The Aligned Two-Higgs-Doublet Model

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1. From the 2HDM to the Aligned 2HDM

2. Phenomenology
   - Tree-level and loop-induced processes
   - CP asymmetries
   - EDMs

3. Conclusions

Outline

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2. Phenomenology
   - Tree-level and loop-induced processes
   - CP asymmetries
   - EDMs
3. Conclusions

SM $\Rightarrow$ unresolved Flavour puzzle

- Basic questions still open: Many free parameters, why 3 families, pattern of masses and mixings, CP violation ...
- Experimentally: Neutrino oscillations $\rightarrow$ LFV

$\boxed{\text{Scalar sector}} \Rightarrow \phi_1, \phi_2, \phi_3, \ldots, \phi_n$

Enlargement of the scalar sector $\longrightarrow$ An economical choice

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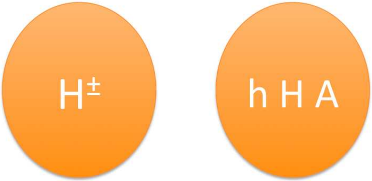

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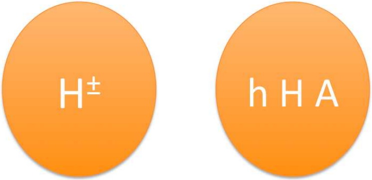
New dynamical possibilites

- Spontaneous CP violation
- Strong CP problem
- Baryogenesis

  → Electroweak phase transition
  → V_{CKM} CP violating effects too small
- Dark matter candidates

- New physics high-energy models require more than one Higgs



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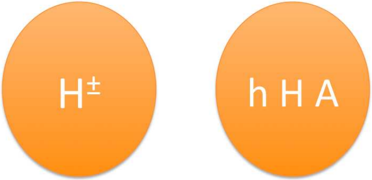

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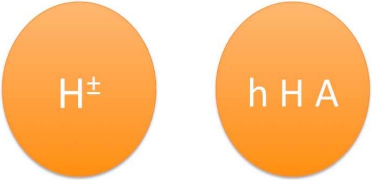

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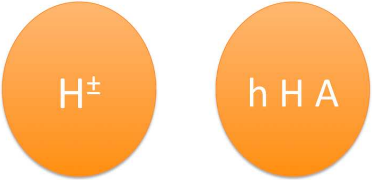

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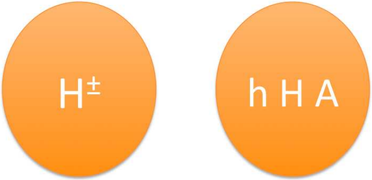

Two Higgs doublets ϕ_a $(a=1,2)$ with $Y=\frac{1}{2}$ whose neutral components acquire VEV's:

$$<0|\phi_a^T(x)|0>=\frac{1}{\sqrt{2}}(0, v_a e^{i\theta_a}) \qquad v=\sqrt{v_1^2+v_2^2} \qquad \text{Choice: } \theta_1=0\,,\ \theta\equiv\theta_2-\theta_1$$

$$\left(\begin{array}{c}\Phi_1\\ -\Phi_2\end{array}\right)\equiv\Omega\left(\begin{array}{c}\phi_1\\ e^{-i\theta}\phi_2\end{array}\right) \qquad ; \qquad \Omega\equiv\frac{1}{v}\left[\begin{array}{cc}v_1 & v_2\\ v_2 & -v_1\end{array}\right]$$

Higgs basis

$$\Phi_1=\left[\begin{array}{c}G^+\\ \frac{1}{\sqrt{2}}(v+S_1+iG^0)\end{array}\right] \qquad ; \qquad \Phi_2=\left[\begin{array}{c}H^+\\ \frac{1}{\sqrt{2}}(S_2+iS_3)\end{array}\right]$$

$$S_1,\ S_2,\ S_3 \xrightarrow{\mathscr{R}} H,\ h,\ A$$

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$$\mathscr{L}_Y = -\overline{Q}'_L(\Gamma_1\phi_1 + \Gamma_2\phi_2)d'_R - \overline{Q}'_L(\Delta_1\widetilde{\phi}_1 + \Delta_2\widetilde{\phi}_2)u'_R - \overline{L}'_L(\Pi_1\widetilde{\phi}_1 + \Pi_2\widetilde{\phi}_2)l'_R + h.c.$$

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Fermion mass eigenstate basis $\mathscr{L}_Y[f' \to f]$ ($f = u,\ d,\ l$):

- $M'_f \longrightarrow M_f$ diagonal
- $Y'_f \longrightarrow Y_f$ NON diagonal and unrelated to M_f

FCNC !

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- Flavour symmetry ⟶ particular Yukawa textures
  [e.g. Yukawa couplings: $g_{ij} \propto \sqrt{m_i m_j}$] (Type III)
- Heavy enough M_H bosons ⟶ suppressed FCNC (Decoupling limit)
- Impossing discrete $\mathcal{Z}_2$ symmetry

$$\phi_1 \to \phi_1\,, \qquad \phi_2 \to -\phi_2\,, \qquad Q_L \to Q_L\,, \qquad L_L \to L_L$$

Only one scalar doublet is coupling to a given right-handed fermion field

Different implementations of $\mathcal{Z}_2$ symmetry

- ϕ_2 to all fermions (Type I)
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The general two-Higgs-doublet model

Avoiding FCNC

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$$\Gamma_2 = \xi_d e^{-i\theta}\Gamma_1 \qquad \Delta_2 = \xi_u^* e^{i\theta}\Delta_1 \qquad \Pi_2 = \xi_l e^{-i\theta}\Pi_1$$

$$Y_{d,l} = \varsigma_{d,l} M_{d,l} \qquad Y_u = \varsigma_u M_u \qquad ; \qquad \varsigma_f \equiv \frac{\xi_f - \tan\beta}{1 + \xi_f \tan\beta} \qquad \left(\tan\beta = \frac{v_2}{v_1}\right)$$

$$\begin{aligned}\mathscr{L}_Y = \; & -\frac{\sqrt{2}}{v} H^+(x)\{\overline{u}(x)\,[\varsigma_d V_{CKM} M_d \mathscr{P}_R - \varsigma_u M_u V_{CKM} \mathscr{P}_L]\, d(x) + \varsigma_l \overline{\nu}(x) M_l \mathscr{P}_R l(x)\} \\ & -\frac{1}{v}\sum_{\phi=H,h,A} \phi(x) \sum_{f=u,d,l} y_f^{\phi}\, \overline{f}(x)\, M_f \mathscr{P}_R\, f(x) \quad + \quad h.c.\end{aligned}$$

$$y^{\phi}_{d,l} = \mathscr{R}_{i1} + (\mathscr{R}_{i2} + i\mathscr{R}_{i3})\varsigma_{d,l}$$
$$y^{\phi}_{u} = \mathscr{R}_{i1} + (\mathscr{R}_{i2} + -\mathscr{R}_{i3})\varsigma_{u}^{*}$$

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$$- \frac{1}{v}\sum_{\phi=H,h,A} \phi(x) \sum_{f=u,d,l} y_f^{\phi}\, \bar{f}(x)\, M_f \mathscr{P}_R f(x) \quad + \quad h.c.$$

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$$\begin{aligned}\mathcal{L}_Y = \; & - \frac{\sqrt{2}}{v} H^+(x)\left\{\bar{u}(x)\left[\varsigma_d V_{CKM} M_d \mathscr{P}_R - \varsigma_u M_u V_{CKM} \mathscr{P}_L\right] d(x) + \varsigma_l \bar{\nu}(x) M_l \mathscr{P}_R l(x)\right\} \\ & - \frac{1}{v} \sum_{\phi=H,h,A} \phi(x) \sum_{f=u,d,l} y_f^{\phi}\, \bar{f}(x)\, M_f \mathscr{P}_R\, f(x) \qquad + \qquad h.c.\end{aligned}$$

$$y^{\phi}_{d,l} = \mathscr{R}_{i1} + (\mathscr{R}_{i2} + i\mathscr{R}_{i3})\varsigma_{d,l}$$
$$y^{\phi}_{u} = \mathscr{R}_{i1} + (\mathscr{R}_{i2} + -\mathscr{R}_{i3})\varsigma_{u}^*$$

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- ς_f: complex numbers → new sources of CP violation without tree-level FCNC
- ς_f: universality and scalar-basis independence and ...
- $\mathcal{Z}_2$-type models are recovered

Model	(ξ_d, ξ_u, ξ_l)	ς_d	ς_u	ς_l
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Aligned two-Higgs-doublet model

Features

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v} H^+(x) \left\{ \bar{u}(x) \left[\varsigma_d V_{CKM} M_d \mathscr{P}_R - \varsigma_u M_u V_{CKM} \mathscr{P}_L \right] d(x) + \varsigma_l \bar{\nu}(x) M_l \mathscr{P}_R l(x) \right\}$$
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Alignment Yukawa couplings is not directly protected by any symmetry: radiative FCNC

Nevertheless $\Longrightarrow$ Built-in flavour symmetries: MFV structures

$$\begin{aligned}\mathcal{L}_{\rm FCNC}^{\text{1-loop}} &= -\frac{\log(\mu/\mu_0)}{4\pi^2 v^3}(1+\varsigma_u^*\varsigma_d)\sum_i \varphi_i^0(x) \\ &\times \Big\{(\mathcal{R}_{i2}+i\mathcal{R}_{i3})(\varsigma_d-\varsigma_u)\left[\overline{d}_L\, V^\dagger\, M_u M_u^\dagger\, V\, Md\, d_R\right] \\ &\quad -(\mathcal{R}_{i2}-i\mathcal{R}_{i3})(\varsigma_d^*-\varsigma_u^*)\left[\overline{u}_L\, V\, M_d M_d^\dagger\, V^\dagger\, Mu\, u_R\right]\Big\} \\ &\quad + h.c.\end{aligned}$$

- Vanishes in all $\mathcal{Z}_2$ models (as it should)
- Suppressed by $m_q m_{q'}/(4\pi^2 v^3)$ and $V_{CKM}^{qq'}$ $\Longrightarrow$ $\bar{s}_L b_R$, $\bar{c}_L t_R$

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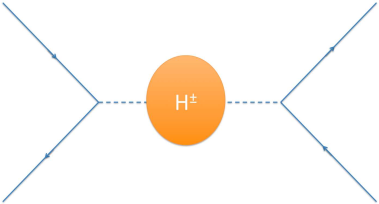
Outline



- Charged Higgs with complex couplings
- $M_{H^\pm} > 78.6$ GeV at 95% CL (LEP) $\longrightarrow H^+ \to u_i \overline{d}_j \, , l^+ \nu_l$

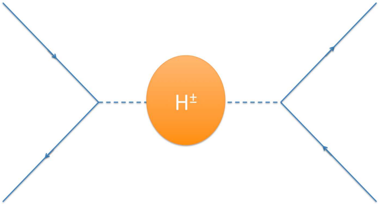
⇒ Tree level decays

⇒ Loop-induced processes

⇒ CP asymmetries in B systems

⇒ EDMs

Statistical treatment ⇒ RFit approach



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Outline

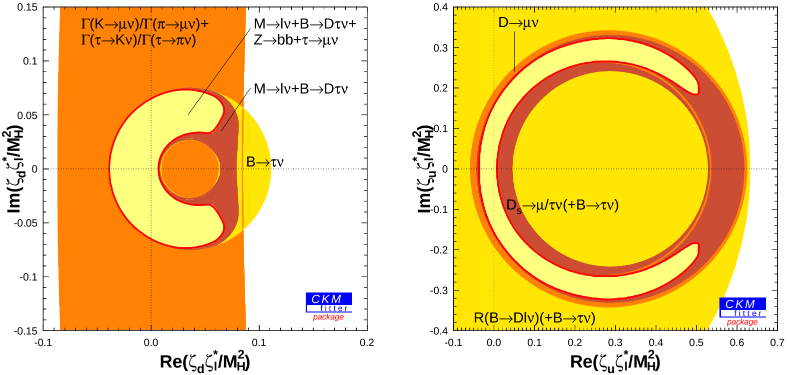
1. From the 2HDM to the Aligned 2HDM
2. Phenomenology
   - Tree-level and loop-induced processes
   - CP asymmetries
   - EDMs
3. Conclusions

Observables

$$\tau \to \mu/e \qquad \Longrightarrow \qquad |\varsigma_l|/M_{H^\pm} < 0.40\ \mathrm{GeV}^{-1}\,(95\%\mathrm{CL})$$

$$\left.\begin{array}{l} P^- \to l^- \overline{\nu}_l \\ \\ P \to P' l^- \overline{\nu}_l \end{array}\right. \qquad \Longrightarrow \qquad \frac{\varsigma_l^* \varsigma_u}{M_{H^\pm}^2} \qquad \frac{\varsigma_l^* \varsigma_d}{M_{H^\pm}^2}$$

Global fit: $P \to l\nu_l$, $\tau \to P\nu_\tau$ and $P \to P' l\nu_l$



[GeV^{-2} units]

Observables

ΔM_{B_s}

ϵ_K

$Z \to b\overline{b}$ $\Longrightarrow$ ς_u ς_d

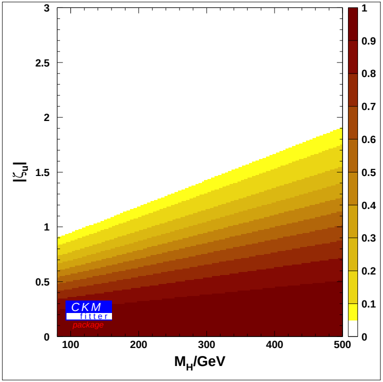
$\overline{B} \to X_s \gamma$

Assumptions

Charged scalar → dominant new physics corrections ($|\varsigma_d| \leq 50$)

Subleading effects to the SM

$\boxed{\Delta M_{B_s} \text{ - } \epsilon_K \text{ - } Z \to b\bar{b}}$ - $\boxed{\overline{B} \to X_s \gamma}$



$\boxed{\Delta M_{B_s} \text{ - } \epsilon_K \text{ - } Z \to b\bar{b}}$ - $\boxed{\overline{B} \to X_s \gamma}$

$$C^{eff}(\mu_0) = C_{SM} + |\varsigma_u|^2 C_{uu} - |\varsigma_u||\varsigma_d| e^{i\varphi} C_{ud}$$

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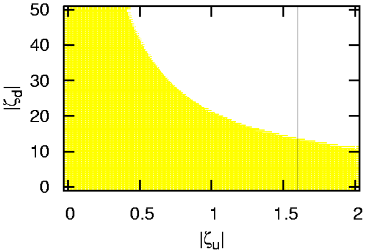
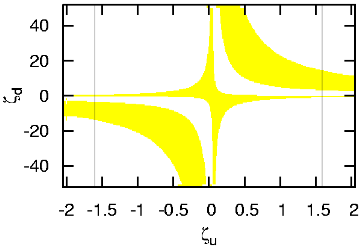
Complex couplings

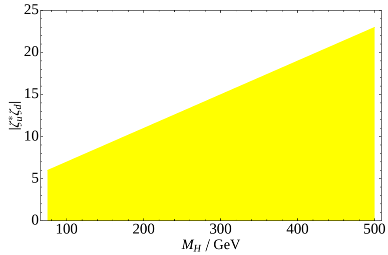


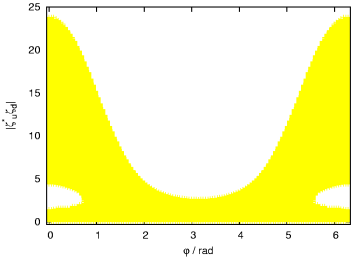
Real couplings



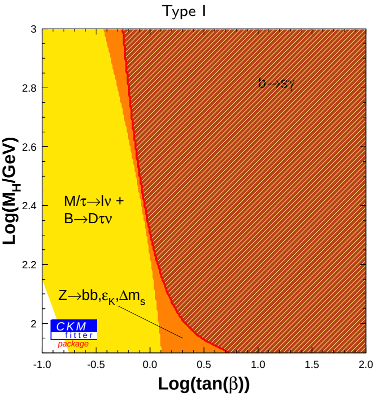
$$\boxed{\Delta M_{B_s} \text{ - } \epsilon_K \text{ - } Z \to b\bar{b}} \text{ - } \boxed{\overline{B} \to X_s \gamma}$$

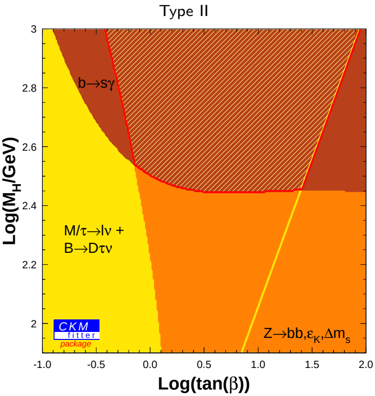
$$A \sim A_{SM} \left\{ 1 - 0.1\, \varsigma_u^* \varsigma_d \left(\frac{500\ \text{GeV}}{M_{H^\pm}} \right)^2 + 0.01\, |\varsigma_u|^2 \left(\frac{500\ \text{GeV}}{M_{H^\pm}} \right)^2 \right\}$$





$\mathcal{Z}_2$ models as particular cases:





Outline

$\boxed{\Delta M_{B_s}}$ - $\boxed{\overline{B} \to X_s\gamma}$

$$a_{CP} = \frac{\mathrm{Br}(\overline{B} \to X_s\gamma) - \mathrm{Br}(B \to X_{\overline{s}}\gamma)}{\mathrm{Br}(\overline{B} \to X_s\gamma) + \mathrm{Br}(B \to X_{\overline{s}}\gamma)}$$

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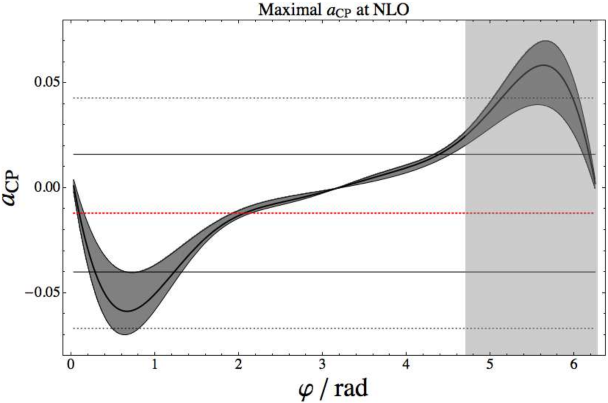

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$$a_{sl}^q = \frac{\Gamma(\overline{B}_q^0 \to \mu^+ X) - \Gamma(B_q^0 \to \mu^- X)}{\Gamma(\overline{B}_q^0 \to \mu^+ X) + \Gamma(B_q^0 \to \mu^- X)} = \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_q$$

A_{sl}^b [D0] + a_{sl}^d [HFAG] and $\Delta M_s^{exp} + \Delta\Gamma_s^{SM} \Longrightarrow \sin\phi_s = -2.7 \pm 1.4 \pm 1.6$!!

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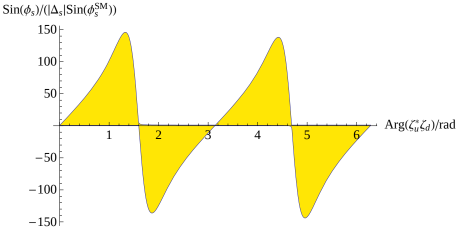

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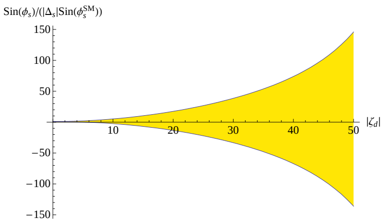

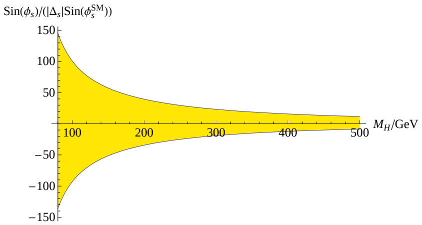

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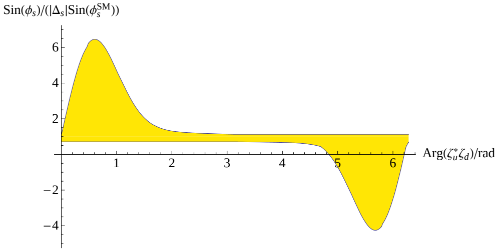
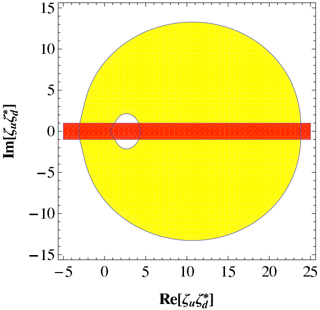
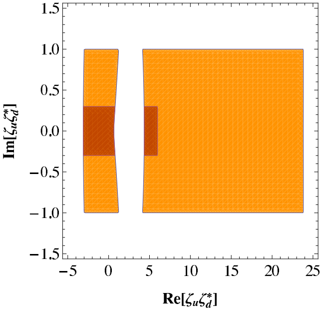


Outline

[Dominated by Weinberg diagram]

$$d_n \sim d_n^{\exp} \frac{500\text{GeV}}{M_{H^\pm}} \text{Im}(\varsigma_d \varsigma_u^*)$$

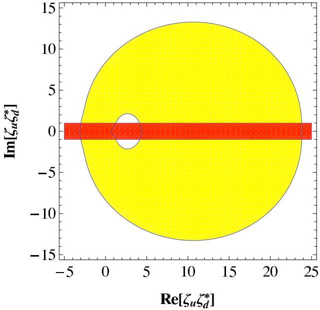


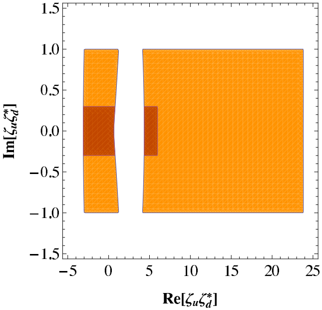


Strong constraint for $\text{Im}(\varsigma_d \varsigma_u^*) \Longrightarrow$ still not tiny

[Dominated by Weinberg diagram]

$$d_n \sim d_n^{\mathrm{exp}} \frac{500\mathrm{GeV}}{M_{H^\pm}} \mathrm{Im}(\varsigma_d \varsigma_u^*)$$

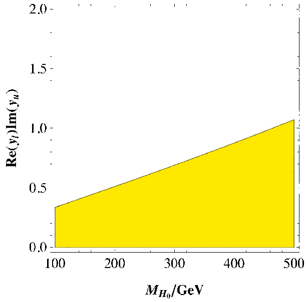


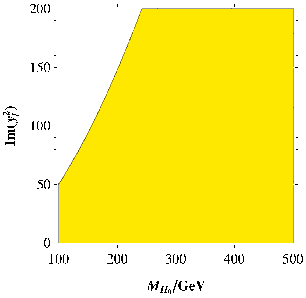


Strong constraint for $\mathrm{Im}(\varsigma_d \varsigma_u^*) \Longrightarrow$ still not tiny

[Dominated by Barr-Zee diagrams]

Thallium (paramagnetic atom, $d_{\mathrm{Tl}} \sim -585 d_e$) and ONE neutral Higgs $\Longrightarrow y_{u,l}$





$\mathcal{O}(1)$ imaginary parts allowed

[Dominated by Barr-Zee diagrams]

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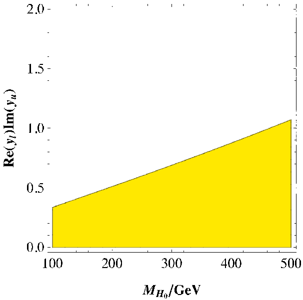

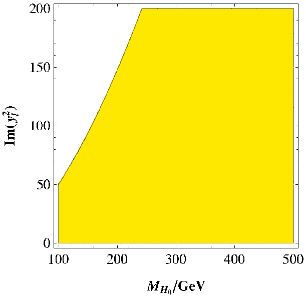

$\mathcal{O}(1)$ imaginary parts allowed

Outline

Conclusions

- Alignment ⟶ **No FCNC** at tree level while introducing new $\not{CP}$ sources in the Yukawa sector

  ⇒ Only 3 new (complex) parameters: $\varsigma_{u,d,l}$ ⟶ flavour **blind** and basis **independent**

  ⇒ $\mathcal{Z}_2$ models particular cases

- Quantum corrections break alignment but... built-in flavour symmetries ⟶ MFV structures

  ⇒ Important in heavy quark systems

- Phenomenology: Additional **freedom** introduced by the phases makes easy to accommodate experimental limits

  ⇒ A2HDM passes the EDM-test

  ⇒ If more accuracy at NA62/LHCb/Super-b or new physics at LHC:

  "**acid test**" for A2HDM and $\mathcal{Z}_2$-2HDM

Conclusions

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    "acid test" for A2HDM and $\mathcal{Z}_2$-2HDM

Gràcies!

Input parameters I

Parameter	Value	Comment
f_{B_s}	$(0.242 \pm 0.003 \pm 0.022)$ GeV	Our average
f_{B_s}/f_{B_d}	$1.232 \pm 0.016 \pm 0.033$	Our average
f_{D_s}	$(0.2417 \pm 0.0012 \pm 0.0053)$ GeV	Our average
f_{D_s}/f_{D_d}	$1.171 \pm 0.005 \pm 0.02$	Our average
f_K/f_π	$1.192 \pm 0.002 \pm 0.013$	Our average
$f_{B_s}\sqrt{\hat{B}_{B_s^0}}$	$(0.266 \pm 0.007 \pm 0.032)$ GeV	
$f_{B_d}\sqrt{\hat{B}_{B_s^0}}/(f_{B_s}\sqrt{\hat{B}_{B_s^0}})$	$1.258 \pm 0.025 \pm 0.043$	
$\hat{B}_K$	$0.732 \pm 0.006 \pm 0.043$	
$\lvert V_{ud}\rvert$	0.97425 ± 0.00022	
λ	0.2255 ± 0.0010	$\left(1-\lvert V_{ud}\rvert^2\right)^{1/2}$
$\lvert V_{ub}\rvert$	$(3.8 \pm 0.1 \pm 0.4)\cdot 10^{-3}$	$b \to u l \nu$ (excl. + incl.)
A	$0.80 \pm 0.01 \pm 0.01$	$b \to c l \nu$ (excl. + incl.)
$\bar{\rho}$	$0.15 \pm 0.02 \pm 0.05$	Our fit
$\bar{\eta}$	$0.38 \pm 0.01 \pm 0.06$	Our fit

Table: *Input values for the hadronic parameters, obtained as described in the text. The first error denotes statistical uncertainty, the second systematic/theoretical.*

Input parameters II

Parameter	Value	Comment
$\overline{m}_u(2\ \mathrm{GeV})$	$(0.00255^{+0.00075}_{-0.00105})$ GeV	
$\overline{m}_d(2\ \mathrm{GeV})$	$(0.00504^{+0.00096}_{-0.00154})$ GeV	
$\overline{m}_s(2\ \mathrm{GeV})$	$(0.105^{+0.025}_{-0.035})$ GeV	
$\overline{m}_c(2\ \mathrm{GeV})$	$(1.27^{+0.07}_{-0.11})$ GeV	
$\overline{m}_b(m_b)$	$(4.20^{+0.17}_{-0.07})$ GeV	
$\overline{m}_t(m_t)$	$(165.1 \pm 0.6 \pm 2.1)$ GeV	
$\delta_{\mathrm{em}}^{K\ell 2/\pi\ell 2}$	-0.0070 ± 0.0018	
$\delta_{\mathrm{em}}^{\tau K2/K\ell 2}$	0.0090 ± 0.0022	
$\delta_{\mathrm{em}}^{\tau\pi 2/\pi\ell 2}$	0.0016 ± 0.0014	
$\rho^2\vert_{B\to Dl\nu}$	$1.18 \pm 0.04 \pm 0.04$	
$\Delta\vert_{B\to Dl\nu}$	0.46 ± 0.02	
$f_+^{K\pi}(0)$	0.965 ± 0.010	
$\overline{g}_{b,SM}^{L}$	$-0.42112^{+0.00035}_{-0.00018}$	
κ_ϵ	0.94 ± 0.02	
$\overline{g}_{b,SM}^{R}$	$0.07744^{+0.00006}_{-0.00008}$	

Table: *Input values for the hadronic parameters, obtained as described in the text. The first error denotes statistical uncertainty, the second systematic/theoretical.*

Observables

Observable	Value
$\lvert g_{RR}^{S}\rvert_{\tau\to\mu}$	< 0.72 (95% CL)
$\mathrm{Br}(\tau\to\mu\nu_\tau\overline{\nu}_\mu)$	$(17.36\pm0.05)\times10^{-2}$
$\mathrm{Br}(\tau\to e\nu_\tau\overline{\nu}_e)$	$(17.85\pm0.05)\times10^{-2}$
$\mathrm{Br}(\tau\to\mu\nu_\tau\overline{\nu}_\mu)/\mathrm{Br}(\tau\to e\nu_\tau\overline{\nu}_e)$	0.9796 ± 0.0039
$\mathrm{Br}(B\to\tau\nu)$	$(1.73\pm0.35)\times10^{-4}$
$\mathrm{Br}(D\to\mu\nu)$	$(3.82\pm0.33)\times10^{-4}$
$\mathrm{Br}(D\to\tau\nu)$	$\leq 1.3\times10^{-3}$ (95% CL)
$\mathrm{Br}(D_s\to\tau\nu)$	$(5.58\pm0.35)\times10^{-2}$
$\mathrm{Br}(D_s\to\mu\nu)$	$(5.80\pm0.43)\times10^{-3}$
$\Gamma(K\to\mu\nu)/\Gamma(\pi\to\mu\nu)$	1.334 ± 0.004
$\Gamma(\tau\to K\nu)/\Gamma(\tau\to\pi\nu)$	$(6.50\pm0.10)\times10^{-2}$
$\log C$	0.194 ± 0.011
$\mathrm{Br}(B\to D\tau\nu)/\mathrm{Br}(B\to D\ell\nu)$	0.392 ± 0.079
$\Gamma(Z\to b\overline{b})/\Gamma(Z\to \text{hadrons})$	0.21629 ± 0.00066
$\mathrm{Br}(\overline{B}\to X_s\gamma)_{E_\gamma>1.6\mathrm{GeV}}$	$(3.55\pm0.26)\times10^{-4}$
$\mathrm{Br}(\overline{B}\to X_c e\overline{\nu}_e)$	$(10.74\pm0.16)\times10^{-2}$
$\Delta m_{B_d^0}$	$(0.507\pm0.005)\ \mathrm{ps}^{-1}$
$\Delta m_{B_s^0}$	$(17.77\pm0.12)\ \mathrm{ps}^{-1}$
$\lvert\epsilon_K\rvert$	$(2.228\pm0.011)\times10^{-3}$

Table: *Measurements used in the analysis. Masses and lifetimes are taken from the PDG.*