$(g-2)_\mu$ in the presence of CPV

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In collaboration with: Kimmo Tuominen & Niko Koivunen

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In praise of the Standard Model

Current formulation finalised in the 70's predicted:

- the W & Z (1983)
- the top quark (1995)
- the tau neutrino (2000)
- "a" Higgs boson (2012)

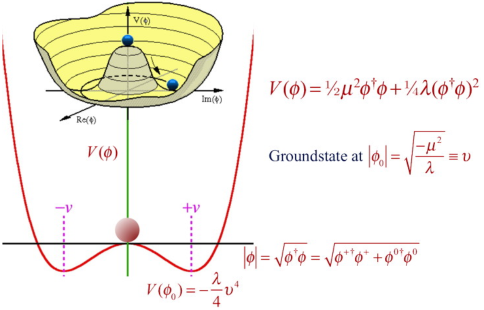
In criticism of the Standard Model

What is missing:

- Femion mass hierarchy
- EW vacuum stability
- Dark Matter
- CP-Violation
- Muon anomalous magnetic moment $a_\mu = (g-2)_\mu/2$
- $\cdots$

Scalars to the rescue!

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\Psi} \not{D} \psi + h.c. \\
& + \bar{\Psi}_i y_{ij} \psi_j \phi + h.c. \\
& + |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$



Two birds with one stone!

- What's up with the muon?

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = (287 \pm 80) \times 10^{-11} \; (3.6\sigma)$$

extra scalars can help!

- Observation $\frac{N(B)}{N(\gamma)} \approx 10^{-9} \quad \gg \quad 10^{-20}$ provided by SM

$\Rightarrow$ new sources of CPV are needed

scalar extensions can help!

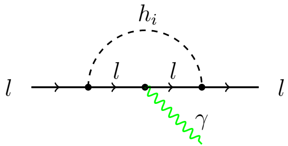
Who is stopping them? EDMs

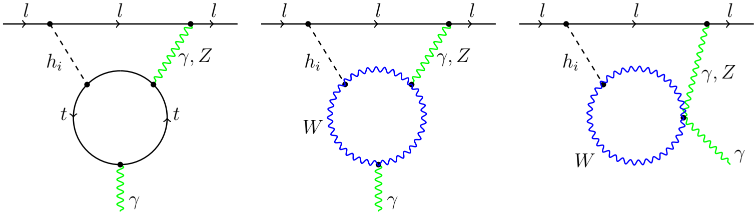
$$d_e < 10.25 \times 10^{-29} \text{ e cm}$$

[Science 343, 269 (2014)], [Phys. Rev. D 73, 072003 (2006)]

Dominant contributions to a_μ and d_e

$$a_\mu = \frac{m_\mu^2}{4\pi^2}\,\mathrm{Re}(c_L + c_R^*), \qquad d_e = \frac{e\ m_e}{4\pi^2}\,\mathrm{Im}(c_L + c_R^*)$$





The important couplings are: $Y^{h_i}_{\mu\mu}$, $Y^{h_i}_{ee}$, $Y^{h_i}_{WW}$, $Y^{h_i}_{tt}$

[arXiv:1511.05225], [Phys.Rev. D64 (2001) 111301]

The 2 Higgs doublet model (2HDM)

2HDM with explicit CP-violation

Two scalar doublets

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1 + h_1^0 + i a_1^0}{\sqrt{2}} \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2 + h_2^0 + i a_2^0}{\sqrt{2}} \end{pmatrix},$$

The scalar potential:

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

Imposing a Z_2 symmetry to avoid FCNCs:

$$\Phi_1 \to +\Phi_1, \quad \Phi_2 \to -\Phi_2 \quad \Rightarrow \quad \lambda_6 = \lambda_7 = 0$$

The three CP-mixed mass eigenstates

Rotating to the Higgs basis

$$\begin{pmatrix} \hat{\Phi}_1 \\ \hat{\Phi}_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix}$$

with $\tan\beta = v_2/v_1$.

$$\hat{\Phi}_1 = \begin{pmatrix} G^+ \\ \frac{v+\phi_1+iG^0}{\sqrt{2}} \end{pmatrix}, \quad \hat{\Phi}_2 = \begin{pmatrix} H^+ \\ \frac{\phi_2+i\phi_3}{\sqrt{2}} \end{pmatrix}$$

Rotation matrix R (assuming all angles are small):

$$\phi_i = R_{ij} h_j, \qquad \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \end{pmatrix} = \begin{pmatrix} 1 & \theta_{12} & \theta_{13} \\ -\theta_{12} & 1 & \theta_{23} \\ -\theta_{13} & -\theta_{23} & 1 \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}$$

What constrains the parameter space?

- Bounded from below potential: $\phi_i \to \infty \;\; \Rightarrow V > 0$
- Vacuum stability: $E_{v_{EW}} < E_{v_i}$ or $\tau_{v_{EW}} >$ age of the universe
- Perturbative unitarity: $|\lambda_i| \leq 4\pi, \;\; |\Lambda_i| \leq 8\pi$
- h_1 being SM-like: $sin(\theta_{12}) < 0.3$
- Electroweak precision data: $m_{H^\pm} \sim m_{h_3}$

The couplings

The Yuakwa couplings

$$-\mathcal{L}_Y = Y_u \bar{Q}'_L i\sigma_2 \Phi_u^* u'_R + Y_d \bar{Q}'_L \Phi_d d'_R + Y_l \bar{L}'_L \Phi_l l'_R + h.c.$$

$$y_u = \bar{u}_L \frac{m_u}{v} u_R \sum_i^3 (R_{1i} + \xi_u (R_{2i} - i\, R_{3i}))\, h_i$$

$$y_d = \bar{d}_L \frac{m_d}{v} d_R \sum_i^3 (R_{1i} + \xi_d (R_{2i} + i\, R_{3i}))\, h_i$$

$$y_l = \bar{e}_L \frac{m_l}{v} e_R \sum_i^3 (R_{1i} + \xi_l (R_{2i} + i\, R_{3i}))\, h_i$$

The gauge couplings

$$\mathcal{L}_{kin} \supset \phi_1 \left(\frac{2m_W^2}{v} W_\mu W^\mu + \frac{m_Z^2}{v} Z_\mu Z^\mu \right) = R_{1i} h_i \left(\frac{2m_W^2}{v} W_\mu W^\mu + \frac{m_Z^2}{v} Z_\mu Z^\mu \right)$$

Different types of 2HDM

	Φ_1	Φ_2	u_R	d_R	e_R	Q_L, L_L	ξ_d	ξ_u	ξ_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	$+$	$-$	$-$	$+$	$-$	$+$	$-\tan\beta$	$\cot\beta$	$\cot\beta$

Recall the couplings contributing to a_μ and d_e:

$$Y^{h_i}_{\mu\mu}, \quad Y^{h_i}_{ee}, \quad Y^{h_i}_{WW}, \quad Y^{h_i}_{tt}$$

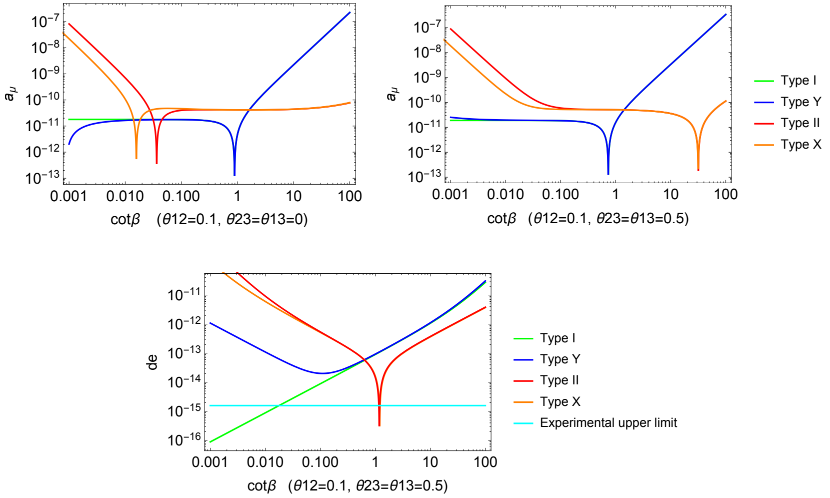
With ξ_d playing a sub-dominant role:

Type-I $\cong$ Type-Y **Type-II $\cong$ Type-X**

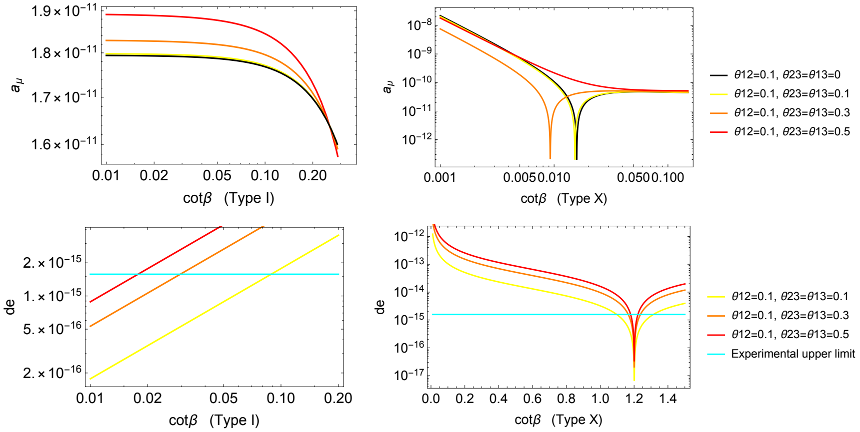
Heavy scalars

$$m_{h_{2,3}} = 200, 300 \text{ GeV}$$

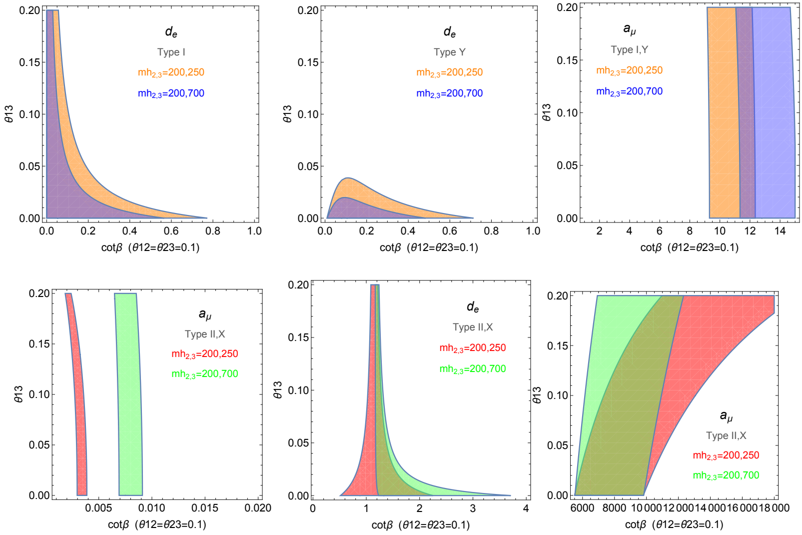
a_μ with/without CPV and d_e



A closer look



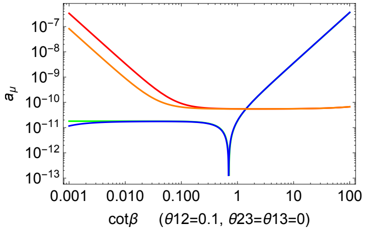
No overlap between d_e and a_μ regions

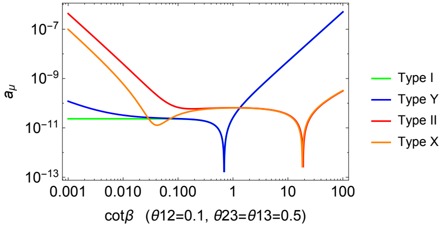


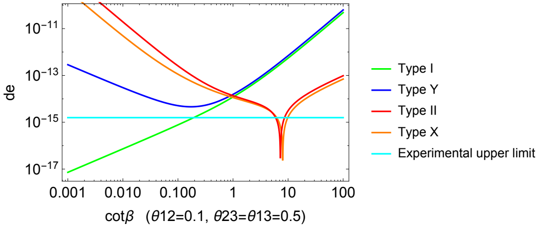
Scalars close in mass

$$m_{h_{2,3}} = 145, 105 \text{ GeV}$$

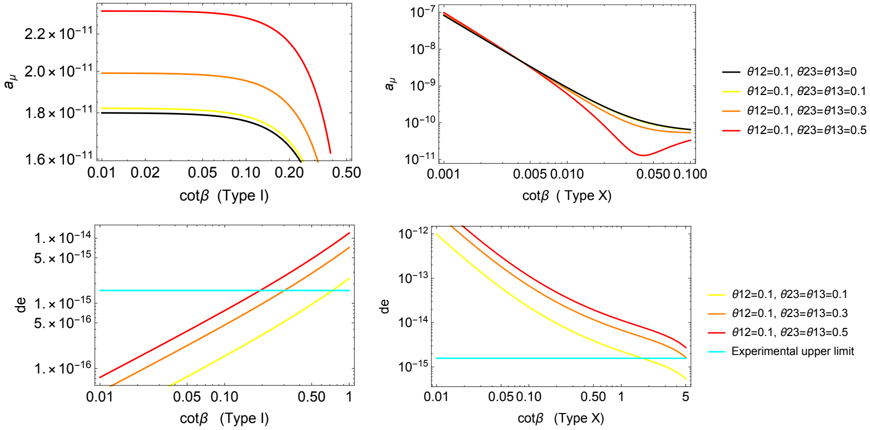
a_μ with/without CPV and d_e



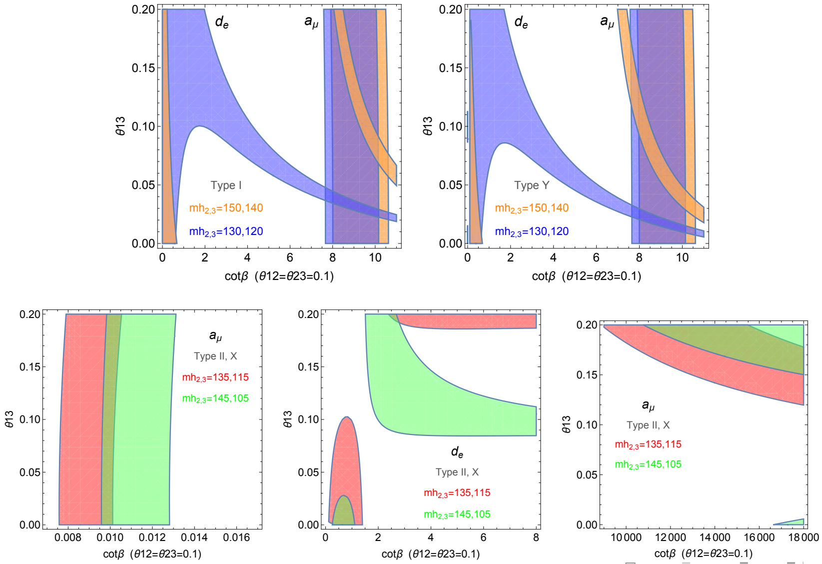




A closer look



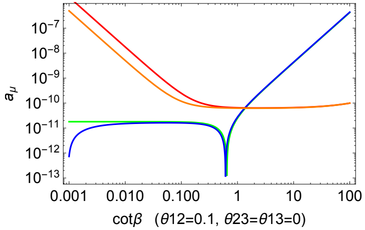
Overlap between d_e and a_μ regions

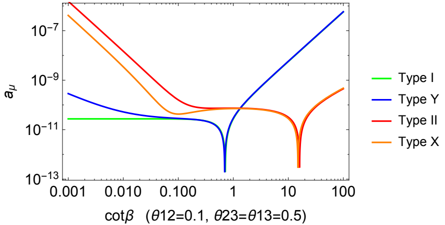


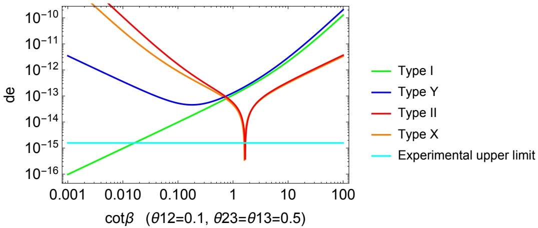
Light scalars

$$m_{h_{2,3}} = 200, 50 \text{ GeV}$$

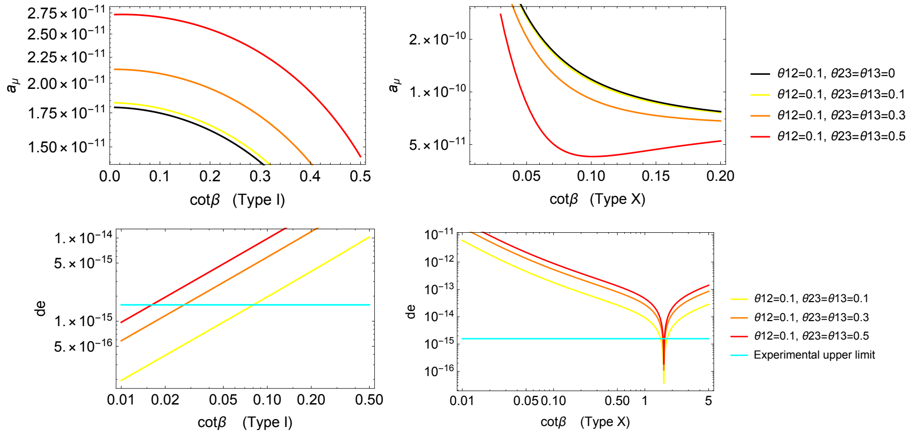
a_μ with/without CPV and d_e



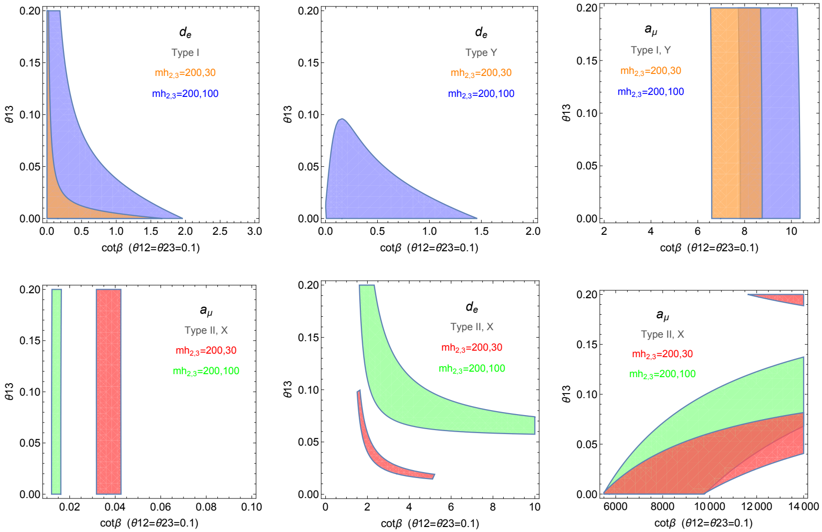




A closer look



No overlap between d_e and a_μ regions



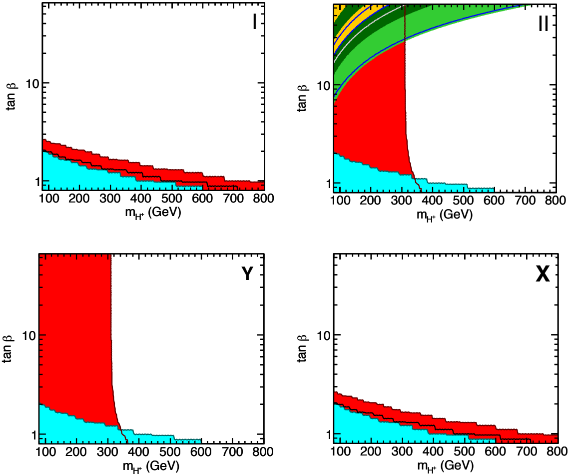
$\tan\beta$ dependant couplings

	Type I	Type II	Type X	Type Y
ξ_h^u	$\cos\theta_{12}/\sin\beta$	$\cos\theta_{12}/\sin\beta$	$\cos\theta_{12}/\sin\beta$	$\cos\theta_{12}/\sin\beta$
ξ_h^d	$\cos\theta_{12}/\sin\beta$	$-\sin\theta_{12}/\cos\beta$	$\cos\theta_{12}/\sin\beta$	$-\sin\theta_{12}/\cos\beta$
ξ_h^ℓ	$\cos\theta_{12}/\sin\beta$	$-\sin\theta_{12}/\cos\beta$	$-\sin\theta_{12}/\cos\beta$	$\cos\theta_{12}/\sin\beta$
ξ_H^u	$\sin\theta_{12}/\sin\beta$	$\sin\theta_{12}/\sin\beta$	$\sin\theta_{12}/\sin\beta$	$\sin\theta_{12}/\sin\beta$
ξ_H^d	$\sin\theta_{12}/\sin\beta$	$\cos\theta_{12}/\cos\beta$	$\sin\theta_{12}/\sin\beta$	$\cos\theta_{12}/\cos\beta$
ξ_H^ℓ	$\sin\theta_{12}/\sin\beta$	$\cos\theta_{12}/\cos\beta$	$\cos\theta_{12}/\cos\beta$	$\sin\theta_{12}/\sin\beta$
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ξ_A^ℓ	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

for most H masses: $\sin\theta_{12} < |0.3|$

our analysis: $\sin\theta_{12} = 0.1$

Flavour constraints



Exluded by $BR(B \to X_s\gamma)$, $B^0 - \bar{B}^0$ mixing, $D_s \to \tau\nu_\tau$, $D_s \to \mu\nu_\mu$, $B \to D\tau\nu_\tau$.

[Phys. Rev. D 81 (2010) 035016

The general picture!

$\tan\beta$	2HDM-Type	d_e	a_μ	Flavour+Collider Exp.
$0.01 - 0.1$	I	$\times$	$\surd$	$\times$
	Y	$\times$	$\surd$	$\times$
$0.01 - 0.1$	II	$\times$	$\times$	$\times$
	X	$\times$	$\times$	$\times$
$\mathcal{O}(1)$	I	$\surd$	$\surd$	$\times$
	Y	$\surd$	$\surd$	$\times$
$\mathcal{O}(1)$	II	$\surd$	$\times$	$\times$
	X	$\surd$	$\times$	$\times$
$10 - 100$	I	$\surd$	$\times$	$\surd$
	Y	$\times$	$\times$	$\times$
$10 - 100$	II	$\times$	$\surd$	$\times$
	X	$\times$	$\surd$	$\surd$

Summary

- When it comes to a_μ and d_e calculations:

  Type-I $\cong$ Type-Y **Type-II $\cong$ Type-X**

- When it comes to flavour and collider bounds:

  Type-I $\cong$ Type-X **Type-II $\cong$ Type-Y**

- Only when scalars are close in mass, the a_μ and d_e regions overlap in Type I & Y.

- For large a_μ: **Type-X**
- For small d_e: **Type-I**

BACKUP SLIDES

a_μ contribution from scalars

$$\Delta a_\mu = a_\mu^{exp} - \left(a_\mu^{SM\ (without\ \ scalars)} + a_\mu^{scalars} \right) = 0$$

$$\Rightarrow \ \ a_\mu^{scalars} = (2.88 \pm 0.8) \times 10^{-9}$$

SM + singlet scalar

SM + real singlet

SM-Higgs doublet Φ and the scalar singlet S:

$$\Phi = \begin{pmatrix} G^+ \\ \frac{v+\phi_1+iG^0}{\sqrt{2}} \end{pmatrix}, \quad S = \left(\frac{w+\phi_2}{\sqrt{2}} \right)$$

The scalar potential:

$$V = -\mu_1^2\Phi^\dagger\Phi - \mu_2^2 S^2 + \lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2 S^4 + \lambda_3(\Phi^\dagger\Phi)S^2 + \kappa_1 S + \kappa_2 S(\Phi^\dagger\Phi) + \kappa_3 S^3$$

Rotation matrix R:

$$\phi_i = R_{ij}h_j, \quad \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

Constrained by experimental and theoretical bounds:

$$|\sin\theta| \lesssim 0.3$$

SM + real singlet

No CPV at the potential level $\Rightarrow$ Higher order operators

$$\mathcal{L}_{CPV} = \frac{\eta}{\Lambda} S \, \bar{Q}_L \, \tilde{\Phi} \, t_R + h.c.$$

$$\eta = \mathrm{Re}\eta + i \, \mathrm{Im}\eta$$

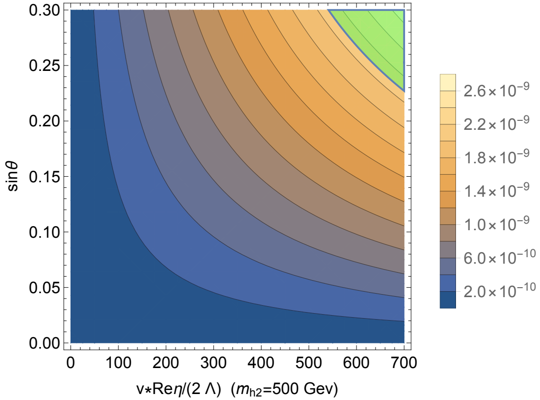
The couplings of h_1, h_2:

$$Y_{ee}^{h_i} = R_{1i} \left(\frac{m_e}{v} \right)$$

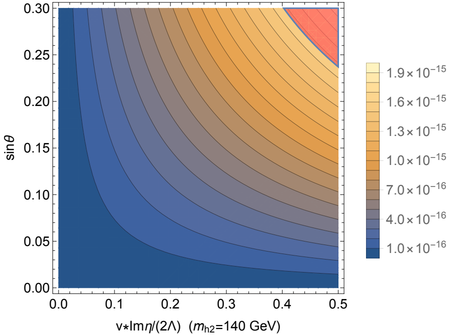
$$Y_{WW}^{h_i} = R_{1i} \left(\frac{2m_W^2}{v} \right)$$

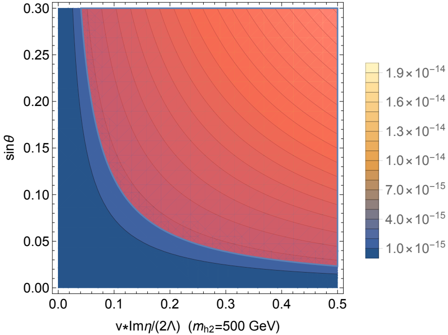
$$Y_{tt}^{h_i} = R_{1i} \left(\frac{m_t}{v} \right) + R_{2i} \left(\frac{v(\mathrm{Re}\eta + i\mathrm{Im}\eta)}{2\Lambda} \right)$$

Contours of a_μ



Contours of d_e





SM + complex singlet

SM-Higgs doublet Φ and the scalar singlet S:

$$\Phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + \phi_1 + iG^0\right) \end{pmatrix}, \quad S = \left(\frac{w + \phi_2 + i\phi_3}{\sqrt{2}}\right)$$

Rotation matrix R:

$$\phi_i = R_{ij} h_j, \quad \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}$$

SM + complex singlet

No CPV at the potential level $\Rightarrow$ Higher order operators

$$\mathcal{L}_{CPV} = \frac{\eta}{\Lambda} S \, \bar{Q}_L \, \tilde{\Phi} \, t_R + h.c.$$

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$$Y^{h_i}_{ee} = R_{1i} \left(\frac{m_e}{v} \right)$$

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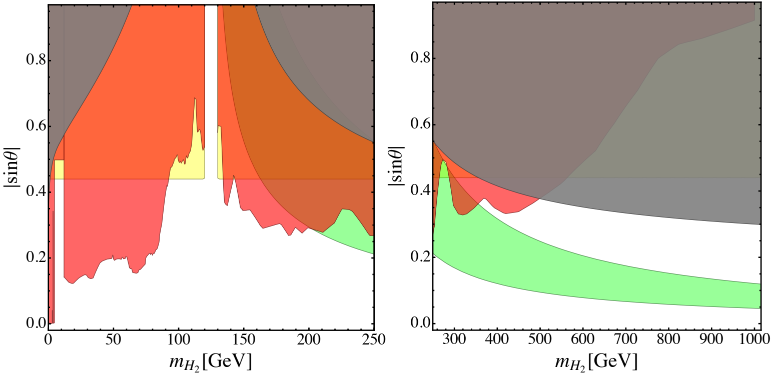
$$Y^{h_i}_{tt} = R_{1i} \left(\frac{m_t}{v} \right) + R_{2i} \left(\frac{v(\mathrm{Re}\eta + i\mathrm{Im}\eta)}{2\Lambda} \right)$$

$\Rightarrow$ Results identical to SM+RS

What constrains the parameter space?



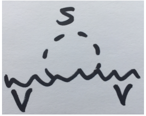
Excluded by direct searches, precision tests, H_1 couplings measurements and preferred by potential stability.

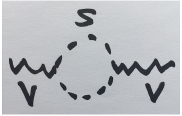
[JHEP 05, 057 (2015)]

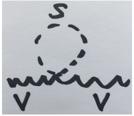
2HDM + singlet scalar

Extra doublets lead to extra constraints

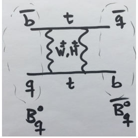
Electroweak precision observables:

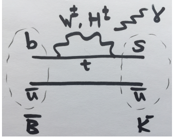


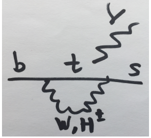


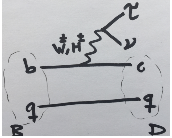


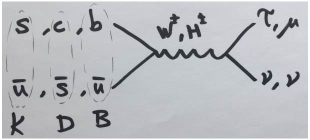
Flavour observables:











2HDM + singlet