

2nd International Workshop on

Particle Physics and Cosmology after Higgs and Planck

後希格斯與普朗克粒子物理與宇宙學國際研討會

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Limiting 2HDMs

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arXiv:1409.3199



Introduction

- 2HDM limited by muon $g-2$?

$$\begin{aligned} a_{\mu}^{\text{SM}} &= 116591829(57) \times 10^{-11} \\ a_{\mu}^{\text{EXP}} &= 116592091(63) \times 10^{-11} \end{aligned} \quad \Delta a_{\mu} \equiv a_{\mu}^{\text{EXP}} - a_{\mu}^{\text{SM}} = +262(85) \times 10^{-11}$$

- Barr-Zee two-loop with a light Higgs and large t_{β} .
- The charged Higgs heavy enough ($b \rightarrow s \gamma$).
- SM-like 126 GeV Higgs at LHC.
- Constraints from EWPD, vacuum stability & perturbativity, B observables & collider searches.
- Selected is Type X with $m_A = 63 - 80$ GeV & $t_{\beta} > 70$ at 2σ .

2HDMs

$$V = m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \Phi_1 \Phi_2^\dagger) \\ + \frac{\lambda_1}{2} |\Phi_1|^4 + \frac{\lambda_2}{2} |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 + \frac{\lambda_5}{2} \left[(\Phi_1^\dagger \Phi_2)^2 + (\Phi_1 \Phi_2^\dagger)^2 \right]$$

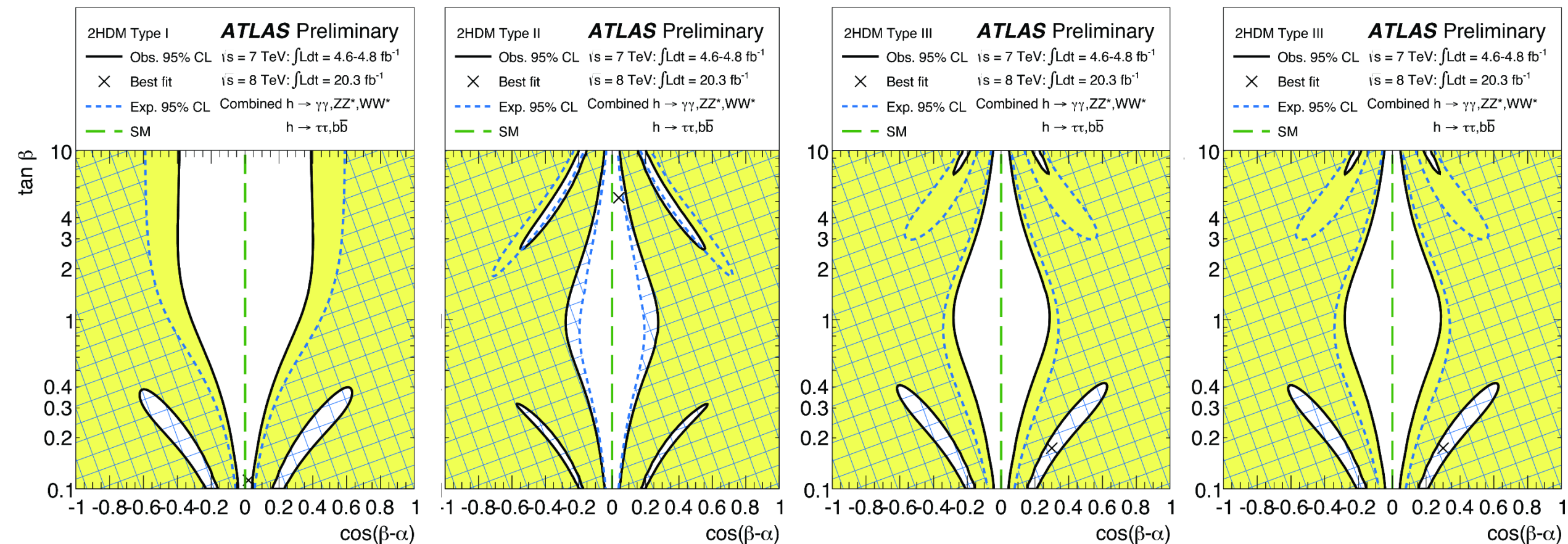
Model	u_R^i	d_R^i	e_R^i		y_u^A	y_d^A	y_l^A	y_u^H	y_d^H	y_l^H	y_u^h	y_d^h	y_l^h
Type I	Φ_2	Φ_2	Φ_2	Type I	$\cot \beta$	$-\cot \beta$	$-\cot \beta$	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\sin \beta}$
Type II	Φ_2	Φ_1	Φ_1	Type II	$\cot \beta$	$\tan \beta$	$\tan \beta$	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\cos \beta}$	$\frac{\cos \alpha}{\cos \beta}$	$\frac{\cos \alpha}{\sin \beta}$	$-\frac{\sin \alpha}{\cos \beta}$	$-\frac{\sin \alpha}{\cos \beta}$
Lepton-specific	Φ_2	Φ_2	Φ_1	Type X	$\cot \beta$	$-\cot \beta$	$\tan \beta$	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\cos \beta}$	$\frac{\cos \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\sin \beta}$	$-\frac{\sin \alpha}{\cos \beta}$
Flipped	Φ_2	Φ_1	Φ_2	Type Y	$\cot \beta$	$\tan \beta$	$-\cot \beta$	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\cos \beta}$	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\sin \beta}$	$-\frac{\sin \alpha}{\cos \beta}$	$\frac{\cos \alpha}{\sin \beta}$

$$\mathcal{L}_{\text{Yukawa}}^{\text{2HDM}} = - \sum_{f=u,d,\ell} \frac{m_f}{v} \left(\xi_h^f \bar{f} f h + \xi_H^f \bar{f} f H - i \xi_A^f \bar{f} \gamma_5 f A \right) \\ - \left\{ \frac{\sqrt{2} V_{ud}}{v} \bar{u} (m_u \xi_A^u P_L + m_d \xi_A^d P_R) d H^+ + \frac{\sqrt{2} m_\ell \xi_A^\ell}{v} \bar{\nu}_L \ell_R H^+ + \text{H.c.} \right\}$$

126 GeV

126 GeV SM Higgs: $g_{hVV} = \sin(\beta - \alpha) \approx 1$

ATLAS-CONF-2014-010



2HDMs

$$V = m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \Phi_1 \Phi_2^\dagger) \\ + \frac{\lambda_1}{2} |\Phi_1|^4 + \frac{\lambda_2}{2} |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 + \frac{\lambda_5}{2} \left[(\Phi_1^\dagger \Phi_2)^2 + (\Phi_1 \Phi_2^\dagger)^2 \right]$$

Model	u_R^i	d_R^i	e_R^i		y_u^A	y_d^A	y_l^A	y_u^H	y_d^H	y_l^H	y_u^h	y_d^h	y_l^h
Type I	Φ_2	Φ_2	Φ_2	Type I	$\cot \beta$	$-\cot \beta$	$-\cot \beta$	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\sin \beta}$
Type II	Φ_2	Φ_1	Φ_1	Type II	$\cot \beta$	$\tan \beta$	$\tan \beta$	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\cos \beta}$	$\frac{\cos \alpha}{\cos \beta}$	$\frac{\cos \alpha}{\sin \beta}$	$-\frac{\sin \alpha}{\cos \beta}$	$-\frac{\sin \alpha}{\cos \beta}$
Lepton-specific	Φ_2	Φ_2	Φ_1	Type X	$\cot \beta$	$-\cot \beta$	$\tan \beta$	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\cos \beta}$	$\frac{\cos \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\sin \beta}$	$-\frac{\sin \alpha}{\cos \beta}$
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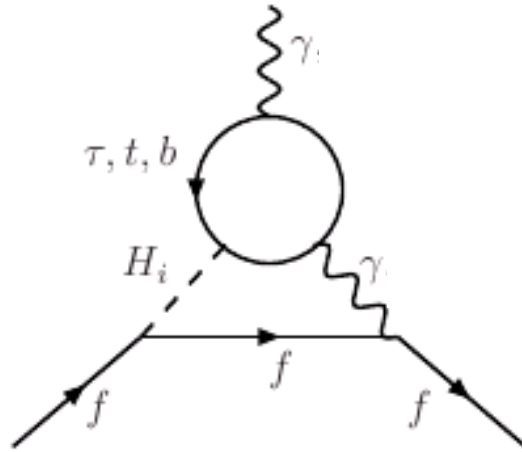
$$\mathcal{L}_{\text{Yukawa}}^{\text{2HDM}} = - \sum_{f=u,d,\ell} \frac{m_f}{v} \left(\xi_h^f \bar{f} f h + \xi_H^f \bar{f} f H - i \xi_A^f \bar{f} \gamma_5 f A \right) \\ - \left\{ \frac{\sqrt{2} V_{ud}}{v} \bar{u} (m_u \xi_A^u P_L + m_d \xi_A^d P_R) d H^+ + \frac{\sqrt{2} m_\ell \xi_A^\ell}{v} \bar{\nu}_L \ell_R H^+ + \text{H.c.} \right\}$$

126 GeV

LHC Higgs data
 $\cos(\beta - \alpha) \approx 0$

Muon $g-2$ vs. $b \rightarrow s \gamma$

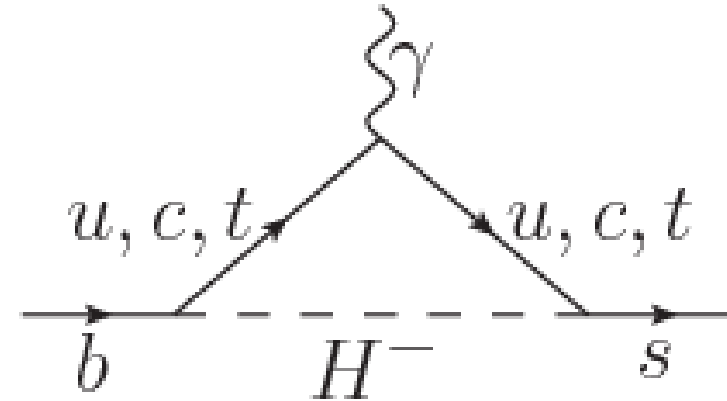
Cheung, Chou, Kong, 0103183



$$\delta a_{\mu}^{2\text{loop}}(\gamma\text{BZ}) = \frac{G_F m_{\mu}^2}{4\pi^2 \sqrt{2}} \frac{\alpha_{\text{em}}}{\pi} \sum_{i,f} N_f^c Q_f^2 y_{\mu}^i y_f^i r_f^i g_i(r_f^i)$$

	τ	t	b
I	$1/t_{\beta}^2$	$-1/t_{\beta}^2$	$1/t_{\beta}^2$
II	t_{β}^2	1	t_{β}^2
X	t_{β}^2	1	-1
Y	$1/t_{\beta}^2$	$-1/t_{\beta}^2$	-1

H : negative
A : positive



$$\frac{m_t}{t_{\beta}} P_L - \frac{m_b}{t_{\beta}} P_R \quad (I, X) \quad \text{NA} \quad \text{for } t_{\beta} > 2$$

$$\frac{m_t}{t_{\beta}} P_L + m_b t_{\beta} P_R \quad (II, Y) \quad m_{H^{\pm}} > 380 \text{ GeV}$$

EWPD

$$M_W^2 = \frac{M_Z^2}{2} \left[1 + \sqrt{1 - \frac{4\pi\alpha}{\sqrt{2}G_F M_Z^2} \frac{1}{1 - \Delta r}} \right]$$

$$\sin^2 \theta_{\text{eff}}^{\text{lept}} = k_l (M_Z^2) \sin^2 \theta_W$$

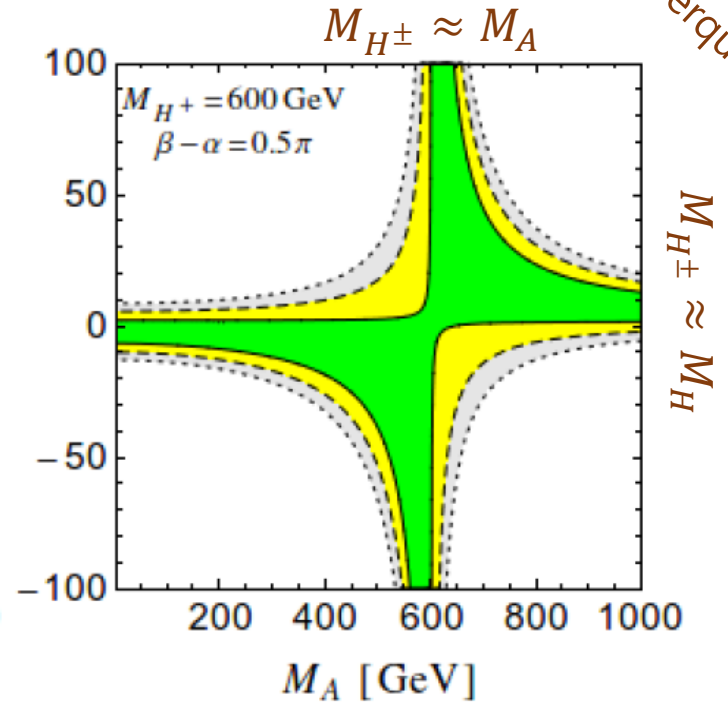
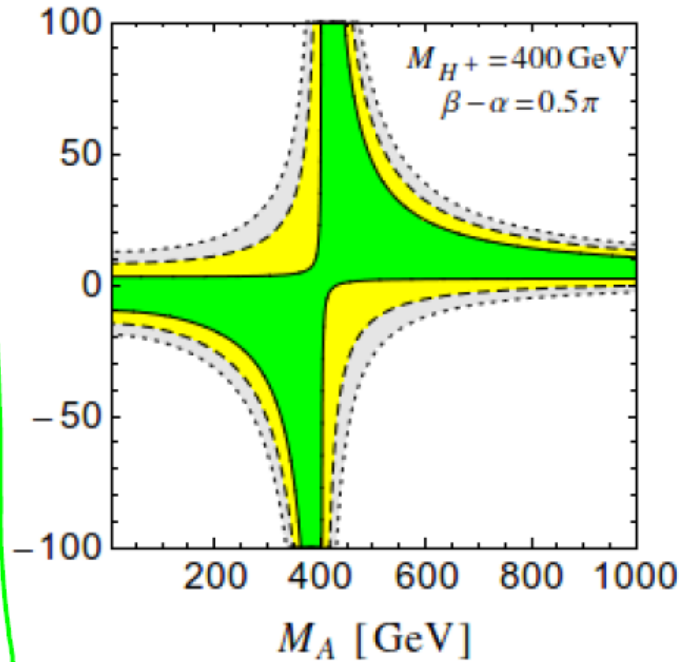
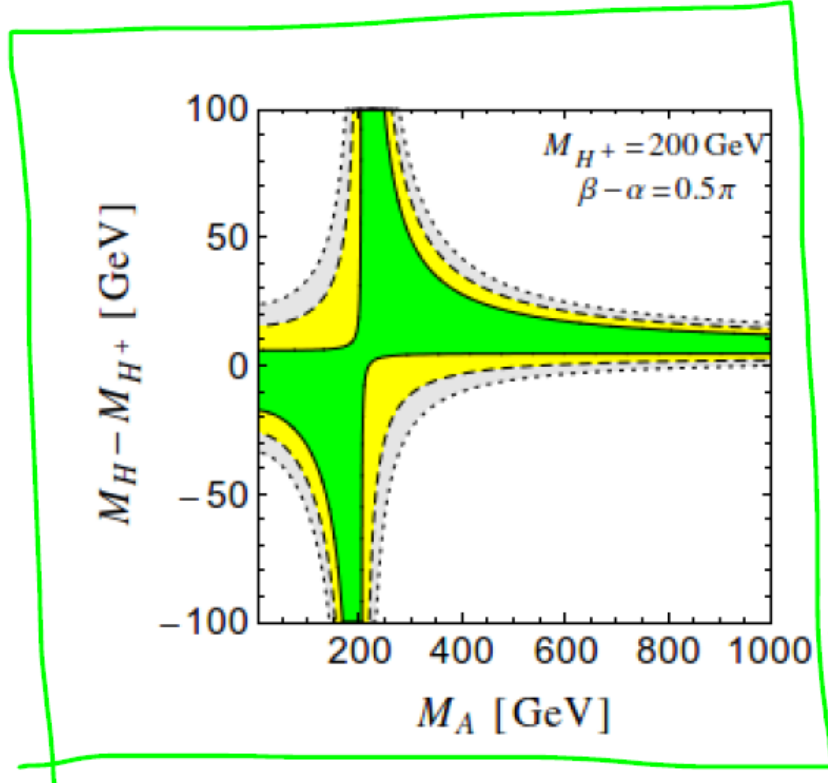
$$M_W^{\text{exp}} = 80.385 \pm 0.015 \text{ GeV},$$

$$\sin^2 \theta_{\text{eff}}^{\text{lept, exp}} = 0.23153 \pm 0.00016.$$

$$\Delta r^{2\text{HDM}} = \Delta \alpha^{2\text{HDM}} - \frac{\cos^2 \theta_W}{\sin^2 \theta_W} \Delta \rho^{2\text{HDM}} + \dots,$$

$$\Delta k_l^{2\text{HDM}} = + \frac{\cos^2 \theta_W}{\sin^2 \theta_W} \Delta \rho^{2\text{HDM}} + \dots,$$

Twisted custodial symmetry:
Gerard-Herquet, 0703051



Vacuum stability & perturbativity

$$\lambda_{1,2} > 0, \quad \lambda_3 > -\sqrt{\lambda_1 \lambda_2}, \quad |\lambda_5| < \lambda_3 + \lambda_4 + \sqrt{\lambda_1 \lambda_2}$$

$$m_{12}^2(m_{11}^2 - m_{22}^2 \sqrt{\lambda_1/\lambda_2})(\tan \beta - (\lambda_1/\lambda_2)^{1/4}) > 0$$

$$M_A^2 = \frac{m_{12}^2}{\sin \beta \cos \beta} - \lambda_5 v^2,$$

$$M_{H^\pm}^2 = M_A^2 + \frac{1}{2} v^2 (\lambda_5 - \lambda_4).$$

For $\tan \beta \gg 1$

$$\lambda_2 v^2 \simeq M_h^2 + \lambda_1 v^2 / \tan^4 \beta,$$

$$\lambda_3 v^2 \simeq 2M_{H^\pm}^2 - 2M_H^2 + M_h^2 + \lambda_1 v^2 / \tan^2 \beta,$$

$$m_{12}^2 \simeq M_H^2 / \tan \beta + (M_h^2 - \lambda_1 v^2) / \tan^3 \beta.$$

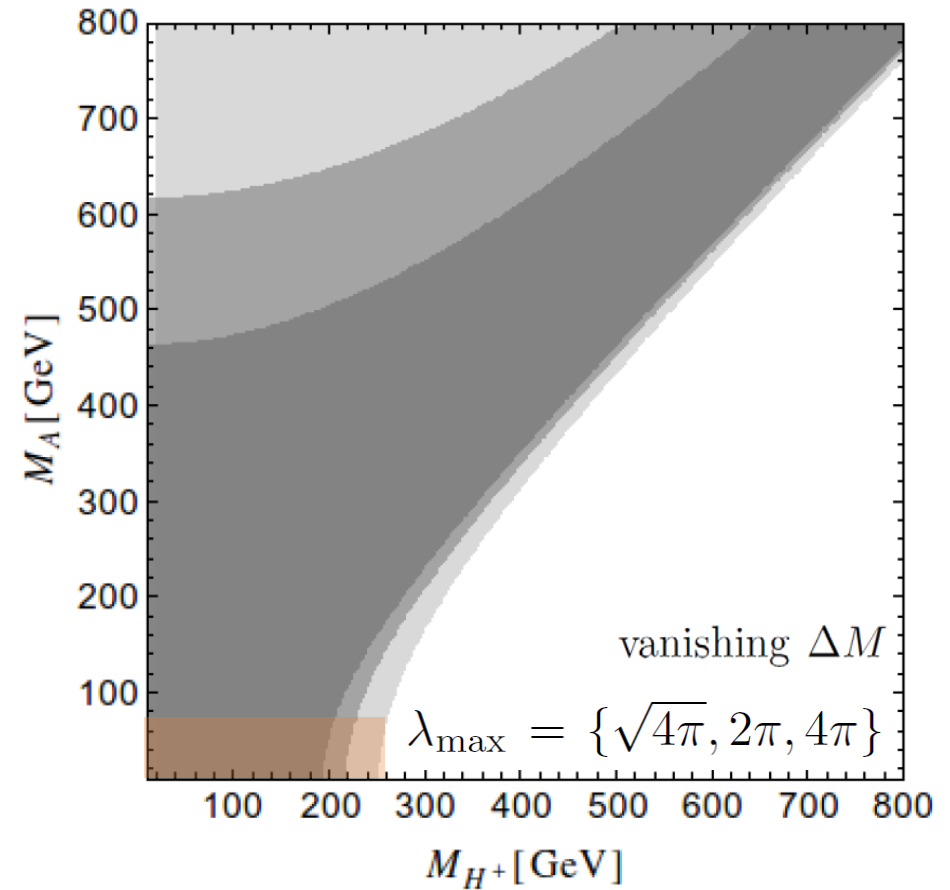
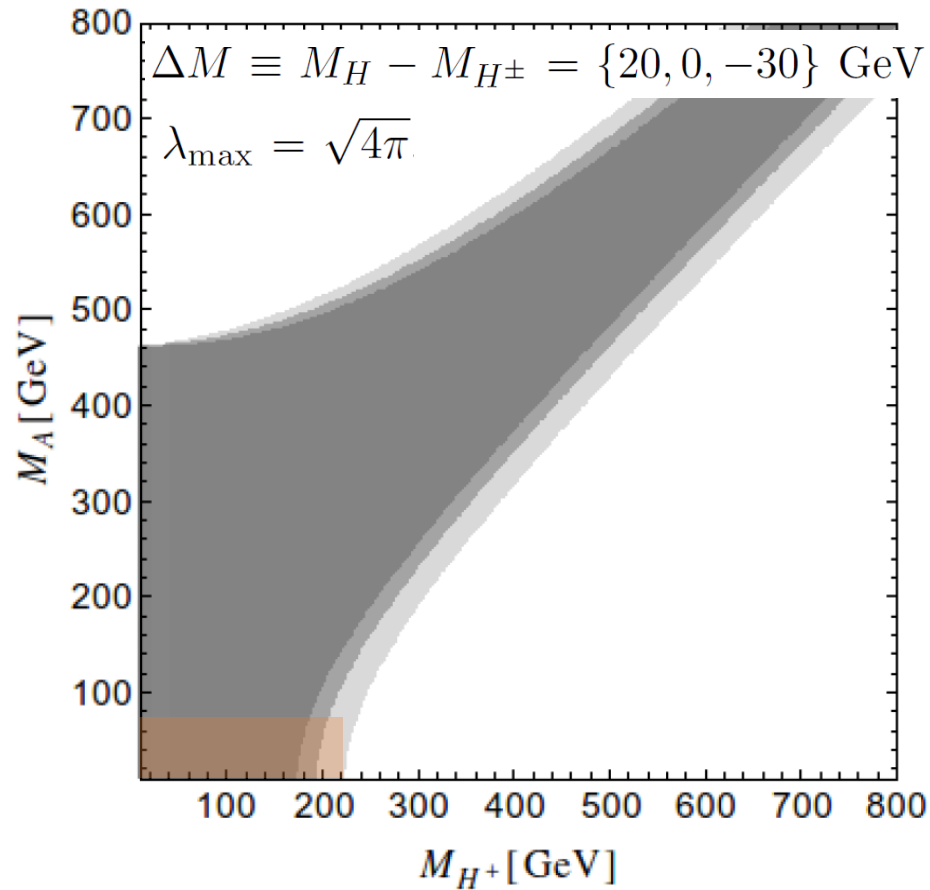
$$\lambda_2 v^2 \approx M_h^2$$

$$\lambda_3 v^2 \approx 2M_{H^\pm}^2 - 2M_H^2 + M_h^2$$

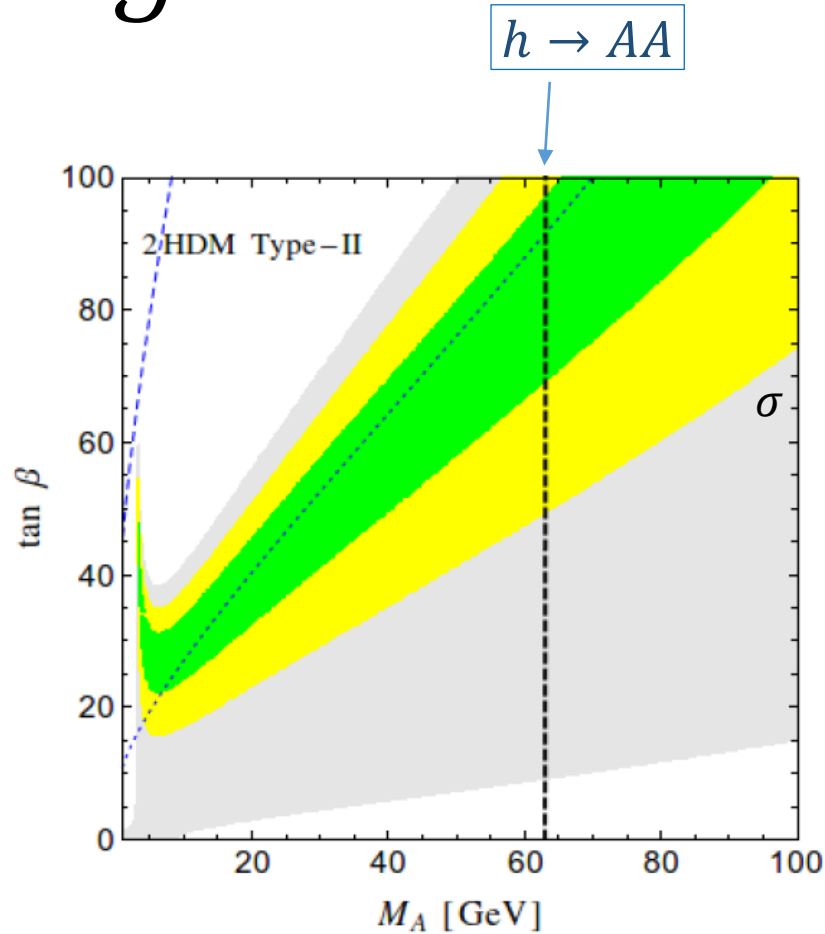
$$\lambda_4 v^2 \approx M_H^2 - 2M_{H^\pm}^2 + M_A^2$$

$$\lambda_5 v^2 \approx M_H^2 - M_A^2$$

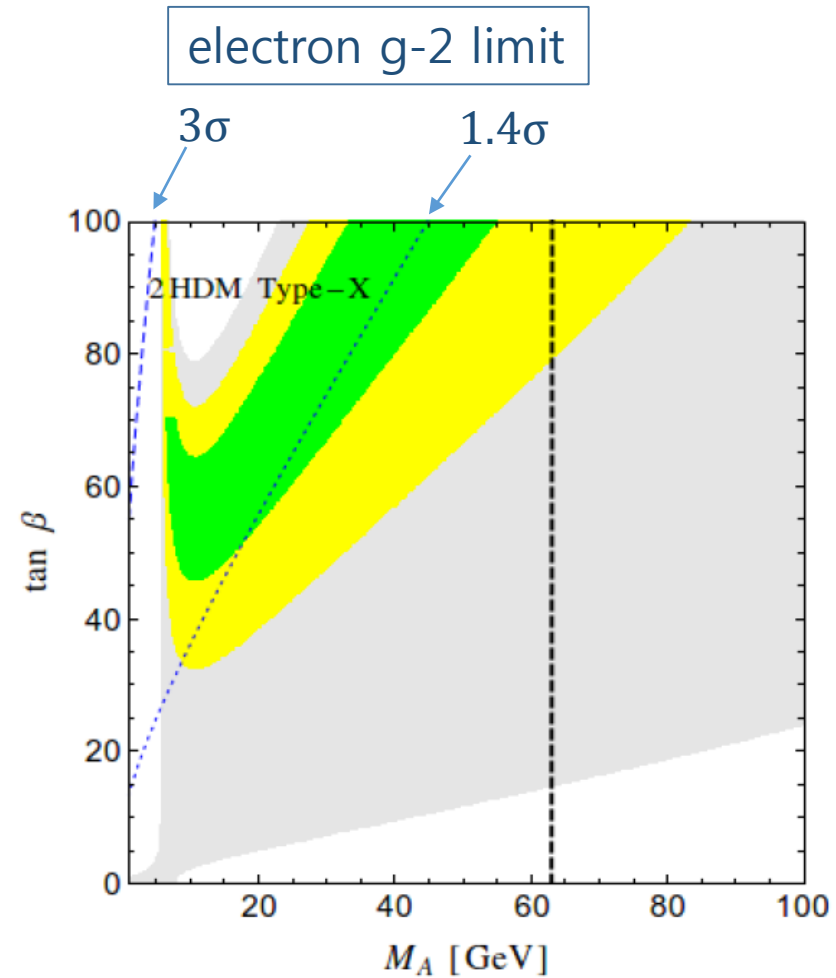
Vacuum stability & perturbativity



Muon $g-2$



$$M_{h(H)} = 126 \text{ (200) GeV}$$



$$\lambda_{hAA} \approx v s_{\beta-\alpha} \frac{[2M_H^2 - M_h^2 - 2M_A^2]}{v^2} \gtrsim 0.3v$$

Conclusion

- Imposing muon $g-2$ singles out Type X 2HDM.
- The 1σ region is excluded by LHC Higgs data forbidding $h \rightarrow AA$.
- At 2σ allowed is $t_\beta > 70$, $m_A = 63 - 80$ GeV & $m_H, m_{H^\pm} \lesssim 220$ GeV.
- Single production of the extra Higgses are suppressed by large t_β or small $c_{\beta-\alpha}$.
- Pair productions will be readily probed at LHC14:
 $pp \rightarrow \gamma/Z/W \rightarrow H^+H^-, HA, H^\pm H, H^\pm A$ with $H^\pm \rightarrow \tau^\pm \nu, H/A \rightarrow \tau^+ \tau^-$.

Kanemura, et.al., 1406.3294