frac{1}{2}(\mu_1 + \mu_2), -\mathrm{Re}\,\mu_3, \mathrm{Im}\,\mu_3, -\frac{1}{2}(\mu_1 - \mu_2) \right],$$

$$\mathtt{r}^\mu = \left[|\Phi_1|^2 + |\Phi_2|^2, 2\,\mathrm{Re}(\Phi_1^\dagger \Phi_2), 2\,\mathrm{Im}(\Phi_1^\dagger \Phi_2), |\Phi_1|^2 - |\Phi_2|^2 \right],$$

$$\Lambda^\mu{}_\nu = \frac{1}{2} \begin{bmatrix} \frac{1}{2}(\lambda_1 + \lambda_2) + \lambda_3 & \mathrm{Re}(\lambda_6 + \lambda_7) & -\mathrm{Im}(\lambda_6 + \lambda_7) & \frac{1}{2}(\lambda_1 - \lambda_2) \\ -\mathrm{Re}(\lambda_6 + \lambda_7) & -\lambda_4 - \mathrm{Re}\lambda_5 & \mathrm{Im}\lambda_5 & -\mathrm{Re}(\lambda_6 - \lambda_7) \\ \mathrm{Im}(\lambda_6 + \lambda_7) & \mathrm{Im}\lambda_5 & -\lambda_4 + \mathrm{Re}\lambda_5 & \mathrm{Im}(\lambda_6 - \lambda_7) \\ -\frac{1}{2}(\lambda_1 - \lambda_2) & -\mathrm{Re}(\lambda_6 - \lambda_7) & \mathrm{Im}(\lambda_6 - \lambda_7) & -\frac{1}{2}(\lambda_1 + \lambda_2) + \lambda_3 \end{bmatrix}$$

Necessary and sufficient conditions:

1. All the eigenvalues ($\Lambda_{0,1,2,3}$) of $\Lambda^\mu{}_\nu$ are real
2. The "timelike" eigenvalue satisfy $\Lambda_0 > 0$ and $\Lambda_0 > \Lambda_{1,2,3}$

- Absolute stability: $D = \mathrm{Det}\left[\frac{m_{H^\pm}^2}{v^2} - \Lambda^\mu{}_\nu \right]$

$D > 0$ or $D < 0$ with $\frac{m_{H^\pm}^2}{v^2} > \Lambda_0$

Theoretical considerations

[Ginzburg, Ivanov, PRD72(2005)11501]
[Bahl, et al., JHEP03(2023)16]

- Tree-level perturbative unitarity: $\frac{1}{16\pi s}\int_{-s}^{0}\mathscr{M}_{i\to f}(s,t)\mathrm{d}t$

$$X_{(1,0)} = \lambda_3 - \lambda_4\,, \qquad X_{(1,1)} = \begin{bmatrix} \lambda_1 & \lambda_5 & \sqrt{2}\lambda_6 \\ \lambda_5^* & \lambda_2 & \sqrt{2}\lambda_7^* \\ \sqrt{2}\lambda_6^* & \sqrt{2}\lambda_7^* & \lambda_3+\lambda_4 \end{bmatrix},$$

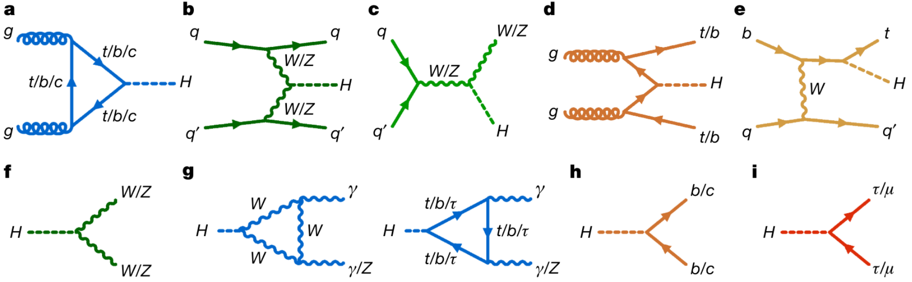
$$X_{(0,1)} = \begin{bmatrix} \lambda_1 & \lambda_4 & \lambda_6 & \lambda_6^* \\ \lambda_4 & \lambda_2 & \lambda_7 & \lambda_7^* \\ \lambda_6^* & \lambda_7^* & \lambda_3 & \lambda_5^* \\ \lambda_6 & \lambda_7 & \lambda_5 & \lambda_3 \end{bmatrix}, \quad X_{(0,0)} = \begin{bmatrix} 3\lambda_1 & 2\lambda_3+\lambda_4 & 3\lambda_6 & 3\lambda_6^* \\ 2\lambda_3+\lambda_4 & 3\lambda_2 & 3\lambda_7 & 3\lambda_7^* \\ 3\lambda_6^* & 3\lambda_7^* & \lambda_3+2\lambda_4 & 3\lambda_5^* \\ 3\lambda_6 & 3\lambda_7 & 3\lambda_5 & \lambda_3+2\lambda_4 \end{bmatrix}.$$

Eigenvalues of $X_{(a,b)}$: $|e_i| < 8\pi$

Yukawa couplings: $\sqrt{2}|\varsigma_f|\frac{m_f}{v} < 1$

Signal Strengths

[ATLAS+CMS, JHEP08(2016)045]
[ATLAS, Nature607(2022)7917,52-59]
[CMS, Nature607(2022)7917,60-68]



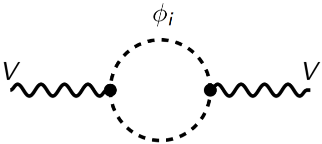
$$\mu_{XY} = \frac{\sigma(pp \to h)\mathrm{Br}(h \to XY)}{[\sigma(pp \to h)\mathrm{Br}(h \to XY)]_{SM}}$$

$$g_{hVV} = \cos\widetilde{\alpha}\, g_{hVV}^{SM}, \qquad y_{u,d,l}^{h} = \cos\widetilde{\alpha} + \varsigma_{u,d,l}\sin\widetilde{\alpha}$$

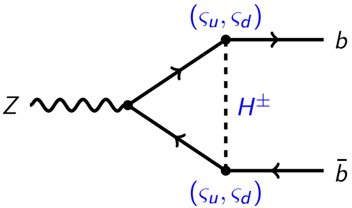
Electroweak precision observables

[Haber, O'Neil, PRD83(2011)055017]
[Haber, Logan, PRD62(2000)015011]

- The additional scalars contribute to the oblique parameters (S & T):



- Modifications of $R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to \text{hadrons})}$:

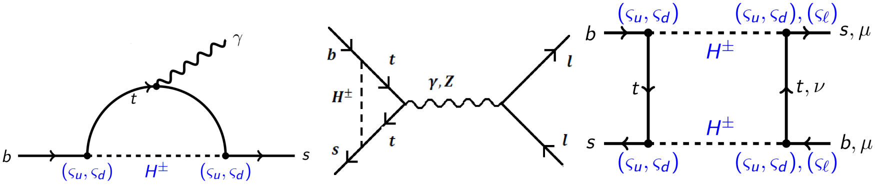


Flavour

[Misiak, et. al. PRL114(2015)22,221801] [Li, Lu, Pich, JHEP06(2014)022]
[Jung, Pich, Tuzón, JHEP11(2010)003]

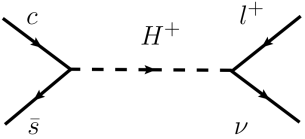
- Contribution to flavour loop processes:

$$b \to s\gamma \quad B_s \to \mu^+\mu^- \quad \Delta M_{B_s}$$



- Contribution to tree-level processes:

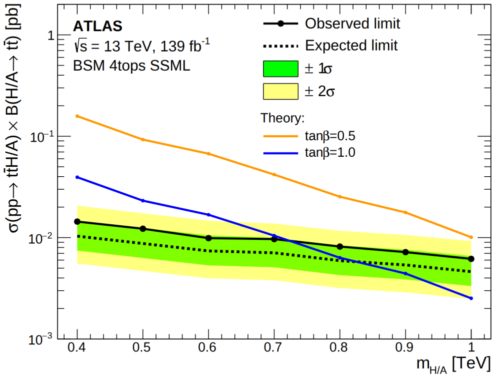
$$B \to \tau\nu \quad D_{(s)} \to l\nu \quad \frac{\Gamma(K \to \mu\nu)}{\Gamma(\pi \to \mu\nu)} \quad \frac{\Gamma(\tau \to K\nu)}{\Gamma(\tau \to \pi\nu)}$$



Collider searches

- Theoretical predictions from: CERN twiki, HDECAY, `Madgraph` and HIGLU

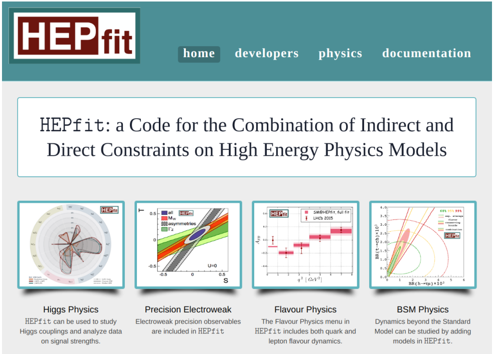
- Experimental data from: LEP, ATLAS & CMS



Global fits

The HEPfit code

- Open source written in C++
- Available under the GPL on GitHub: https://github.com/silvest/HEPfit
- The MCMC sampling based on BAT [Caldwell, Kollar, Kroninger, Comput.Phys.Commun.180(2009)2197-2209]
- Sampling likelihoods with MCMC
- Parallelised with MPI



HEPfit webpage [J. de Blas et al., 1910.14012]

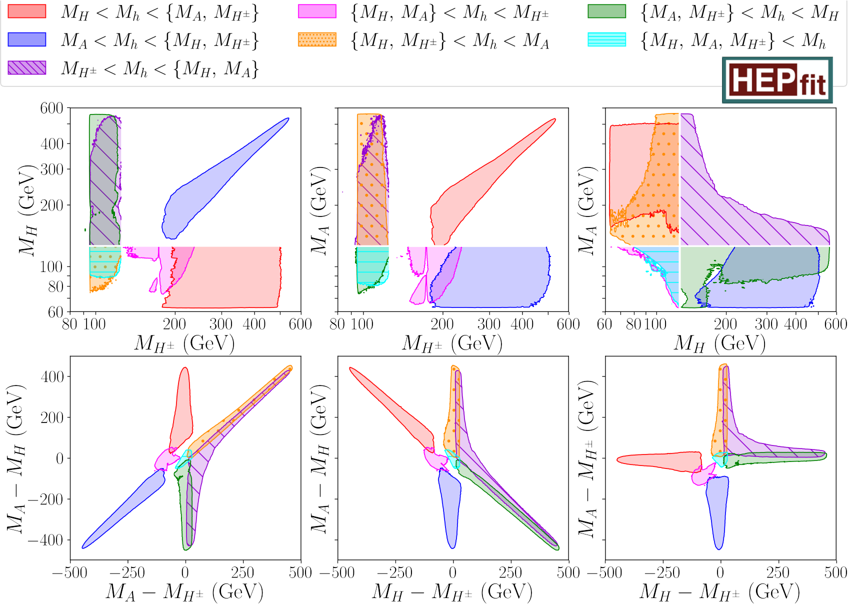
Fit setup

- The fit contains 10 parameters $M_{H^\pm,H,A}$, $\widetilde{\alpha}$, $\lambda_{2,3,7}$, & $\varsigma_{u,d,l}$

Priors						
$M_{\phi_{\text{light}}} \in [10 \text{ GeV}, \ M_h]$				$M_{\phi_{\text{heavy}}} \in [M_h, \ 700 \text{ GeV}]$		
$\lambda_2 \in [-1, \ 10]$		$\lambda_3 \in [-1, \ 10]$			$\lambda_7 \in [-3.5, \ 3.5]$	
$\tilde{\alpha} \in [-0.2, \ 0.2]$	$\varsigma_u \in [-0.5, \ 0.5]$		$\varsigma_d \in [-10, \ 10]$			$\varsigma_l \in [-100, \ 100]$

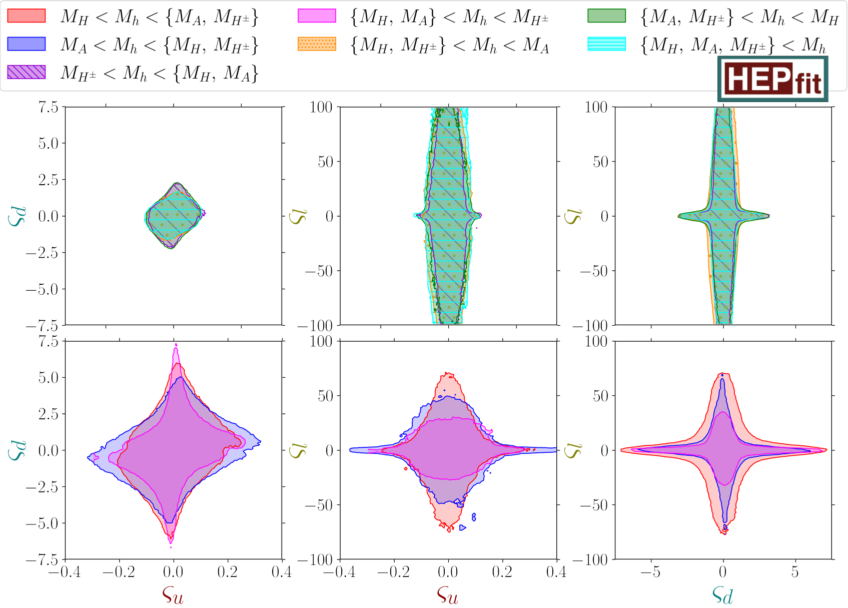
- We study seven possible scenarios:
  * 3 cases with only one BSM scalar light
  * 3 cases with two BSM scalar light
  * 1 case with all BSM scalars light

Masses

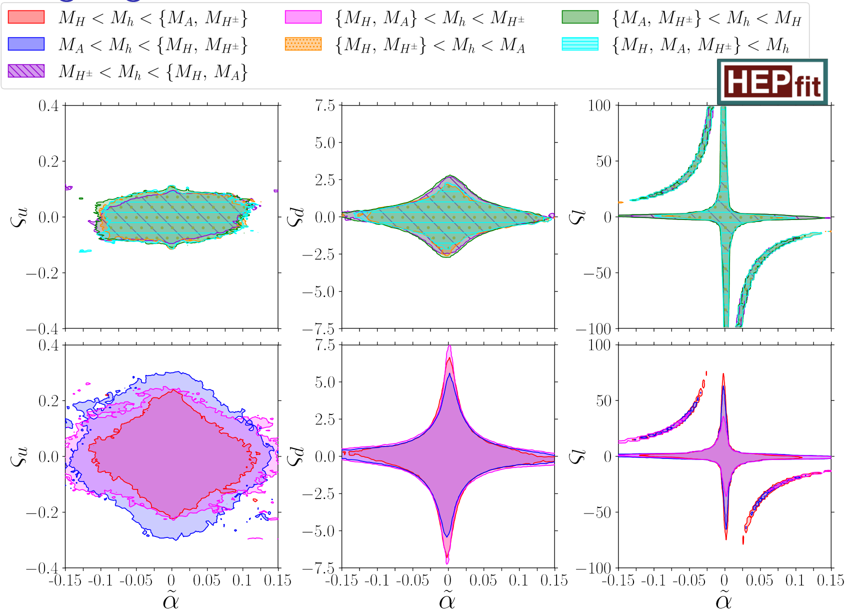


$M_H < M_h < \{M_A, M_{H^\pm}\}$
$\{M_H, M_A\} < M_h < M_{H^\pm}$
$\{M_A, M_{H^\pm}\} < M_h < M_H$
$M_A < M_h < \{M_H, M_{H^\pm}\}$
$\{M_H, M_{H^\pm}\} < M_h < M_A$
$\{M_H, M_A, M_{H^\pm}\} < M_h$
$M_{H^\pm} < M_h < \{M_H, M_A\}$
HEPfit
M_H (GeV)
M_A (GeV)
$M_{H^\pm}$ (GeV)
M_H (GeV)
$M_A - M_H$ (GeV)
$M_A - M_{H^\pm}$ (GeV)
$M_H - M_{H^\pm}$ (GeV)
600
400
300
200
100
80
60
−500
−250
0
250
500
−400
−200

Yukawas

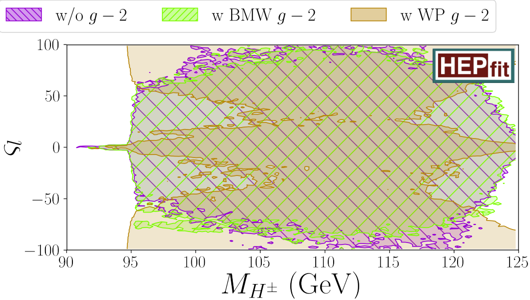

$M_H < M_h < \{M_A, M_{H^\pm}\}$
$M_A < M_h < \{M_H, M_{H^\pm}\}$
$M_{H^\pm} < M_h < \{M_H, M_A\}$
$\{M_H, M_A\} < M_h < M_{H^\pm}$
$\{M_H, M_{H^\pm}\} < M_h < M_A$
$\{M_A, M_{H^\pm}\} < M_h < M_H$
$\{M_H, M_A, M_{H^\pm}\} < M_h$
HEPfit
ς_d
ς_l
ς_u
ς_d

Mixing angle and Yukawa



Muon anomalous magnetic moment

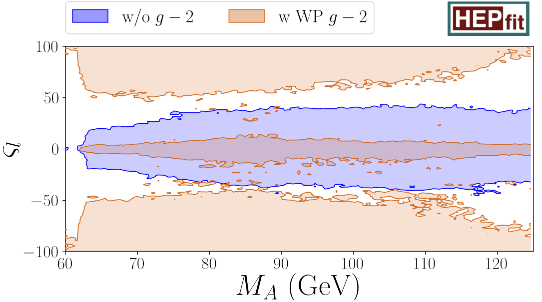
- Light charged scalar



- Light pseudoscalar

  $\mathrm{IC} = -2\,\overline{\log\mathscr{L}} + 4\,\sigma^2_{\log\mathscr{L}}$

  $\Delta IC \sim 40$ when adding the WP $(g-2)_\mu$



Final remarks

Summary

- Neutral scalars masses as low as 60 GeV and charged scalar masses of 95 GeV seem feasible
- Masses below these ranges are completely forbidden by direct searches
- For these low masses values to be compatible with (specially) flavour data relatively small values of $\varsigma_u < 0.3$ and $\varsigma_d < 6$ are needed
- The coupling to leptons could reach quite high values
- The constraints from $(g-2)_\mu$ also do not help
- This model with a light pseudoscalar would also not be a good solution for the discrepancy on the $(g-2)_\mu$ from the White Paper (anyway the new lattice and data driven calculations are compatible with the measurements)

Thanks for your attention!

Back up

Outlook

- The ATHDM is a more general than the usual THDM with Z_2 symmetries

- We can recover them by imposing

$$\mu_3 = \lambda_6 = \lambda_7 = 0$$

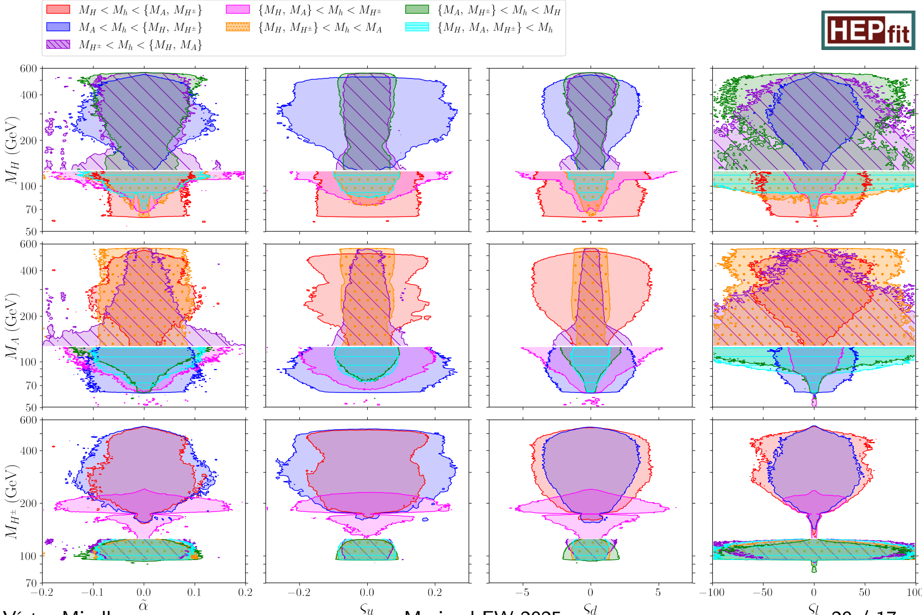
$$\text{Type I: } \varsigma_u = \varsigma_d = \varsigma_l = \cot\beta, \;\; \text{Type II: } \varsigma_u = -\frac{1}{\varsigma_d} = -\frac{1}{\varsigma_l} = \cot\beta\,,$$

$$\text{Inert: } \varsigma_u = \varsigma_d = \varsigma_l = 0\,,$$

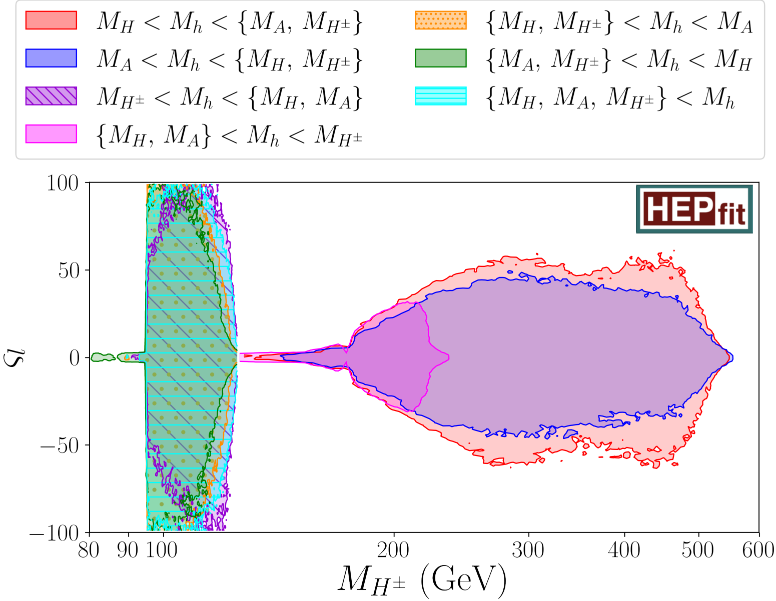
$$\text{Type X: } \varsigma_u = \varsigma_d = -\frac{1}{\varsigma_l} = \cot\beta, \qquad \text{and} \qquad \text{Type Y: } \varsigma_u = -\frac{1}{\varsigma_d} = \varsigma_l = \cot\beta\,.$$

- We are working on including perturbative unitarity at NLO to study each particular scenario

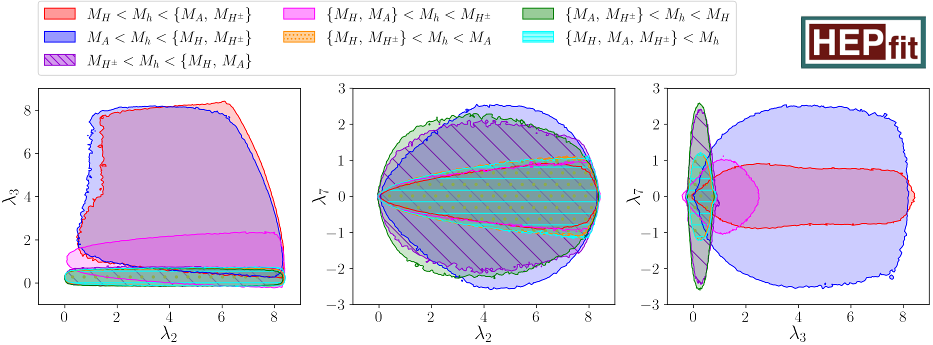
Mixing angle and Yukawa vs Masses



ς_l vs $M_{H^\pm}$



Potential parameters



Marginalised one dimensional results

Marginalised Individual Results					
$M_H \leq M_h$	IC: 84.06	$65 \leq M_H \leq M_h$	$168 \leq M_A \leq 496$	$196 \leq M_{H^\pm} \leq 500$	
	$\lambda_2 : 4.969 \pm 1.925$	$\lambda_3 : 3.854 \pm 2.067$	$\lambda_7 : 0.005 \pm 0.382$		
	$\tilde{\alpha} : (0.8 \pm 34.0) \times 10^{-3}$	$\varsigma_u : 0.001 \pm 0.073$	$\varsigma_d : 0.017 \pm 1.716$	$\varsigma_l : -0.325 \pm 20.100$	
$M_A \leq M_h$	IC: 83.74	$182 \leq M_H \leq 500$	$69 \leq M_A \leq M_h$	$196 \leq M_{H^\pm} \leq 500$	
	$\lambda_2 : 4.609 \pm 1.891$	$\lambda_3 : 3.817 \pm 1.973$	$\lambda_7 : 0.006 \pm 1.164$		
	$\tilde{\alpha} : (-0.8 \pm 42.5) \times 10^{-3}$	$\varsigma_u : 0.003 \pm 0.106$	$\varsigma_d : 0.008 \pm 1.348$	$\varsigma_l : 0.105 \pm 15.380$	
$M_{H^\pm} \leq M_h$	IC: 88.48	$M_h \leq M_H \leq 500$	$M_h \leq M_A \leq 440$	$97 \leq M_{H^\pm} \leq M_h$	
	$\lambda_2 : 4.342 \pm 2.185$	$\lambda_3 : 0.280 \pm 0.214$	$\lambda_7 : 0.004 \pm 0.873$		
	$\tilde{\alpha} : (-1.7 \pm 41.9) \times 10^{-3}$	$\varsigma_u : 0.0006 \pm 0.0364$	$\varsigma_d : 0.004 \pm 0.706$	$\varsigma_l : 0.528 \pm 34.450$	

Marginalised one dimensional results

$M_{H,A} \leq M_h$	IC: 89.48	$89 \leq M_H \leq M_h$	$78 \leq M_A \leq M_h$	$154 \leq M_{H^\pm} \leq 226$
	λ_2 : 4.890 ± 2.166	λ_3: 1.042 ± 0.5718	λ_7 : 0.002 ± 0.362	
	$\tilde{\alpha}$: $(-0.6 \pm 47.4) \times 10^{-3}$	ς_u : 0.002 ± 0.082	ς_d : 0.007 ± 1.620	ς_l : 0.370 ± 9.574
$M_{H,H^\pm} \leq M_h$	IC: 89.51	$85 \leq M_H \leq M_h$	$M_h \leq M_A \leq 534$	$95 \leq M_{H^\pm} \leq 120$
	λ_2 : 4.639 ± 2.208	λ_3 : 0.254 ± 0.191	λ_7 : 0.002 ± 0.453	
	$\tilde{\alpha}$: $(0.2 \pm 38.2) \times 10^{-3}$	ς_u : -0.0004 ± 0.0400	ς_d : -0.010 ± 0.656	ς_l : -0.603 ± 41.45
$M_{A,H^\pm} \leq M_h$	IC: 89.35	$M_h \leq M_H \leq 163$ $\cup\ 211 \leq M_H \leq 553$	$85 \leq M_A \leq M_h$	$95 \leq M_{H^\pm} \leq 120$
	λ_2 : 4.082 ± 2.157	λ_3 : 0.246 ± 0.192	λ_7 : -0.005 ± 0.993	
	$\tilde{\alpha}$: $(-0.9 \pm 41.0) \times 10^{-3}$	ς_u : -0.0004 ± 0.0402	ς_d : 0.001 ± 0.779	ς_l : 0.261 ± 31.090
$M_{H,A,H^\pm} \leq M_h$	IC: 89.22	$91 \leq M_H \leq M_h$	$83 \leq M_A \leq M_h$	$95 \leq M_{H^\pm} \leq 122$
	λ_2 : 4.740 ± 2.232	λ_3 : 0.275 ± 0.201	λ_7 : -0.002 ± 0.463	
	$\tilde{\alpha}$: $(0.4 \pm 38.3) \times 10^{-3}$	ς_u : -0.001 ± 0.043	ς_d : -0.005 ± 0.613	ς_l : -0.560 ± 41.890