CSIC
Consejo Superior de Investigaciones Científicas
Vniversitat de València
IFIC Institut de Física Corpuscular
Excelencia Severo Ochoa

A. Coutinho, A. Karan, V. Miralles, A.P., JHEP 02 (2025) 057
A. Karan, V. Miralles, A.P., Phys. Rev. D 109 (2024) 3

Phenomenological status of the Aligned Two-Higgs-Doublet model

Antonio Pich

IFIC, Univ. Valencia – CSIC

Two Higgs Doublets:

$$\langle 0|\, \phi_a^T(x)\,|0\rangle = \frac{1}{\sqrt{2}}\,(0\,,\, v_a\, \mathrm{e}^{i\theta_a}) \quad , \quad \theta_1 = 0 \quad , \quad \theta \equiv \theta_2 - \theta_1$$

$$v^2 \equiv v_1^2 + v_2^2 \qquad , \qquad \tan\beta \equiv v_2/v_1$$

Higgs basis

$$\begin{pmatrix} \Phi_1 \\ -\Phi_2 \end{pmatrix} \equiv \begin{bmatrix} \cos\beta & \sin\beta \\ \sin\beta & -\cos\beta \end{bmatrix} \begin{pmatrix} \phi_1 \\ \mathrm{e}^{-i\theta}\,\phi_2 \end{pmatrix}$$

$$\Phi_1 = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + S_1 + i\, G^0\right) \end{bmatrix} \qquad , \qquad \Phi_2 = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}}\left(S_2 + i\, S_3\right) \end{bmatrix}$$

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

$$+ \left[\left(\frac{\lambda_5}{2}\,\Phi_1^\dagger\Phi_2 + \lambda_6\,\Phi_1^\dagger\Phi_1 + \lambda_7\,\Phi_2^\dagger\Phi_2\right)(\Phi_1^\dagger\Phi_2) + \mathrm{h.c.}\right]$$

Two Higgs Doublets:

$$\langle 0|\, \phi_a^T(x)|0\rangle = \frac{1}{\sqrt{2}}\,(0\,,\, v_a\, e^{i\theta_a}) \quad , \quad \theta_1 = 0 \quad , \quad \theta \equiv \theta_2 - \theta_1$$

$$v^2 \equiv v_1^2 + v_2^2 \qquad , \qquad \tan\beta \equiv v_2/v_1$$

Higgs basis

$$\begin{pmatrix} \Phi_1 \\ -\Phi_2 \end{pmatrix} \equiv \begin{bmatrix} \cos\beta & \sin\beta \\ \sin\beta & -\cos\beta \end{bmatrix} \begin{pmatrix} \phi_1 \\ e^{-i\theta}\phi_2 \end{pmatrix}$$

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

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

$$+ \left[\left(\frac{\lambda_5}{2}\,\Phi_1^\dagger\Phi_2 + \lambda_6\,\Phi_1^\dagger\Phi_1 + \lambda_7\,\Phi_2^\dagger\Phi_2\right)(\Phi_1^\dagger\Phi_2) + \mathrm{h.c.}\right]$$

- **Mass eigenstates:** $H^\pm \quad , \quad \varphi_i^0(x) \equiv \{h(x), H(x), A(x)\} = \mathcal{R}_{ij}\; S_j(x)$
- **CP-conserving potential:** $A(x) = S_3(x) \quad , \quad \begin{pmatrix} h \\ H \end{pmatrix} = \begin{bmatrix} \cos\tilde\alpha & \sin\tilde\alpha \\ -\sin\tilde\alpha & \cos\tilde\alpha \end{bmatrix} \begin{pmatrix} S_1 \\ S_2 \end{pmatrix}$
- **Gauge couplings:** $g_{\varphi_i^0 VV} = \mathcal{R}_{i1}\; g_{hVV}^{\mathrm{SM}} \quad , \quad g_{hVV}^2 + g_{HVV}^2 + g_{AVV}^2 = \left(g_{hVV}^{\mathrm{SM}}\right)^2$

Yukawa interactions in 2HDMs

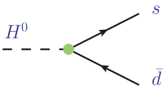
$$\mathcal{L}_Y = -\bar{Q}'_L \left(\Gamma_1 \phi_1 + \Gamma_2 \phi_2 \right) d'_R - \bar{Q}'_L \left(\Delta_1 \tilde{\phi}_1 + \Delta_2 \tilde{\phi}_2 \right) u'_R$$

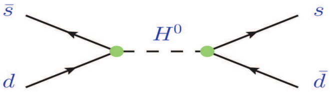
SSB ⬇

$$\phi_i^{(0)} = \frac{v_i}{\sqrt{2}} \quad , \quad v = \sqrt{v_1^2 + v_2^2}$$

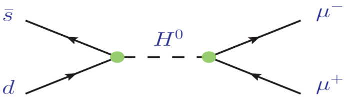
$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v} \left\{ \bar{Q}'_L \left(M_d' \Phi_1 + Y_d' \Phi_2 \right) d'_R - \bar{Q}'_L \left(M_u' \tilde{\Phi}_1 + Y_u' \tilde{\Phi}_2 \right) u'_R \right\}$$

M_q' and Y_q' unrelated ➡ **FCNCs**





$K^0 \leftrightarrow \bar{K}^0$



$K^0 \to \mu^-\mu^+$

Phenomenological disaster!

Aligned 2HDM

Pich-Tuzón, 0908.1554

Yukawa alignment in Flavour Space: $Y_{d,l} = \varsigma_{d,\ell}\, M_{d,\ell} \quad , \quad Y_u = \varsigma_u^*\, M_u$

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v}\, H^+ \left\{ \bar{u} \left[\varsigma_d\, V_{\mathrm{CKM}} M_d \mathcal{P}_R - \varsigma_u\, M_u^\dagger V_{\mathrm{CKM}} \mathcal{P}_L \right] d + \varsigma_l\, \left(\bar{\nu}\, M_\ell\, \mathcal{P}_R\, \ell \right) \right\}$$

$$-\frac{1}{v} \sum_{\varphi_i^0, f} y_f^{\varphi_i^0}\, \varphi_i^0\, \left(\bar{f}\, M_f\, \mathcal{P}_R\, f \right) \quad + \quad \mathrm{h.c.}$$

$$y_{d,\ell}^{\varphi_i^0} = \mathcal{R}_{i1} + (\mathcal{R}_{i2} + i\,\mathcal{R}_{i3})\, \varsigma_{d,\ell} \qquad , \qquad y_u^{\varphi_i^0} = \mathcal{R}_{i1} + (\mathcal{R}_{i2} - i\,\mathcal{R}_{i3})\, \varsigma_u^*$$

ς_f → **New sources of CP violation without tree-level FCNCs**

$\mathcal{Z}_2$ models

Model	ς_d	ς_u	ς_ℓ
Type I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type II	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
Type X	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type Y	$-\tan\beta$	$\cot\beta$	$\cot\beta$
Inert	0	0	0

Only one ϕ_a couples to f_R
(Glashow-Weinberg, Paschos '77)

Quantum Misalignment

Pich-Tuzón, 0908.1554

$\mathcal{L}_{\rm A2HDM}$ is invariant under the phase transformation: $(\alpha_i^\nu = \alpha_i^\ell)$

$$f_L^i(x) \;\to\; e^{i\alpha_i^{f,L}}\; f_L^i(x) \qquad , \qquad f_R^i(x) \;\to\; e^{i\alpha_i^{f,R}}\; f_R^i(x)$$

$$V_{\rm CKM}^{ij} \;\to\; e^{i\alpha_i^{u,L}}\; V_{\rm CKM}^{ij}\; e^{-i\alpha_j^{d,L}} \qquad , \qquad M_{f,ij} \;\to\; e^{i\alpha_i^{f,L}}\; M_{f,ij}\; e^{-i\alpha_j^{f,R}}$$

- **Leptonic FCNCs absent to all orders in perturbation theory**
- **Loop-induced FCNC local terms must have the flavour structure:**

$$\bar u_L V_{\rm CKM} (M_d M_d^\dagger)^n V_{\rm CKM}^\dagger (M_u M_u^\dagger)^m M_u u_R \qquad , \qquad \bar d_L V_{\rm CKM}^\dagger (M_u M_u^\dagger)^n V_{\rm CKM} (M_d M_d^\dagger)^m M_d d_R$$

➡ **MFV structure** D'Ambrosio et al, Chivukula-Georgi, Hall-Randall, Buras et al, Cirigliano et al

Strongly suppressed by quark mass and CKM factors

FCNCs at one Loop

General 2HDM 1-loop RGE (Cvetic et al, Ferreira et al)

Jung-Pich-Tuzón, Braeuninger-Ibarra-Simonetto, Bijnens-Lu-Rathsman
Gori-Haber-Santos, Peñuelas-Pich

$$\mathcal{L}_{\rm FCNC} = \frac{(1+\varsigma_u^*\varsigma_d)}{4\pi^2 v^3} \sum_i \varphi_i^0(x) \Big\{ C_d(\mu)\, (\mathcal{R}_{i2} + i\,\mathcal{R}_{i3})\, (\varsigma_d - \varsigma_u) \left[\bar d_L\, V_{\rm CKM}^\dagger M_u M_u^\dagger\, V_{\rm CKM} M_d\, d_R\right] - C_u(\mu)\, (\mathcal{R}_{i2} - i\,\mathcal{R}_{i3})\, (\varsigma_d^* - \varsigma_u^*) \left[\bar u_L\, V_{\rm CKM} M_d M_d^\dagger\, V_{\rm CKM}^\dagger M_u\, u_R\right] \Big\} + \text{h.c.}$$

- $C_f(\mu) = C_f(\mu_0) - \log(\mu/\mu_0)$
- Vanish in all $\mathcal{Z}_2$ models as it should
- Suppressed by $m_q\, m_{q'}^2/(4\pi^2 v^3)$ and $V_{\rm CKM}^{qq'}$ ➔ $\bar s_L b_R$, $\bar c_L t_R$
- $\Delta M_{B_s^0}$ ➔ $\frac{1}{4\pi^2}\, |C_d(M_W)\, (1+\varsigma_u^*\varsigma_d)\, (\varsigma_d - \varsigma_u)| \lesssim \mathcal{O}(1)$
- Assuming alignment at $\Lambda_A \le M_{\rm Planck} \sim 10^{19}$ GeV ➔ $C_f(M_W) = \log(\Lambda_A/M_W) \le 40$

➔ **All experimental constraints are easily satisfied**

Global Fit:

$2+10$ input parameters. Bayesian statistics

HEPfit

Assumption: No new sources of CP violation beyond the CKM phase

Heavy Scalars: $M_{H^\pm}, M_H, M_A > M_h$

$v = 246$ GeV

$M_h = (125.20 \pm 0.11)$ GeV

Priors			
$M_{H^\pm} \subset [0.125,\ 1.0\ \ (1.5)]$ TeV		$M_H \subset [0.125,\ 1.0\ \ (1.5)]$ TeV	$M_A \subset [0.125,\ 1.0\ \ (1.5)]$ TeV
$\lambda_2 \subset [0,\ 11]$		$\lambda_3 \subset [-3,\ 17]$	$\lambda_7 \subset [-5,\ 5]$
$\tilde{\alpha} \subset [-0.16,\ 0.16]$	$\varsigma_u \subset [-1.5,\ 1.5]$	$\varsigma_d \subset [-50,\ 50]$	$\varsigma_l \subset [-100,\ 100]$

Fit Constraints:

- **Theory:** Perturbative unitarity. Scalar potential bounded from below. Stable neutral minimum
- **Experiment:** Direct searches. Higgs signal strengths. EW precision observables. Flavour data

Oblique and CKM parameters fitted removing observables sensitive to the new scalars

Global Fit

Heavy Scalars: $M_{H^\pm}, M_H, M_A > M_h$

Karan-Miralles-AP, 2307.15419

Marginalised Individual results

Masses up to 1 TeV			
$M_{H^\pm} \geq 390$ GeV	$M_H \geq 410$ GeV	$M_A \geq 370$ GeV	
λ_2: 3.2 ± 1.9	λ_3: 5.9 ± 3.5	$\lambda_7 : 0.0 \pm 1.1$	
$\tilde{\alpha} : (0.05 \pm 21.0) \cdot 10^{-3}$	$\varsigma_u : 0.006 \pm 0.257$	$\varsigma_d : 0.12 \pm 4.12$	$\varsigma_l : -0.39 \pm 11.69$

Masses up to 1.5 TeV			
$M_{H^\pm} \geq 480$ GeV	$M_H \geq 490$ GeV	$M_A \geq 480$ GeV	
λ_2: 3.2 ± 1.9	λ_3: 5.9 ± 3.8	$\lambda_7 : 0.0 \pm 1.2$	
$\tilde{\alpha} : (0.8 \pm 16.8) \cdot 10^{-3}$	$\varsigma_u : -0.011 \pm 0.407$	$\varsigma_d : -0.096 \pm 6.22$	$\varsigma_l : -1.18 \pm 17.54$

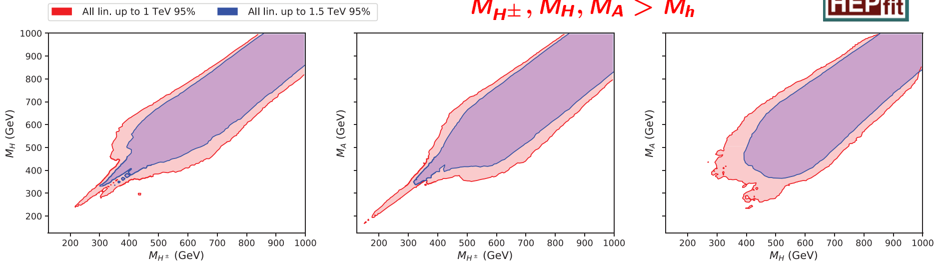
Mass limits are at 95% probability. For the other parameters, the mean value and standard deviation are shown.

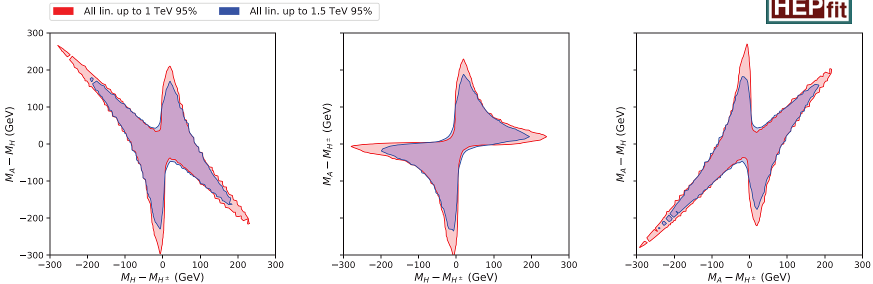
Information Criterion: $\mathrm{IC} = -2\,\overline{\log \mathcal{L}} + 4\,\sigma^2_{\log \mathcal{L}} = 83$

Global Fit

Karan-Miralles-AP, 2307.15419

$M_{H^\pm}, M_H, M_A > M_h$

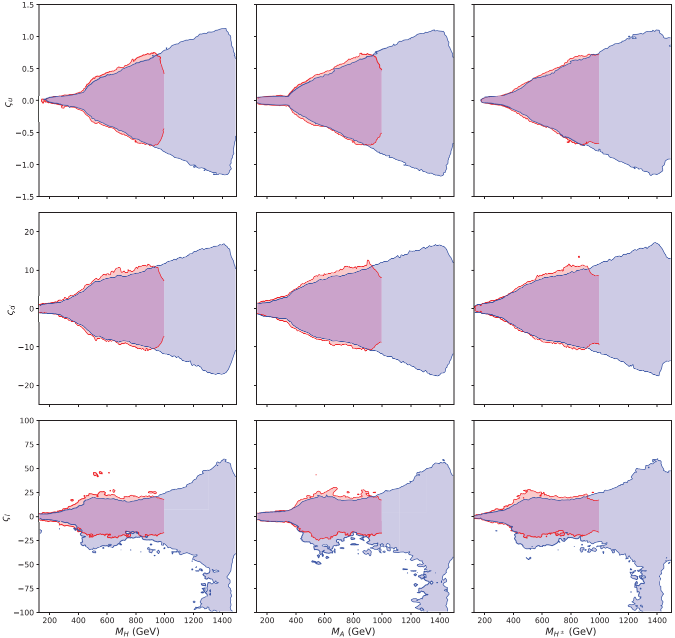




Global Fit

$M_{H^\pm}, M_H, M_A > M_h$

Karan-Miralles-AP, 2307.15419



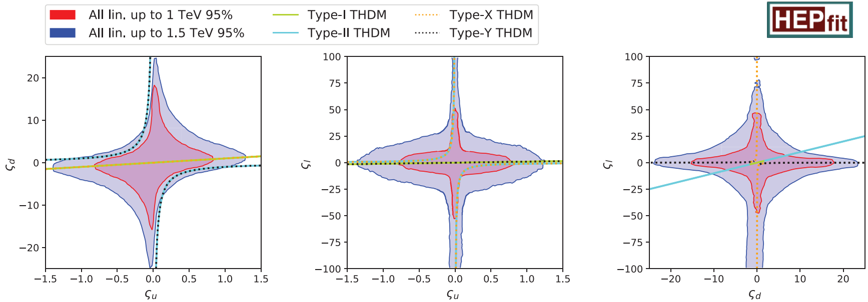
All lin. up to 1 TeV 95%

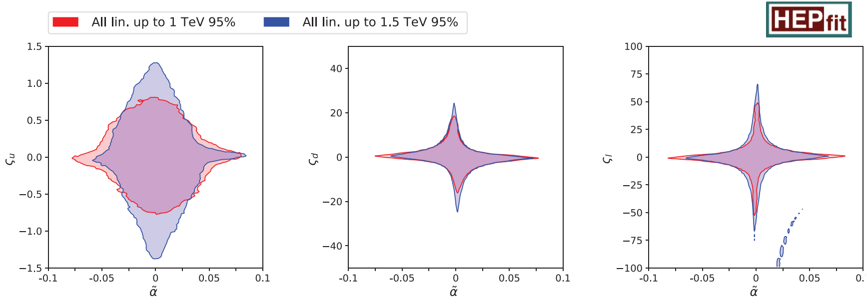
All lin. up to 1.5 TeV 95%

Global Fit

$M_{H^\pm}, M_H, M_A > M_h$

Karan-Miralles-AP, 2307.15419





Global Fit to $\mathcal{Z}_2$ Models

$M_{H^\pm}, M_H, M_A > M_h$

Coutinho-Karan-Miralles-AP, preliminary

Marginalised Individual results

	Heavy scenario – with NLO unitarity			
Type I	IC : 91.39	$M_H \geq 610.5$	$M_A \geq 667.7$	$M_{H^\pm} \geq 634.0$
	$\tan\beta$: 2.311 ± 0.866	$\beta - \alpha - \frac{\pi}{2}$: 0.014 ± 0.019	m_{12}^2 : 2.300 ± 0.817	
Type II	IC : 96.69	$M_H \geq 697.7$	$M_A \geq 733.4$	$M_{H^\pm} \geq 736.8$
	$\tan\beta$: 2.304 ± 0.716	$\beta - \alpha - \frac{\pi}{2}$: -0.010 ± 0.009	m_{12}^2 : 2.519 ± 0.696	
Type X	IC : 92.15	$M_H \geq 536.7$	$M_A \geq 581.2$	$M_{H^\pm} \geq 569.2$
	$\tan\beta$: 2.389 ± 0.750	$\beta - \alpha - \frac{\pi}{2}$: -0.009 ± 0.013	m_{12}^2 : 2.130 ± 0.822	
Type Y	IC : 97.98	$M_H \geq 680.7$	$M_A \geq 718.9$	$M_{H^\pm} \geq 731.5$
	$\tan\beta$: 2.254 ± 0.786	$\beta - \alpha - \frac{\pi}{2}$: -0.002 ± 0.010	m_{12}^2 : 2.538 ± 0.783	

$\Delta_{\rm IC} \equiv {\rm IC} - {\rm IC}_{\rm A2HDM}$

- Type I: $\Delta_{\rm IC} = 8$
- Type II: $\Delta_{\rm IC} = 13.5$
- Type X: $\Delta_{\rm IC} = 9$
- Type Y: $\Delta_{\rm IC} = 14.5$

Mass limits are at 95% probability. For the other parameters, the mean value and standard deviation are shown. m_{12}^2 is given in units of $10^5\ {\rm GeV}^2$. $\quad {\rm IC} = -2\,\overline{\log\mathcal{L}} + 4\,\sigma^2_{\log\mathcal{L}}$ (Information Criterion)

Information Criterion: $\mathrm{IC} = -2\,\overline{\log\mathcal{L}} + 4\,\sigma^2_{\log\mathcal{L}}$

- The first term yields an estimate of the predictive accuracy of the model, and the second term serves as a penalty factor for the number of parameters used in the fit
- The actual value of an IC is not of much relevance, but rather the difference between the IC values that correspond to different hypotheses
- The preference for a model against another is given according to which one has the smallest IC
- **Qualitative scale of evidence against an hypothesis:**
  - IC_i - IC_j = 0 to 2: "Not significant"
  - IC_i - IC_j = 2 to 6: "Positive"
  - IC_i - IC_j = 6 to 10: "Strong"
  - IC_i - IC_j = above 10: "Very strong"

Global Fit to $\mathcal{Z}_2$ Models

$M_{H^\pm}, M_H, M_A > M_h$

Coutinho-Karan-Miralles-AP, preliminary

Marginalised Individual results

Heavy scenario – with NLO unitarity				
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	$\tan\beta: 2.311 \pm 0.866$	$\beta - \alpha - \frac{\pi}{2}: 0.014 \pm 0.019$	$m_{12}^2: 2.300 \pm 0.817$	
Type II	$\mathrm{IC}: 96.69$	$M_H \geq 697.7$	$M_A \geq 733.4$	$M_{H^\pm} \geq 736.8$
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Type X	$\mathrm{IC}: 92.15$	$M_H \geq 536.7$	$M_A \geq 581.2$	$M_{H^\pm} \geq 569.2$
	$\tan\beta: 2.389 \pm 0.750$	$\beta - \alpha - \frac{\pi}{2}: -0.009 \pm 0.013$	$m_{12}^2: 2.130 \pm 0.822$	
Type Y	$\mathrm{IC}: 97.98$	$M_H \geq 680.7$	$M_A \geq 718.9$	$M_{H^\pm} \geq 731.5$
	$\tan\beta: 2.254 \pm 0.786$	$\beta - \alpha - \frac{\pi}{2}: -0.002 \pm 0.010$	$m_{12}^2: 2.538 \pm 0.783$	

$\Delta_{\mathrm{IC}} \equiv \mathrm{IC} - \mathrm{IC}_{\mathrm{A2HDM}}$

Type I: $\Delta_{\mathrm{IC}} = 8$

Type II: $\Delta_{\mathrm{IC}} = 13.5$

Type X: $\Delta_{\mathrm{IC}} = 9$

Type Y: $\Delta_{\mathrm{IC}} = 14.5$

(Very) Strong evidence against $\mathcal{Z}_2$ hypothesis

Mass limits are at 95% probability. For the other parameters, the mean value and standard deviation are shown. m_{12}^2 is given in units of $10^5\ \mathrm{GeV}^2$. $\mathrm{IC} = -2\,\overline{\log\mathcal{L}} + 4\,\sigma^2_{\log\mathcal{L}}$ (Information Criterion)

Global Fit

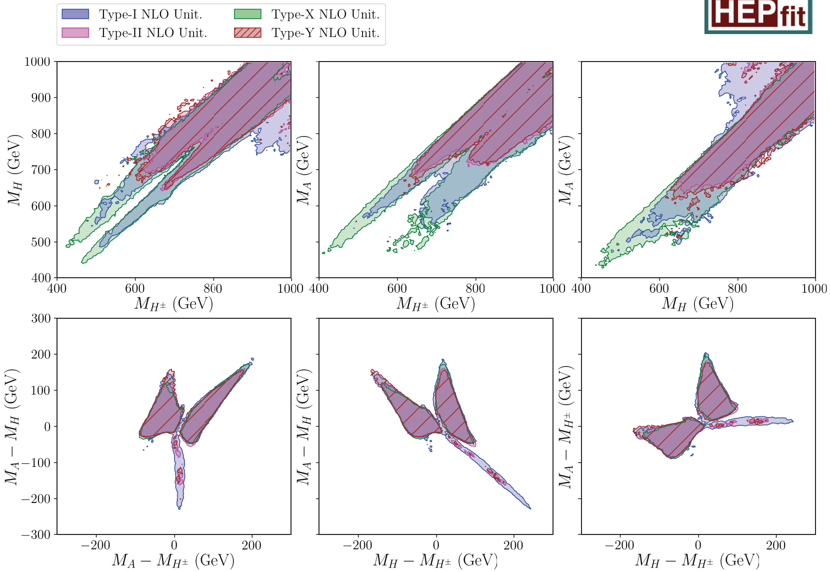
$\mathcal{Z}_2$ Models

Coutinho-Karan-Miralles-AP

(preliminary)

Heavy Scalars

95% probability regions



Is there room for Light Scalars?

Seven possible scenarios: 1 scalar (3), 2 scalars (3) or 3 scalars (1) lighter than h

Global Fit:

2 + 10 input parameters. Bayesian statistics

HEPfit

Assumption: No new sources of CP violation beyond the CKM phase

$\{\phi_{\mathrm{light}}, \phi_{\mathrm{heavy}}\} \in \{H, A, H^{\pm}\}$

$v = 246$ GeV

$M_h = (125.20 \pm 0.11)$ GeV

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

Seven possible scenarios: 1 scalar (3), 2 scalars (3) or 3 scalars (1) lighter than h

Fit Constraints:

- **Theory:** Perturbative unitarity. Scalar potential bounded from below. Stable neutral minimum
- **Experiment:** Direct searches. Higgs signal strengths. EW precision observables. Flavour data. (Left-handed) slepton searches

Oblique and CKM parameters fitted removing observables sensitive to the new scalars

Global Fit

Coutinho-Karan-Miralles-AP, 2412.14906

Marginalised Individual Results of the 7 Light Scenarios

All scenarios contain regions of parameter space compatible with current data and similar fit quality

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

(Information Criterion)

Remember: $\mathrm{IC}_{\mathrm{Heavy}} = 83$

Scenario				
$M_H \le M_h$	IC: 84.06	$65 \le M_H \le M_h$	$168 \le M_A \le 496$	$196 \le M_{H^\pm} \le 500$
	$\lambda_2:\ 4.969 \pm 1.925$	$\lambda_3:\ 3.854 \pm 2.067$	$\lambda_7: 0.005 \pm 0.382$	
	$\tilde{\alpha}: (0.8 \pm 34.0)\times 10^{-3}$	$\varsigma_u: 0.001 \pm 0.073$	$\varsigma_d: 0.017 \pm 1.716$	$\varsigma_l: -0.325 \pm 20.100$
$M_A \le M_h$	IC: 83.74	$182 \le M_H \le 500$	$69 \le M_A \le M_h$	$196 \le M_{H^\pm} \le 500$
	$\lambda_2:\ 4.609 \pm 1.891$	$\lambda_3:\ 3.817 \pm 1.973$	$\lambda_7:\ 0.006 \pm 1.164$	
	$\tilde{\alpha}: (-0.8 \pm 42.5)\times 10^{-3}$	$\varsigma_u: 0.003 \pm 0.106$	$\varsigma_d: 0.008 \pm 1.348$	$\varsigma_l: 0.105 \pm 15.380$
$M_{H^\pm} \le M_h$	IC: 88.48	$M_h \le M_H \le 500$	$M_h \le M_A \le 440$	$97 \le M_{H^\pm} \le M_h$
	$\lambda_2:\ 4.342 \pm 2.185$	$\lambda_3:\ 0.280 \pm 0.214$	$\lambda_7: 0.004 \pm 0.873$	
	$\tilde{\alpha}: (-1.7 \pm 41.9)\times 10^{-3}$	$\varsigma_u: 0.0006 \pm 0.0364$	$\varsigma_d: 0.004 \pm 0.706$	$\varsigma_l: 0.528 \pm 34.450$
$M_{H,A} \le M_h$	IC: 89.48	$89 \le M_H \le M_h$	$78 \le M_A \le M_h$	$154 \le M_{H^\pm} \le 226$
	$\lambda_2:\ 4.890 \pm 2.166$	λ_3: 1.042 ± 0.5718	$\lambda_7: 0.002 \pm 0.362$	
	$\tilde{\alpha}: (-0.6 \pm 47.4)\times 10^{-3}$	$\varsigma_u: 0.002 \pm 0.082$	$\varsigma_d: 0.007 \pm 1.620$	$\varsigma_l: 0.370 \pm 9.574$
$M_{H,H^\pm} \le M_h$	IC: 89.51	$85 \le M_H \le M_h$	$M_h \le M_A \le 534$	$95 \le M_{H^\pm} \le 120$
	$\lambda_2:\ 4.639 \pm 2.208$	$\lambda_3:\ 0.254 \pm 0.191$	$\lambda_7: 0.002 \pm 0.453$	
	$\tilde{\alpha}: (0.2 \pm 38.2)\times 10^{-3}$	$\varsigma_u: -0.0004 \pm 0.0400$	$\varsigma_d: -0.010 \pm 0.656$	$\varsigma_l: -0.603 \pm 41.45$
$M_{A,H^\pm} \le M_h$	IC: 89.35	$M_h \le M_H \le 163$ $\cup\ 211 \le M_H \le 553$	$85 \le M_A \le M_h$	$95 \le M_{H^\pm} \le 120$
	$\lambda_2:\ 4.082 \pm 2.157$	$\lambda_3:\ 0.246 \pm 0.192$	$\lambda_7:\ -0.005 \pm 0.993$	
	$\tilde{\alpha}: (-0.9 \pm 41.0)\times 10^{-3}$	$\varsigma_u: -0.0004 \pm 0.0402$	$\varsigma_d: 0.001 \pm 0.779$	$\varsigma_l: 0.261 \pm 31.090$
$M_{H,A,H^\pm} \le M_h$	IC: 89.22	$91 \le M_H \le M_h$	$83 \le M_A \le M_h$	$95 \le M_{H^\pm} \le 122$
	$\lambda_2:\ 4.740 \pm 2.232$	$\lambda_3:\ 0.275 \pm 0.201$	$\lambda_7:\ -0.002 \pm 0.463$	
	$\tilde{\alpha}: (0.4 \pm 38.3)\times 10^{-3}$	$\varsigma_u: -0.001 \pm 0.043$	$\varsigma_d: -0.005 \pm 0.613$	$\varsigma_l: -0.560 \pm 41.890$

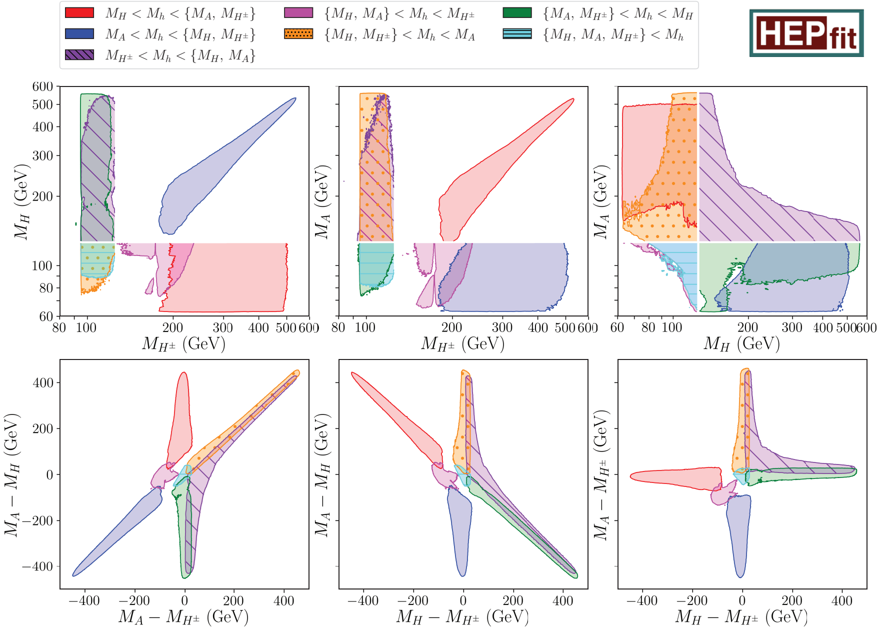
Global Fit

Coutinho-Karan-Miralles-AP

2412.14906

7 Light Scenarios

95% probability regions



Global Fit

Coutinho-Karan-Miralles-AP

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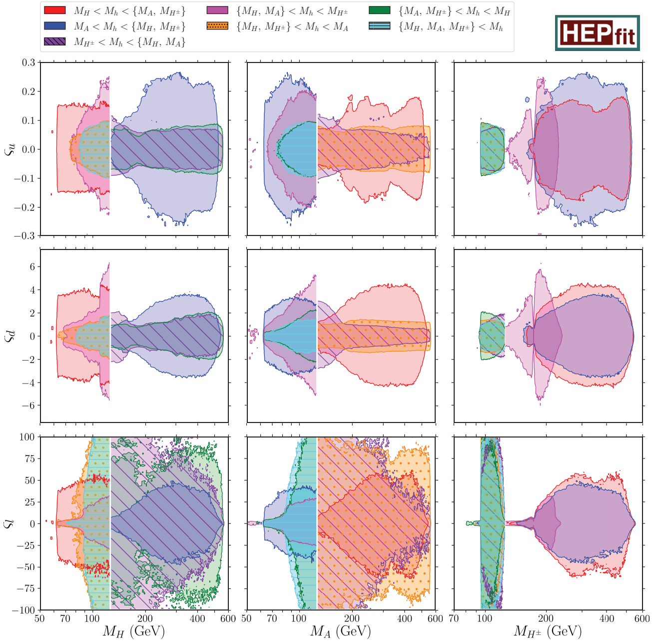
7 Light Scenarios

95% probability regions



Summary

- The **Aligned 2HDM** provides a **general phenomenological setting** (includes all $\mathcal{Z}_2$ models)
- Tree-level FCNCs absent & loop-induced quark FCNCs very constrained (MFV like)
- New sources of CP violation through $\varsigma_f, \lambda_{6,7}$ ➡ eEDM (Davila, Karan, Passemar, AP, Vale-Silva, 2504.16700)
- **Global Fits of all current data:** HEPfit
  - Bounds on Scalar Masses and Alignment Parameters are strongly correlated
  - Tight constraints on Mass Splittings
  - **Heavy-mass scenario:** $M_H, M_A, M_{H^\pm} \gtrsim 400 - 500$ GeV (95% probability)
  - Strong statistical evidence against $\mathcal{Z}_2$ hypothesis
  - **Light-mass scenarios:** Strong constraints. Ample regions of parameter space still allowed

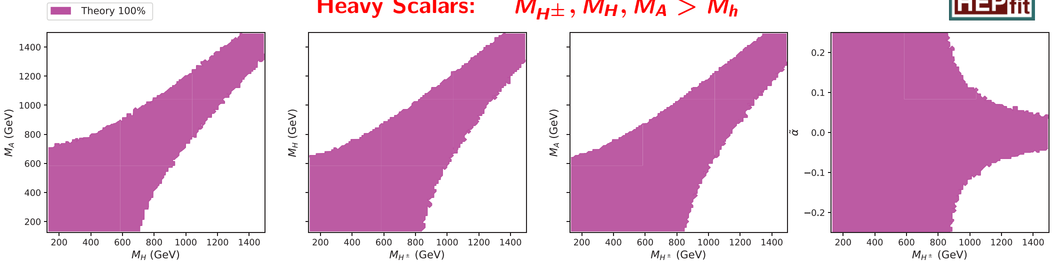
➡ **Neutral and charged scalars within (HL) LHC reach**

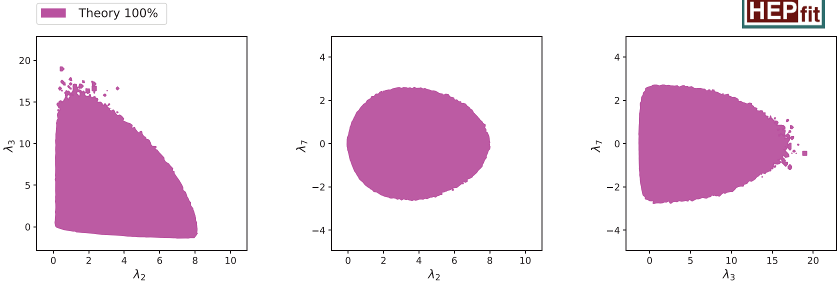
Backup

Theoretical Constraints

Karan-Miralles-AP, 2307.15419

Heavy Scalars: $M_{H^\pm}, M_H, M_A > M_h$

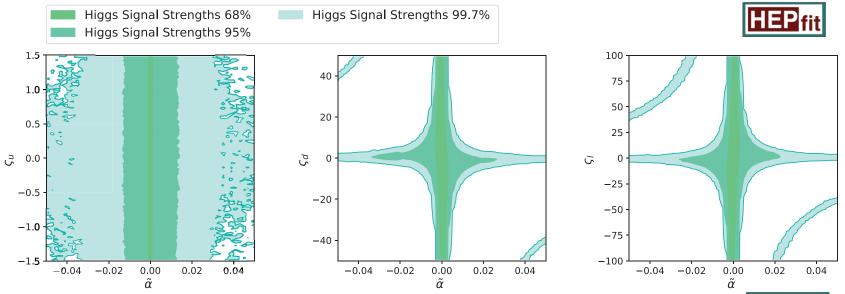




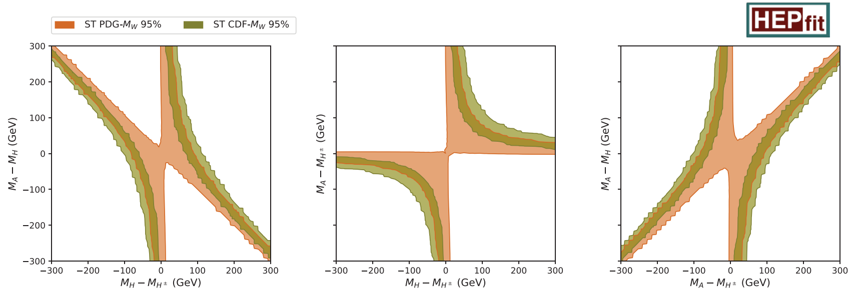
Electroweak Constraints

Karan-Miralles-AP, 2307.15419

$M_{H^\pm}, M_H, M_A > M_h$



Higgs Signal Strengths

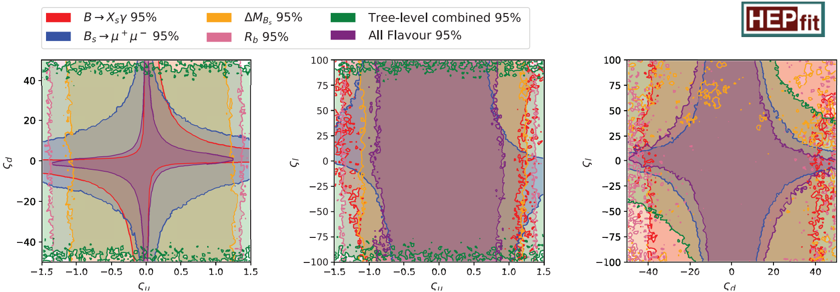


Oblique Parameters

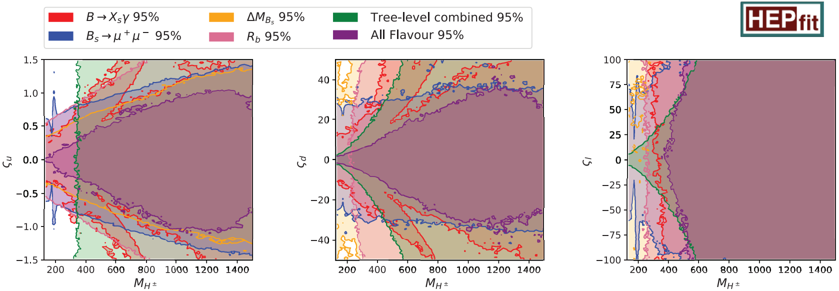
Flavour Constraints

Karan-Miralles-AP, 2307.15419

$M_{H^\pm}, M_H, M_A > M_h$



Alignment Parameters



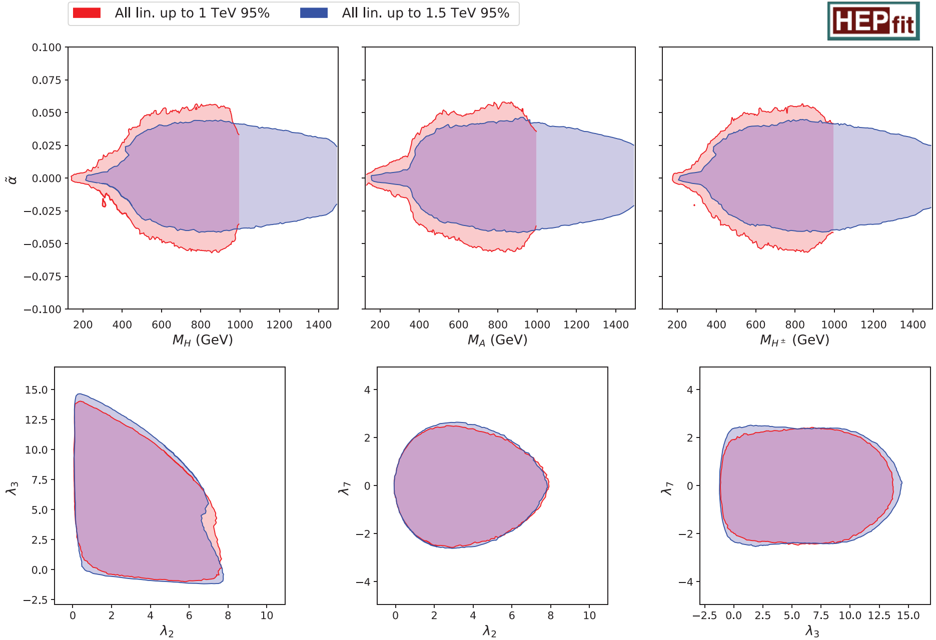
Alignment Parameters vs Masses

Global Fit

$M_{H^\pm,H,A} > M_h$

Karan-Miralles-AP

2307.15419



Global $\mathcal{Z}_2$ Fit:

$2+6$ input parameters. Bayesian statistics

HEPfit

Assumption: No new sources of CP violation beyond the CKM phase

Heavy Scalars: $M_{H^\pm}, M_H, M_A > M_h$

$v = 246$ GeV

$M_h = (125.20 \pm 0.11)$ GeV

Priors			
$M_\phi \in [M_h, 1\ \text{TeV}]$	$\tan\beta \in [0.1, 15.0]$	$(\beta - \alpha - \frac{\pi}{2}) \in [-0.1, 0.1]$	$m_{12}^2 \in [-5, 5] \times 10^5\ \text{GeV}^2$

Fit Constraints:

- **Theory:** Perturbative unitarity. Scalar potential bounded from below. Stable neutral minimum
- **Experiment:** Direct searches. Higgs signal strengths. EW precision observables. Flavour data

Oblique and CKM parameters fitted removing observables sensitive to the new scalars

Global Fit to $\mathcal{Z}_2$ Models

$M_{H^\pm}, M_H, M_A > M_h$

Coutinho-Karan-Miralles-AP, preliminary

Marginalised Individual results

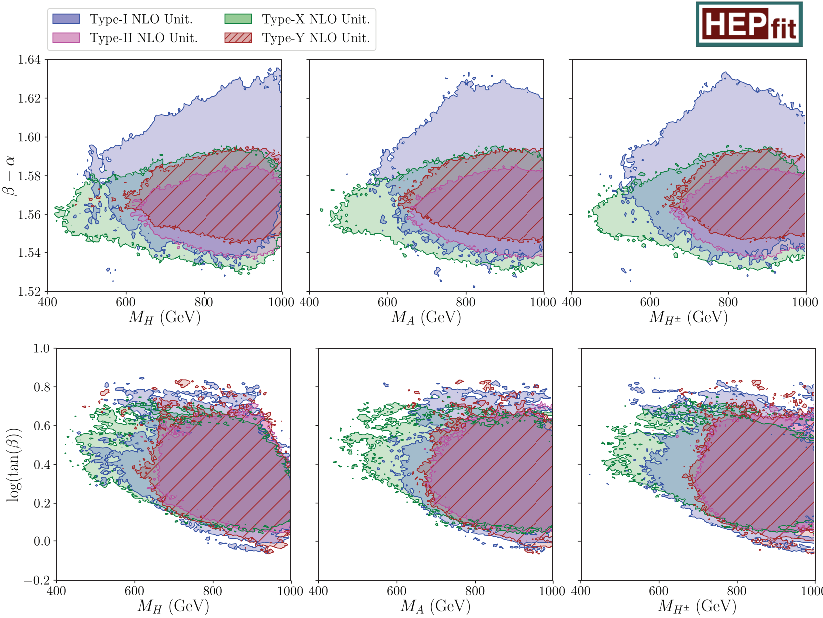
Heavy scenario – with LO unitarity				
Type I	IC : 91.18	$M_H \geq 593.6$	$M_A \geq 652.3$	$M_{H^\pm} \geq 686.8$
	$\tan\beta$: 1.754 ± 0.585	$\beta - \alpha - \frac{\pi}{2}$: 0.023 ± 0.020	m_{12}^2 : 2.347 ± 0.732	
Type II	IC : 97.68	$M_H \geq 648.1$	$M_A \geq 713.8$	$M_{H^\pm} \geq 745.9$
	$\tan\beta$: 1.905 ± 0.611	$\beta - \alpha - \frac{\pi}{2}$: -0.008 ± 0.011	m_{12}^2 : 2.532 ± 0.701	
Type X	IC : 93.58	$M_H \geq 521.9$	$M_A \geq 621.5$	$M_{H^\pm} \geq 636.8$
	$\tan\beta$: 1.933 ± 0.644	$\beta - \alpha - \frac{\pi}{2}$: -0.005 ± 0.015	m_{12}^2 : 2.201 ± 0.809	
Type Y	IC : 98.37	$M_H \geq 647.6$	$M_A \geq 716.1$	$M_{H^\pm} \geq 753.1$
	$\tan\beta$: 1.747 ± 0.534	$\beta - \alpha - \frac{\pi}{2}$: 0.002 ± 0.011	m_{12}^2 : 2.569 ± 0.690	

Mass limits are at 95% probability. For the other parameters, the mean value and standard deviation are shown. m_{12}^2 is given in units of 10^5 GeV^2

Global Fit
$\mathcal{Z}_2$ Models

Coutinho-Karan-Miralles-AP

(preliminary)



Heavy Scalars

95% probability regions

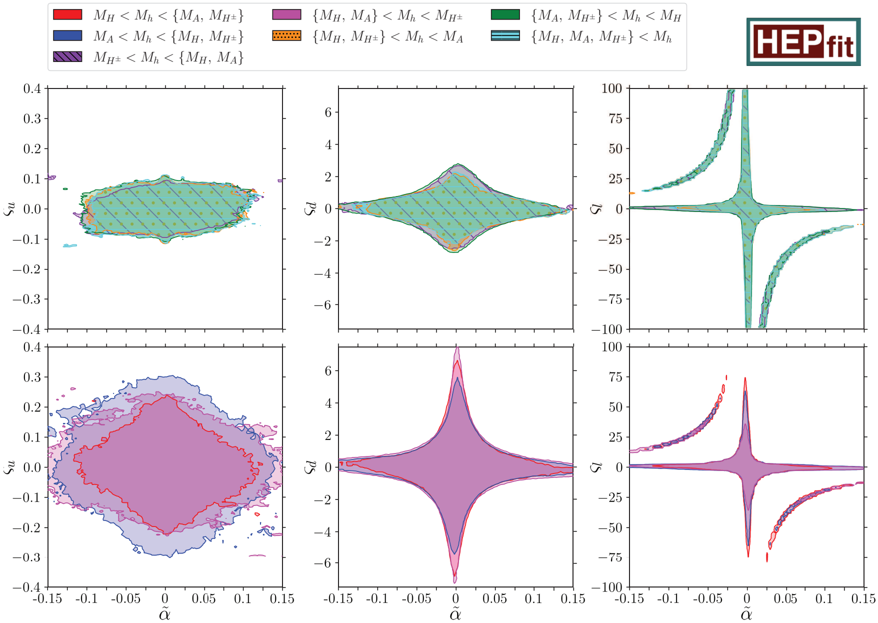
Global Fit

Coutinho-Karan-Miralles-AP

2412.14906

7 Light Scenarios

95% probability regions



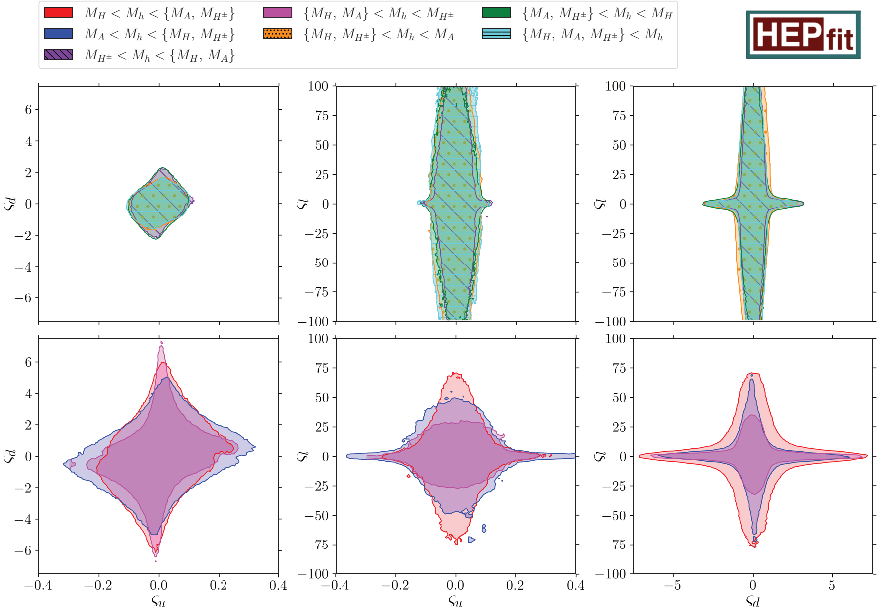
Global Fit

Coutinho-Karan-Miralles-AP

2412.14906

7 Light Scenarios

95% probability regions



Global Fit

Coutinho-Karan-Miralles-AP

2412.14906

7 Light Scenarios

95% probability regions