Aligned Two Higgs Doublet Model and the Global Fits

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In Collaboration With: Victor Miralles and Antonio Pich

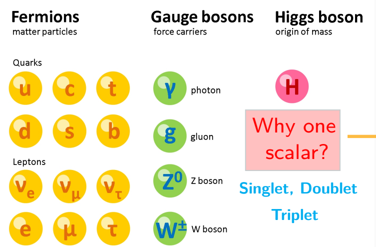
ArXiv: 2307.15419

Updated version of Eberhardt, Peñuelas, Pich JHEP 05 (2021) 005.

IFIC (CSIC – Universitat de València)

EPS-HEP2023, Universität Hamburg
23rd August, 2023

Motivation



Why one scalar?

Singlet, Doublet

Triplet

⟶ $$\rho = \frac{\sum_i c_i \langle \phi_i^0 \rangle^2 [T_i(T_i+1) - Y_i^2]}{2 \sum_i \langle \phi_i^0 \rangle^2 Y_i^2}$$ ⟶ 2HDM

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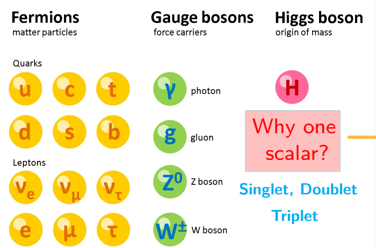

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➠ **Prospects:** New sources of CP violation, Axion-like phenomenology, Dark matter aspects, Electroweak Baryogenesis, Stability of scalar potential till Planck scale, EFT for SUSY, etc.

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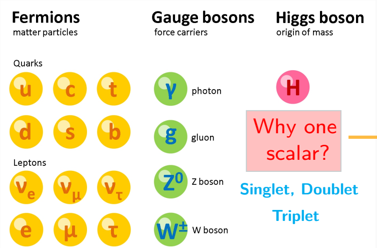

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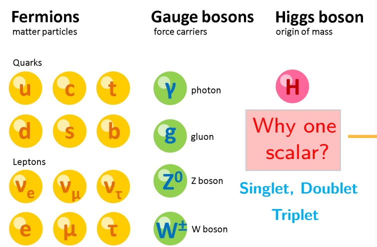

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➠ **Problems:** **FCNC**

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

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...

Scalar Potential

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

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

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

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CP-odd

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Goldstone: G^+, G^0

Charged: H^+

CP-even: S_1, S_2

CP-odd: S_3

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Goldstone (G^+, G^0)

Charged (H^+)

CP-even (S_1, S_2)

CP-odd (S_3)

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

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✏ **Scalar Potential:**

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

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✏ **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:** $\mu_1, \mu_2, \boldsymbol{\mu_3}, \lambda_{1,2,3,4}, \boldsymbol{\lambda_{5,6,7}}$

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- ✯ **Independent parameters:** v, μ_2, $\lambda_{1,2,3,4}$, $|\lambda_{5,6,7}|$, two relative phases between $\lambda_{5,6,7}$.
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  - ❋ **Masses:**

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

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

  - ❋ **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:** $v,\ M_h,\ M_{H^\pm},\ M_H,\ M_A,\ \tilde{\alpha},\ \lambda_2,\ \lambda_3$ and λ_7

Independent parameters for scalar potential

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

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- **Mixing angle:** $\tan\tilde{\alpha} = \frac{M_h^2 - v^2\lambda_1}{v^2\lambda_6} = \frac{v^2\lambda_6}{v^2\lambda_1 - M_H^2}$.

- **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:

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

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

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

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

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

Fit Set Up

Package: `HEPfit` (Bayesian approach)

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]	$\varsigma_\ell \subset$ [-100, 100]

- 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.

Theoretical Constraints: Stability

- **Bounded from below:**

$$V = -\, \mathtt{M}_\mu\, \mathtt{r}^\mu + \frac{1}{2}\, \Lambda^\mu{}_\nu\, \mathtt{r}_\mu\, \mathtt{r}^\nu\ , \text{ where,}$$

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

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

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

✓ 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:**

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

✓ 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

Theoretical Constraints: Perturbativity

❍ **Tree-level partial-wave amplitudes:** $$(a_0)_{i,f} = \frac{1}{16\pi s}\int_{-s}^{0} dt\, \mathcal{M}_{i\to f}(s,t)$$

❍ **Eigenvalue in the j th partial wave:** $$(a_j^0)^2 \leq \frac{1}{4}$$

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

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

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

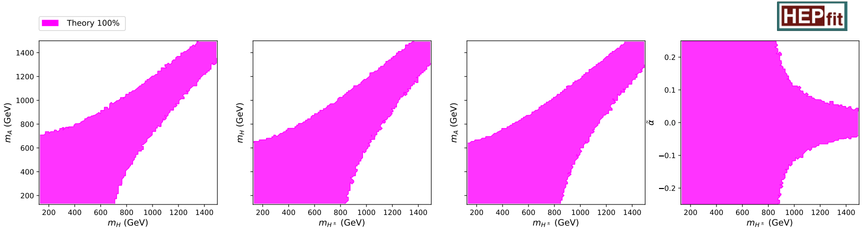
$$X_{(0,0)} = \begin{pmatrix} 3\lambda_1 & 2\lambda_3+\lambda_4 & 3\lambda_6 & 3\lambda_6^* \\ 2\lambda_3+\lambda_4 & 3\lambda_2 & 3\lambda_7 & 3\lambda_7^* \\ 3\lambda_6^* & 3\lambda_7^* & \lambda_3+2\lambda_4 & 3\lambda_5^* \\ 3\lambda_6 & 3\lambda_7 & 3\lambda_5 & \lambda_3+2\lambda_4 \end{pmatrix}.$$

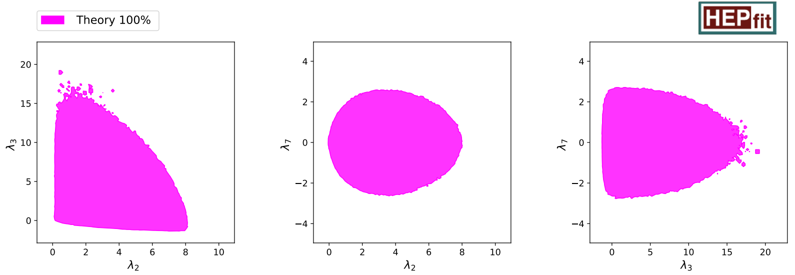
❍ **Eigenvalue:** $|e_i| < 8\pi$.

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

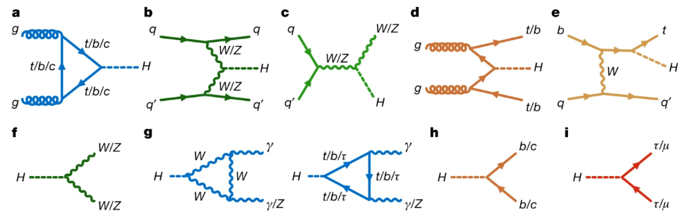
❍ **Charged scalar coupling to fermions:** $\sqrt{2}\,|\varsigma_f|m_f/v < 1$

Theoretical Constraints: Fit Results

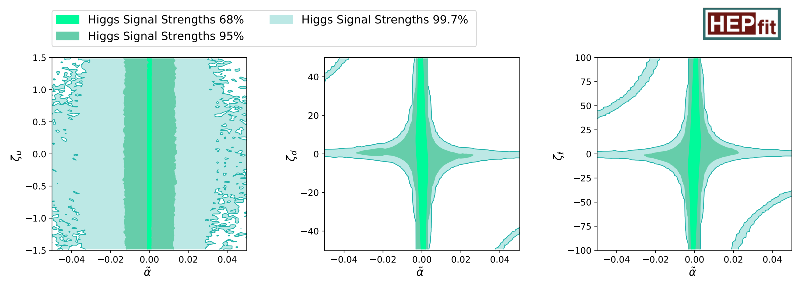




Signal Strength



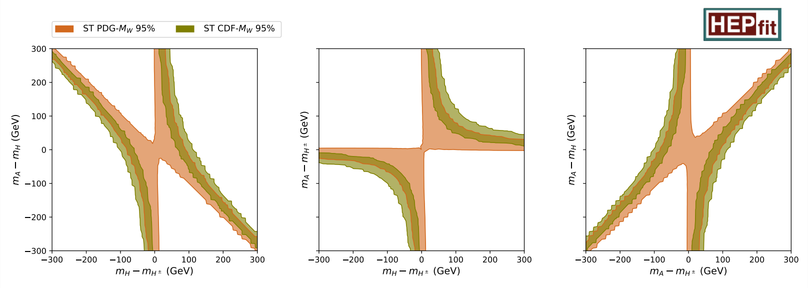
ATLAS, Nature 607(2022) 52–59



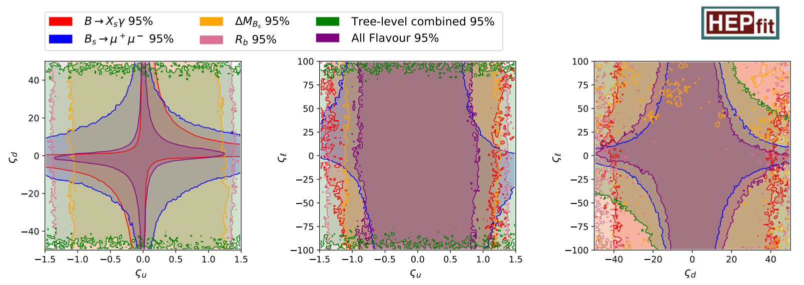
Data: ATLAS and CMS

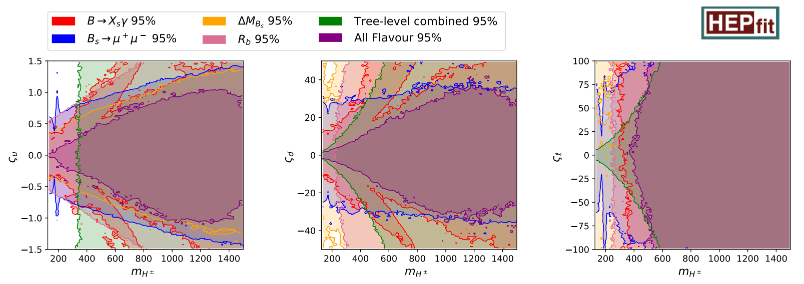
EWPO

✤ M_W (PDG): PDG, PTEP 2022 (2022) 083C01
✤ M_W (CDF): CDF, Science 376 (2022) 170; Blas, et al. PRL 129 (2022) 271801



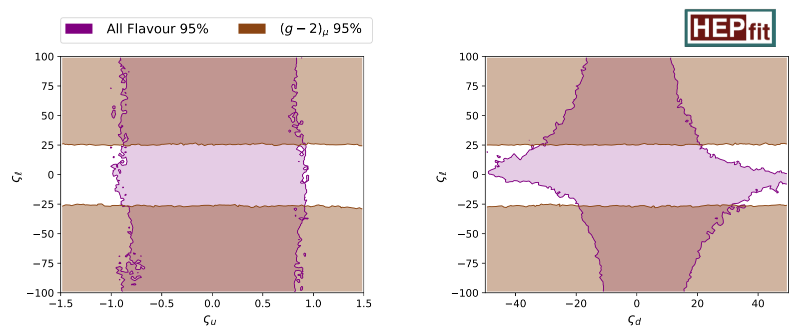
Flavour Observables





ArXiv: 2307.15419

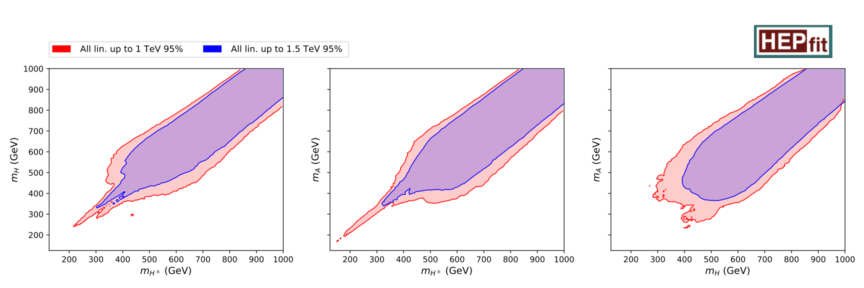
Flavour Observables: muon g-2



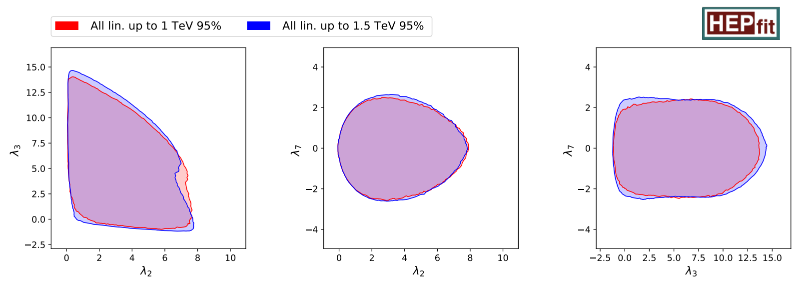
Global Fits

- Theoretical Constraints
- EWPO
- Flavour Observables
- Higgs Signal Strength
- Direct Searches

Global Fits

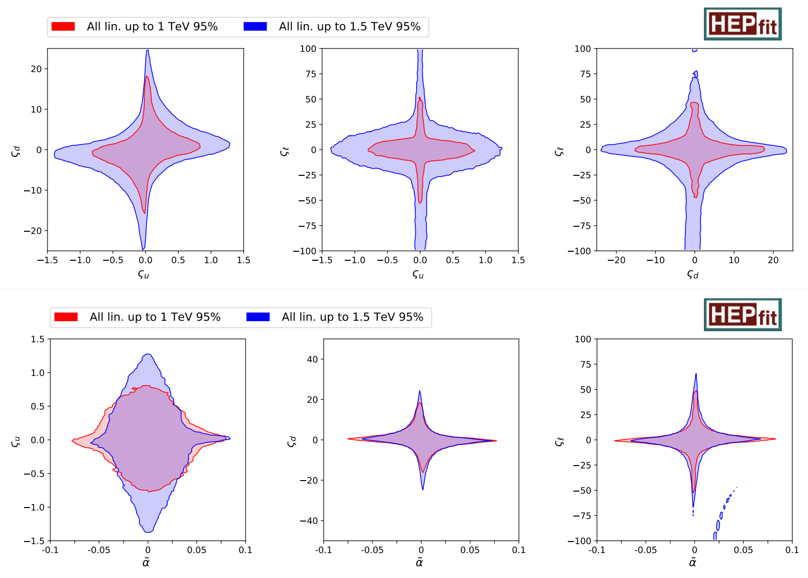


All lin. up to 1 TeV 95%
All lin. up to 1.5 TeV 95%
HEPfit
m_H (GeV)
$m_{H^\pm}$ (GeV)
m_A (GeV)
$m_{H^\pm}$ (GeV)
m_A (GeV)
m_H (GeV)



All lin. up to 1 TeV 95%
All lin. up to 1.5 TeV 95%
HEPfit
λ_3
λ_2
λ_7
λ_2
λ_7
λ_3

Global Fits

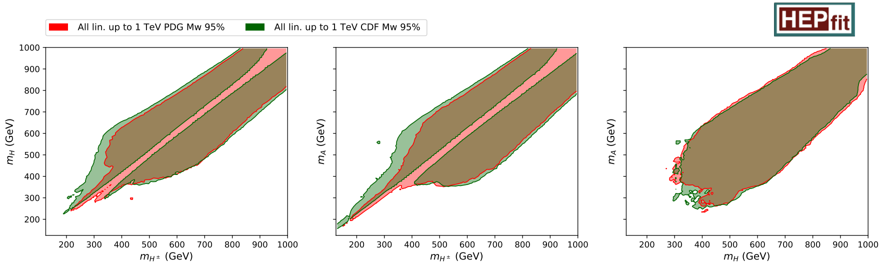


All lin. up to 1 TeV 95%
All lin. up to 1.5 TeV 95%
HEPfit
ς_u
ς_d
ς_ℓ
$\tilde{\alpha}$

Fit Results

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

CDF measurement of M_W



Summary

✍ We fitted total 10 parameters: 3 masses, 3 quartic couplings, 3 alignment parameters and one angle.

✍ The lower limit on masses are constrained from direct searches and flavour observables.

✍ Mass splittings are constrained by EWPO and theoretical bounds.

✍ Quartic couplings are bounded by theoretical constraints.

✍ Alignment parameters are constrained by direct searches and flavour observables.

✍ Mixing angle is restricted by Higgs signal strength.

✍ We also studied the effects of $(g-2)_\mu$ and CDF measurement of M_W, but did not include into the fit. However, parameter-space of A2HDM has the flexibility to accommodate both.

Back up

V_{ud}: $0^+ \rightarrow 0^+$ nuclear β decay
V_{ud}: Semi-leptonic decays of kaons to electrons (not muons). Cabibbo Anomaly $\rightarrow$ Double the error.

V_{cd}: Semileptonic (Not the leptonic) decays of D and neutrino scattering.
V_{cs}: Semileptonic (Not the leptonic) decays of D_s

V_{ub}: PDG
V_{cb}: PDG

V_{td}/V_{ts}: PDG; The ratio kills the NP contribution in $B - \bar{B}$ mixing.