Aligned two Higgs doublet model and the global fits

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Based on: **Phys.Rev.D 109 (2024) 3, 3**

8th Red LHC Workshop
Universidad Complutense de Madrid, Spain
28th - 30th May, 2024

Motivation

➠ **2HDM:** SM + another scalar doublet.

➠ **Prospects:** New sources of CP violation, Axion-like phenomenology, Dark matter aspects, Electroweak Baryogenesis, Stability of scalar potential till Planck scale, EFT for SUSY, etc.

➠ **Problems:** **FCNC**

➠ **Solutions:** 1) Additional $\mathcal{Z}_2$ symmetry, 2) **A2HDM**

➠ **A2HDM:** The Yukawa matrices corresponding to two scalars are proportional to each other.

➠ **Advantages:** 1) More generic framework to study 2HDM.
2) There could be additional sources of CP violation.
3) Rich phenomenology.

Pich, Tuzon PRD 80 (2009) 091702; Ferreira, Lavoura, Silva PLB 688 (2010) 341; Jung, Pich, Tuzon JHEP 11 (2010) 003; Braeuninger, Ibarra, Simonetto PLB 692 (2010) 189; Bijnens, Lu, Rathsman JHEP 05 (2012) 118; Li, Lu, Pich JHEP 06 (2014) 022; Abbas, et al. JHEP 06 (2015) 005; Botella, et al. EPJC 75 (2015) 286; Gori, Haber, Santos JHEP 06 (2017) 110; Kanemura, Mondal, Yagyu JHEP 02 (2023) 237; etc...

The Model: A2HDM

Scalar Potential

$$\phi_a : \langle 0|\, \phi_a^T \,|0\rangle = (0, v_a e^{i\theta_a}) \quad a \in \{1, 2\}$$

Global $SU(2)$ $\Longrightarrow$ "Higgs basis"

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

Goldstone: G^+, G^0 — Charged: H^+ — CP-even: S_1, S_2 — CP-odd: S_3

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

✏ **Scalar Potential:**

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

✏ **Gauge-Higgs Coupling:**

$$g_{hVV} = \cos\tilde{\alpha}\; g_{hVV}^{SM}\,, \quad g_{HVV} = -\sin\tilde{\alpha}\; g_{hVV}^{SM}\,, \quad g_{AVV} = 0\,, \quad VV \equiv (W^+W^-,\, ZZ)$$

Independent parameters for scalar potential

- ✯ **Parameters:** $\mu_1, \mu_2, \boldsymbol{\mu_3}, \lambda_{1,2,3,4}, \boldsymbol{\lambda_{5,6,7}} \Longrightarrow$ 14 parameters.
- ✯ **Minimization Condition:** $v^2 = -\dfrac{2\mu_1}{\lambda_1} = -\dfrac{2\mu_3}{\lambda_6}$
- ✯ **Independent parameters:** $v,\ \mu_2,\ \lambda_{1,2,3,4},\ |\lambda_{5,6,7}|$, two relative phases between $\lambda_{5,6,7}$.
  $\Longrightarrow$ 11 parameters.

  - ❃ **CP conserving case:** 9 independent parameters.
  - ❃ **Masses:**

$$M^2_{H\pm} = \mu_2 + \tfrac{\lambda_3}{2}\, v^2\,, \qquad M^2_{h,H} = \tfrac{1}{2}\,(\Sigma \mp \Delta), \qquad M^2_A = M^2_{H\pm} + \tfrac{v^2}{2}\,(\lambda_4 - \lambda_5)\,,$$

$$\text{with} \quad \Sigma = M^2_{H\pm} + \left(\lambda_1 + \tfrac{\lambda_4}{2} + \tfrac{\lambda_5}{2}\right) v^2 \quad \text{and} \quad \Delta = \sqrt{\left(\Sigma - 2\lambda_1 v^2\right)^2 + 4\,\lambda_6^2\, v^4}\,.$$

  - ❃ **Mixing angle:** $\tan\tilde{\alpha} = \dfrac{M_h^2 - v^2\,\lambda_1}{v^2\,\lambda_6} = \dfrac{v^2\,\lambda_6}{v^2\,\lambda_1 - M_H^2}\,.$
  - ❃ **Parameter set:** v, M_h, $M_{H\pm}$, M_H, M_A, $\tilde{\alpha}$, λ_2, λ_3 and λ_7 $\Longrightarrow$ 7 parameters.

Fermionic interaction

- **Yukawa interaction:**

$$
\begin{aligned}
-\mathcal{L}_Y = & \left(1+\frac{S_1}{v}\right)\left\{\bar{u}_L\, M_u\, u_R + \bar{d}_L\, M_d\, d_R + \bar{\ell}_L\, M_\ell\, \ell_R\right\} \\
& + \frac{1}{v}\,(S_2 + iS_3)\left\{\bar{u}_L\, Y_u\, u_R + \bar{d}_L\, Y_d\, d_R + \bar{\ell}_L\, Y_\ell\, \ell_R\right\} \\
& + \frac{\sqrt{2}}{v}\, H^+ \left\{\bar{u}_L\, V\, Y_d\, d_R - \bar{u}_R\, Y_u^\dagger\, V\, d_L + \bar{\nu}_L\, Y_\ell\, \ell_R\right\} + \mathrm{h.c.}\,,
\end{aligned}
$$

- **Alignment:** $Y_u = \varsigma_u^*\, M_u$ and $Y_{d,\ell} = \varsigma_{d,\ell}\, M_{d,\ell}\,,$

$$
-\mathcal{L}_Y = \sum_{i,f}\left(\frac{y_f^{\varphi_i^0}}{v}\right)\varphi_i^0\left[\bar{f}M_f\mathcal{P}_R f\right] + \left(\frac{\sqrt{2}}{v}\right)H^+\left[\bar{u}\left\{\varsigma_d V M_d \mathcal{P}_R - \varsigma_u M_u^\dagger V \mathcal{P}_L\right\}d + \varsigma_\ell\,\bar{\nu}M_\ell\mathcal{P}_R\ell\right] + \mathrm{h.c.}
$$

$$
\begin{aligned}
y_u^H &= -\sin\tilde{\alpha} + \varsigma_u^*\,\cos\tilde{\alpha}\,, & y_u^h &= \cos\tilde{\alpha} + \varsigma_u^*\,\sin\tilde{\alpha}\,, & y_u^A &= -i\varsigma_u^*\,, \\
y_{d,\ell}^H &= -\sin\tilde{\alpha} + \varsigma_{d,\ell}\,\cos\tilde{\alpha}\,, & y_{d,\ell}^h &= \cos\tilde{\alpha} + \varsigma_{d,\ell}\,\sin\tilde{\alpha}\,, & y_{d,\ell}^A &= i\varsigma_{d,\ell}.
\end{aligned}
$$

Type I: $\varsigma_u = \varsigma_d = \varsigma_\ell = \cot\beta,$ **Type II:** $\varsigma_u = -\frac{1}{\varsigma_d} = -\frac{1}{\varsigma_\ell} = \cot\beta\,,$ **Inert:** $\varsigma_u = \varsigma_d = \varsigma_\ell = 0\,,$

Type X: $\varsigma_u = \varsigma_d = -\frac{1}{\varsigma_\ell} = \cot\beta$ and **Type Y:** $\varsigma_u = -\frac{1}{\varsigma_d} = \varsigma_\ell = \cot\beta\,.$

Constraints and Fits

Fit Set Up

Package: `HEPfit` (Bayesian approach)

<table>
<tr><th colspan="12">Priors</th></tr>
<tr><td colspan="4">$M_{H^\pm} \subset$ [0.125, 1.0 (1.5)] TeV</td><td colspan="4">$M_H \subset$ [0.125, 1.0 (1.5)] TeV</td><td colspan="4">$M_A \subset$ [0.125, 1.0 (1.5)] TeV</td></tr>
<tr><td colspan="4">$\lambda_2 \subset$ [0, 11]</td><td colspan="4">$\lambda_3 \subset$ [-3, 17]</td><td colspan="4">$\lambda_7 \subset$ [-5, 5]</td></tr>
<tr><td colspan="3">$\tilde{\alpha} \subset$ [-0.16, 0.16]</td><td colspan="3">$\varsigma_u \subset$ [-1.5, 1.5]</td><td colspan="3">$\varsigma_d \subset$ [-50, 50]</td><td colspan="3">$\varsigma_\ell \subset$ [-100, 100]</td></tr>
</table>

- Linear prior on masses.
- Ranges for quartic couplings and alignment parameters are chosen from theoretical constraints.
- Range of $\tilde{\alpha}$ is chosen to incorporate the 5σ region.
- Taken the experimental values of CKM matrix element carefully and fitted the Wolfenstein parameters.

1. Theoretical Constraints

Stability of Scalar Potential

- **Z_2-sym cases:** $\lambda_{1,2} > 0, \quad \lambda_3 + \sqrt{\lambda_1\lambda_2} > 0, \quad \lambda_3 + \lambda_4 - |\lambda_5| + \sqrt{\lambda_1\lambda_2} > 0.$

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

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

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

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

✓ ***The necessary & sufficient conditions for bounded below potential :***

1. All the eigenvalues ($\Lambda_{0,1,2,3}$) of $\Lambda^\mu{}_\nu$ are real.
2. $\Lambda_0 > 0$ with $\Lambda_0 > \Lambda_i\ \forall\, i \in \{1,2,3\}$.

For several necessary conditions:
H. Bahl, et al., JHEP 03 (2023) 165

- **Absolute stability:** $D = Det[\xi\,\mathbb{I}_4 - \Lambda^\mu{}_\nu] = -\prod_{k=0}^{3}(\xi - \Lambda_k)$ with $\xi = \frac{m_{H^\pm}^2}{v^2}$.

✓ ***The conditions for global minimum :*** 1) $D > 0$, or 2) $D < 0$ with $\xi > \Lambda_0$.

Ivanov, PRD 75 (2007) 035001; Ivanov and Silva, PRD 92 (2015) 055017

LO Perturbativity

❍ **Tree-level partial-wave amplitudes:** $(\mathcal{A}_0)_{i,f} = \frac{1}{16\pi s}\int_{-s}^{0} dt\ \mathcal{M}_{i\to f}(s,t)$

❍ **Eigenvalues in the j th partial wave:** $(a_0^j)^2 \leq 1/4$

❍ There are fourteen neutral, eight single-charged and three doubly-charged two-body scalar $2 \to 2$ scattering states. $\Longrightarrow$ $a_0^{(0,+1,+2)} = \frac{1}{16\pi}\left(\oplus \{X_{Y,\sigma}\}\right)$

$$X_{(1,0)} = \lambda_3 - \lambda_4\,,$$

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

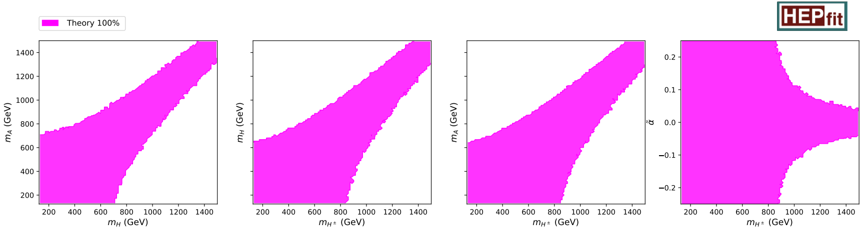
$$X_{(0,0)} = \begin{pmatrix} 3\lambda_1 & 2\lambda_3+\lambda_4 & 3\lambda_6 & 3\lambda_6^* \\ 2\lambda_3+\lambda_4 & 3\lambda_2 & 3\lambda_7 & 3\lambda_7^* \\ 3\lambda_6^* & 3\lambda_7^* & \lambda_3+2\lambda_4 & 3\lambda_5^* \\ 3\lambda_6 & 3\lambda_7 & 3\lambda_5 & \lambda_3+2\lambda_4 \end{pmatrix}.$$

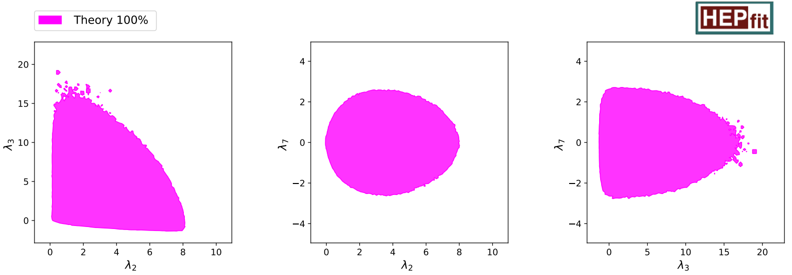
❍ **Eigenvalues of $X_{(a,b)}$:** $|e_i| < 8\pi$

Ginzburg, Ivanov, PRD 72 (2005) 115010; H. Bahl, et al., JHEP 03 (2023) 165

❍ **Charged scalar coupling to fermions:** $\sqrt{2}\,|\varsigma_f| m_f/v < 1$

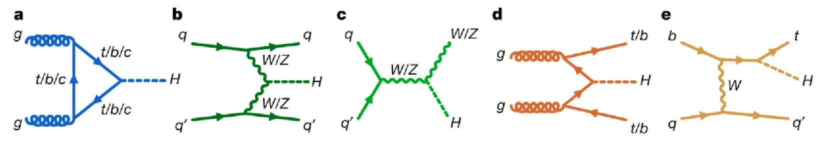
Stability & Perturbativity Fits



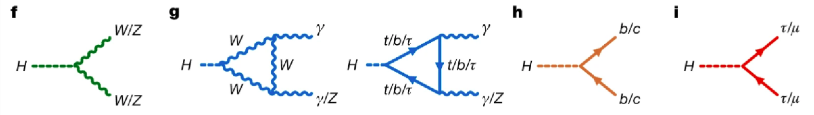


2. Signal Strength

Signal Strength



SM Higgs Production channels at LHC



SM Higgs Decay channels

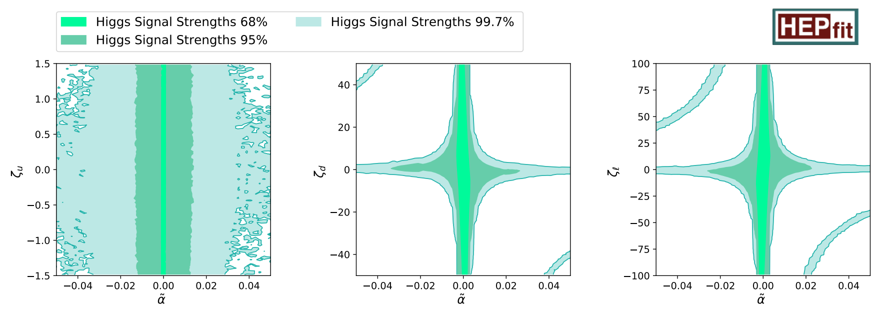
ATLAS, Nature 607(2022) 52–59

Signal strength: $\mu_{XY} = \dfrac{\sigma(pp \to h)\; Br(h \to XY)}{[\sigma(pp \to h)\; Br(h \to XY)]_{SM}}$

Modifications: $hVV \to \cos\alpha$ and $hff \to \varsigma_{u,d,l}$

Signal Strength Fits

Data: ATLAS and CMS (8 TeV and 13 TeV)



3. EWPO

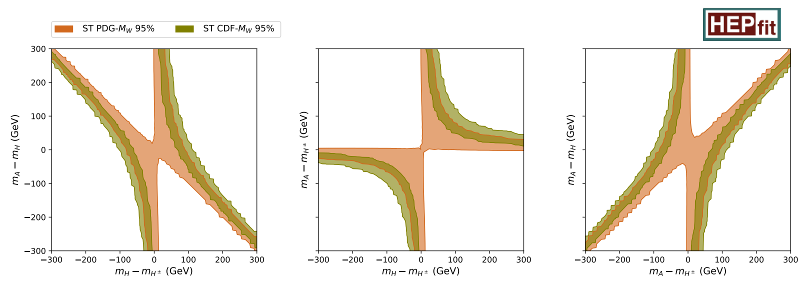
EWPO

✤ We remove $R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to hadrons)}$ from the global fit of EW precision data to fit S,T,U.

✤ Fitting with S,T,U and fitting with S,T (assuming negligible U) provide similar results.

✤ M_W (PDG): PDG, PTEP 2022 (2022) 083C01

✤ M_W (CDF): CDF, Science 376 (2022) 170; Blas, et al. PRL 129 (2022) 271801



4. Flavour Observables

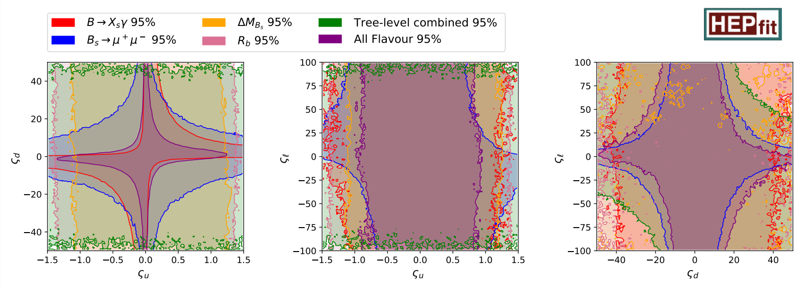
Flavour Observables

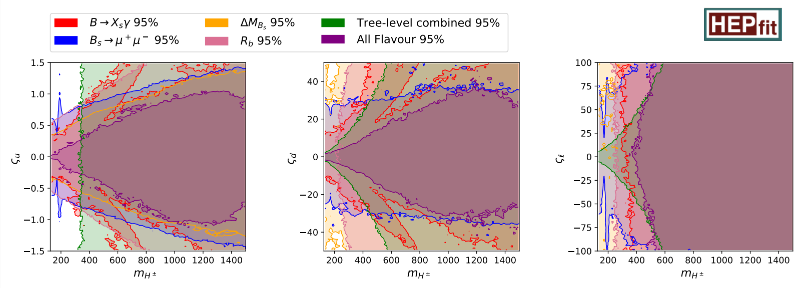
- **Loop Processes:** ΔM_{B_s}, $B \to X_s\gamma$ and $B_s \to \mu\mu$
- **Tree level Processes:** $B \to \tau\nu$, $D_{(s)} \to \tau\nu$, $D_{(s)} \to \mu\nu$, $\frac{\Gamma(K\to\mu\nu)}{\Gamma(\pi\to\mu\nu)}$, $\frac{\Gamma(\tau\to K\nu)}{\Gamma(\tau\to\pi\nu)}$
- **Anomaly:** $(g-2)_\mu$ [Not included in global fits]

Data: PDG PDG, PTEP 2022 (2022) 083C01

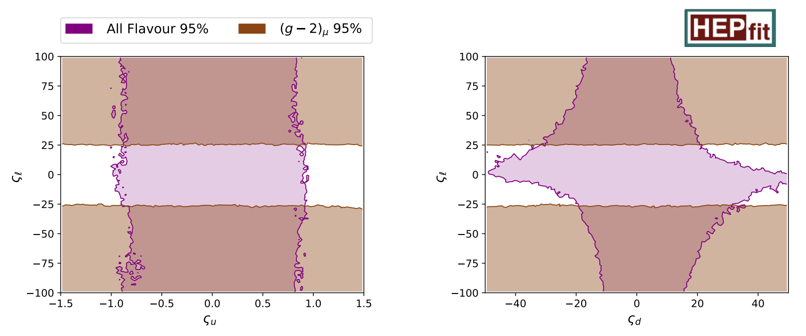
We fit the CKM parameters form the observables that are not contaminated by the presence of additional scalars.

Flavour Observables





Flavour Observables: muon g-2



5. Direct Searches

Direct Searches

- $pp \to \phi_i \to hh$
- $pp \to \phi_i \to hZ$
- $pp \to \phi_i \to \phi_j Z$
- $pp \to \phi_i \to VV$
- $pp \to \phi_i \to Z\gamma$
- $pp \to \phi_i \to f\bar{f}$
- $pp \to H^+ \to f'\bar{f}$

Data: CMS & ATLAS 8 TeV and 13 TeV

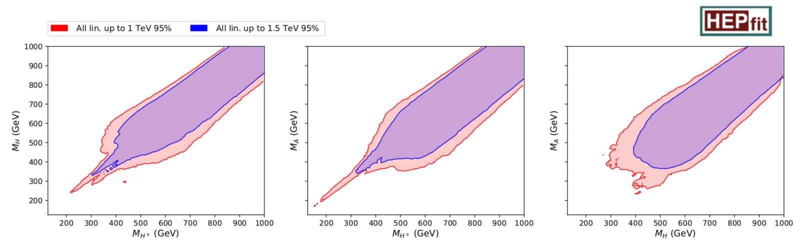
Scalar production: cern twiki

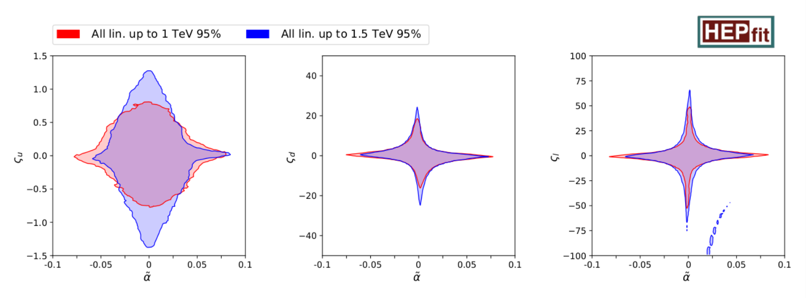
Scalar Decay: HDECAY

Pseudoscalar: Madgraph5_aMC@NLO, HIGLU, HDECAY

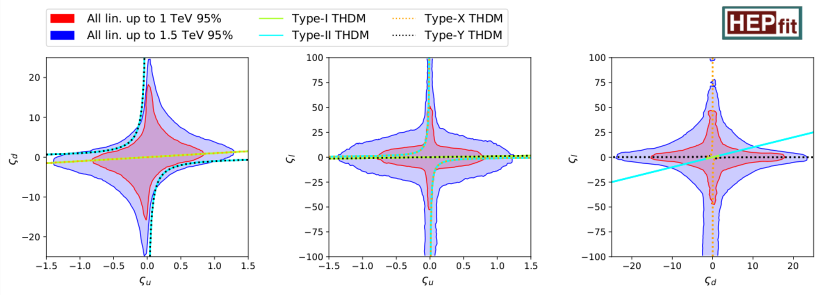
Global Fits

Global Fits


All lin. up to 1 TeV 95%
All lin. up to 1.5 TeV 95%
HEPfit
M_H (GeV)
$M_{H^\pm}$ (GeV)
M_A (GeV)
$M_{H^\pm}$ (GeV)
M_A (GeV)
M_H (GeV)


All lin. up to 1 TeV 95%
All lin. up to 1.5 TeV 95%
HEPfit
ς_u
$\tilde{\alpha}$
ς_d
$\tilde{\alpha}$
ς_l
$\tilde{\alpha}$

Global Fits



Marginalised Individual results			
Masses up to 1 TeV			
$M_{H^\pm} \geq 390$ GeV (95%)	$M_H \geq 410$ GeV (95%)	$M_A \geq 370$ GeV (95%)	
λ_2: 3.2 ± 1.9	λ_3: 5.9 ± 3.5	λ_7 : 0.0 ± 1.1	
$\tilde{\alpha}$: $(0.05 \pm 21.0) \cdot 10^{-3}$	ς_u : 0.006 ± 0.257	ς_d : 0.12 ± 4.12	ς_ℓ : -0.39 ± 11.69
Masses up to 1.5 TeV			
$M_{H^\pm} \geq 480$ GeV (95%)	$M_H \geq 490$ GeV (95%)	$M_A \geq 480$ GeV (95%)	
λ_2: 3.2 ± 1.9	λ_3: 5.9 ± 3.8	λ_7 : 0.0 ± 1.2	
$\tilde{\alpha}$: $(0.8 \pm 16.8) \cdot 10^{-3}$	ς_u : -0.011 ± 0.407	ς_d : -0.096 ± 6.22	ς_ℓ : -1.18 ± 17.54

Thank you for your attention!!