KOREA INSTITUTE FOR ADVANCED STUDY

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The (g-2)$_\mu$ in Lepton-specific 2HDM

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In collaboration with A. Broggio, M. Passera, K.M. Patel, S.K. Vempati, arXiv:1409.3199;
Z. Kang, M. Takeuchi, Y.L.S. Tsai, work in progress.

Introduction

- "Can the muon g-2 be accounted for in 2HDMs?"

$$\boxed{\Delta a_\mu \equiv a_\mu^{\rm EXP} - a_\mu^{\rm SM} = +262\,(85) \times 10^{-11}}$$

a lot of studies in SUSY, much less in 2HDMs…

0102145, 146, 147, … vs. Dedes, Haber, 0102297
Cheung, Chou, Kong, 0103183

- Constraints from the 126 GeV Higgs data at LHC.
- Extra Higgs spectrum constrained by EWPD, vacuum stability & perturbativity, and also by $B_q \to X_s\gamma, \mu^+\mu^-, etc.$
- The unique choice: Type X with Barr-Zee two loop in the ranges of $20 < m_A(GeV) < 120$, $t_\beta > 50$, & $200 < m_H \sim m_{H^\pm}(GeV) < 600$.

2HDMs

- Two Higgs Doublets:

$$\Phi_{1,2} = (\phi_{1,2}^{+}, \frac{1}{\sqrt{2}}[v_{1,2} + \rho_{1,2} + i\,\eta_{1,2}]) \rightarrow h, H, A, H^{\pm}; \quad t_\beta = \frac{v_1}{v_2}$$

$$G^0 = \eta_1 c_\beta + \eta_2 s_\beta \qquad h = \rho_1 c_\alpha - \rho_2 s_\alpha$$

$$A = \eta_1 s_\beta - \eta_2 c_\beta \qquad H = \rho_1 s_\alpha + \rho_2 c_\alpha$$

- Gauge coupling: $\mathcal{L}_g = g_V m_V \left(s_{\beta-\alpha} h + c_{\beta-\alpha} H \right) VV + \cdots$
- FCNC: Mass diagonalization ≠ Yukawa diagonalization

$$\mathcal{L}_{Yuk} = y_{ij}^{u2} \Phi_2 q_i u_j^c + y_{ij}^{dp} \Phi_p q_i d_j^c + y_{ij}^{eq} \Phi_q l_i e_j^c + h.c.$$

$$M_{ij}^{f} = y_{ij}^{f1} \frac{v_1}{\sqrt{2}} + y_{ij}^{f2} \frac{v_2}{\sqrt{2}} \quad \rightarrow \quad y_{ij}^{d}\, h d_i d_j^c + \cdots$$

4 types of 2HDMs

Natural flavor conservation imposed by Z_2 :
only one Higgs to each Yukawa type (d, e)

Nb) Type III : aligned Yukawa
$y^1_{ij} \sim y^2_{ij}$

$\Phi_2(+), \Phi_1(-); t_R(+), d_R(\pm), e_R(\pm)$

Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

	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	$\cot\beta$	$-\cot\beta$	$-\cot\beta$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$
Type II	$\cot\beta$	$\tan\beta$	$\tan\beta$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$-\frac{\sin\alpha}{\cos\beta}$
Type X	$\cot\beta$	$-\cot\beta$	$\tan\beta$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$
Type Y	$\cot\beta$	$\tan\beta$	$-\cot\beta$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$

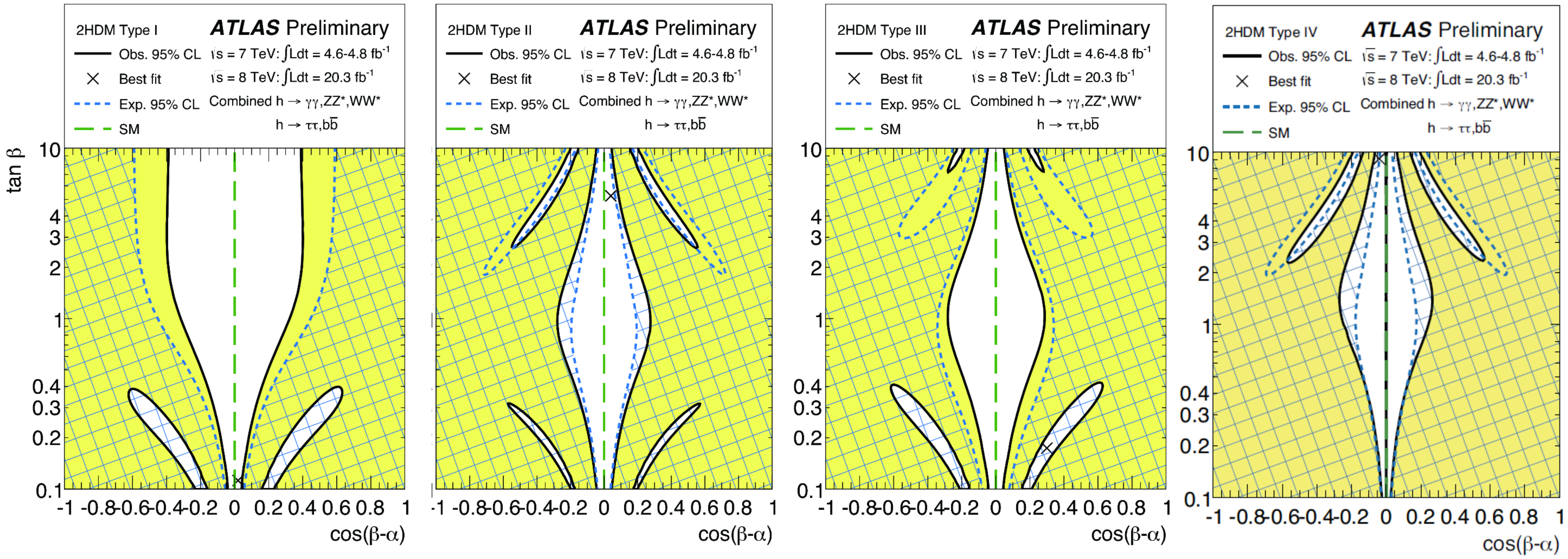
$$\mathcal{L}_{\rm Yukawa}^{\rm 2HDM} = -\sum_{f=u,d,\ell} \frac{m_f}{v}\left(\xi_h^f \overline{f} f h + \xi_H^f \overline{f} f H - i\xi_A^f \overline{f}\gamma_5 f A\right)$$

126 GeV

$$-\left\{\frac{\sqrt{2}V_{ud}}{v}\,\overline{u}\left(m_u\xi_A^u \mathrm{P}_L + m_d\xi_A^d \mathrm{P}_R\right) d H^+ + \frac{\sqrt{2}m_\ell \xi_A^\ell}{v}\,\overline{\nu_L}\ell_R H^+ + \mathrm{H.c.}\right\}$$

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

ATLAS-CONF-2014-010



Aligned/decoupled 2HDMs

$$
\begin{aligned}
V_H \;=\;& m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left(m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{H.c.} \right) \\
&+ \tfrac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 + \tfrac{1}{2}\lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) \\
&+ \left[\tfrac{1}{2}\lambda_5 \left(\Phi_1^\dagger \Phi_2\right)^2 + \cancel{\lambda_6} \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_1^\dagger \Phi_2\right) + \cancel{\lambda_7} \left(\Phi_2^\dagger \Phi_2\right)\left(\Phi_1^\dagger \Phi_2\right) + \text{H.c.} \right],
\end{aligned}
$$

Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

	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	$\cot\beta$	$-\cot\beta$	$-\cot\beta$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$
Type II	$\cot\beta$	$\tan\beta$	$\tan\beta$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$-\frac{\sin\alpha}{\cos\beta}$
Type X	$\cot\beta$	$-\cot\beta$	$\tan\beta$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$
Type Y	$\cot\beta$	$\tan\beta$	$-\cot\beta$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$

$\approx$

1

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

$$
\begin{aligned}
\mathcal{L}_{\text{Yukawa}}^{\text{2HDM}} =& - \sum_{f=u,d,\ell} \frac{m_f}{v} \left(\xi_h^f \overline{f} f h + \xi_H^f \overline{f} f H - i \xi_A^f \overline{f} \gamma_5 f A \right) \\
& - \left\{ \frac{\sqrt{2} V_{ud}}{v} \overline{u} \left(m_u \xi_A^u \mathrm{P}_L + m_d \xi_A^d \mathrm{P}_R \right) d H^+ + \frac{\sqrt{2} m_\ell \xi_A^\ell}{v} \overline{\nu_L} \ell_R H^+ + \text{H.c.} \right\}
\end{aligned}
$$

126 GeV

Muon g-2

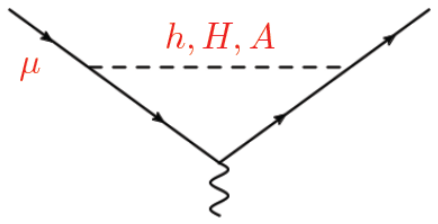
- **One-loop contribution:**

$$\delta a_\mu^{\rm 2HDM}(1\mathrm{loop}) = \frac{G_F\, m_\mu^2}{4\pi^2\sqrt{2}} \sum_{j=h,H,A,H^\pm} \left(y_\mu^j\right)^2 r_\mu^j\, f_j(r_\mu^j)$$

roughly scales with m_μ^4!

For $r_\mu^j = m_\mu^2/M_j^2 \ll 1$:

$$\begin{aligned} f_{h,H}(r) &\sim -\ln r - 7/6 + O(r) > 0 \\ f_A(r) &\sim +\ln r + 11/6 + O(r) < 0 \\ f_{H^\pm}(r) &\sim -1/6 + O(r) < 0 \end{aligned}$$



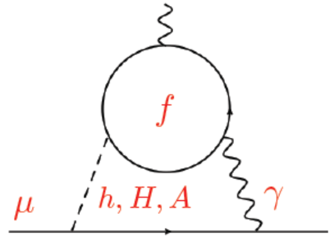
- **Two-loop Barr-Zee type diagrams:**

m_f^2/m_μ^2 w.r.t. 1 loop

$$\delta a_\mu^{\rm 2HDM}(2\mathrm{loop}-\mathrm{BZ}) = \frac{G_F\, m_\mu^2}{4\pi^2\sqrt{2}} \frac{\alpha_{\rm em}}{\pi} \sum_{f;\, i=h,H,A} N_f^c\, Q_f^2\, y_\mu^i\, y_f^i\, r_f^i\, g_i(r_f^i)$$

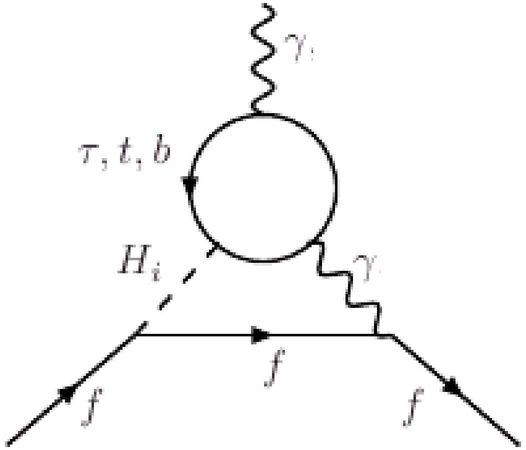
$$\begin{aligned} g_{h,H}(r) &< 0 \\ g_A(r) &> 0 \end{aligned}$$

Type II, $M_A \gtrsim$ 3GeV & $\tan\beta \gtrsim 5$: $(2\mathrm{loop})_A > (1\mathrm{loop})_A$. Similar for X.



Muon g-2 vs. b → $s\,\gamma$

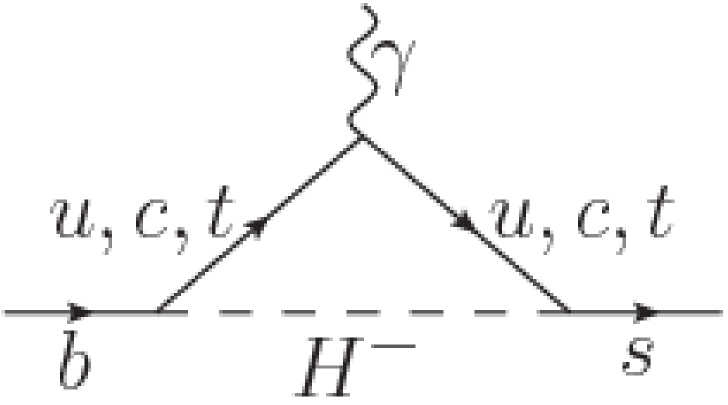
Cheung, Chou, Kong, 0103183
Cao, et.al, 0909.5148



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

	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



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

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

EWPD

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

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

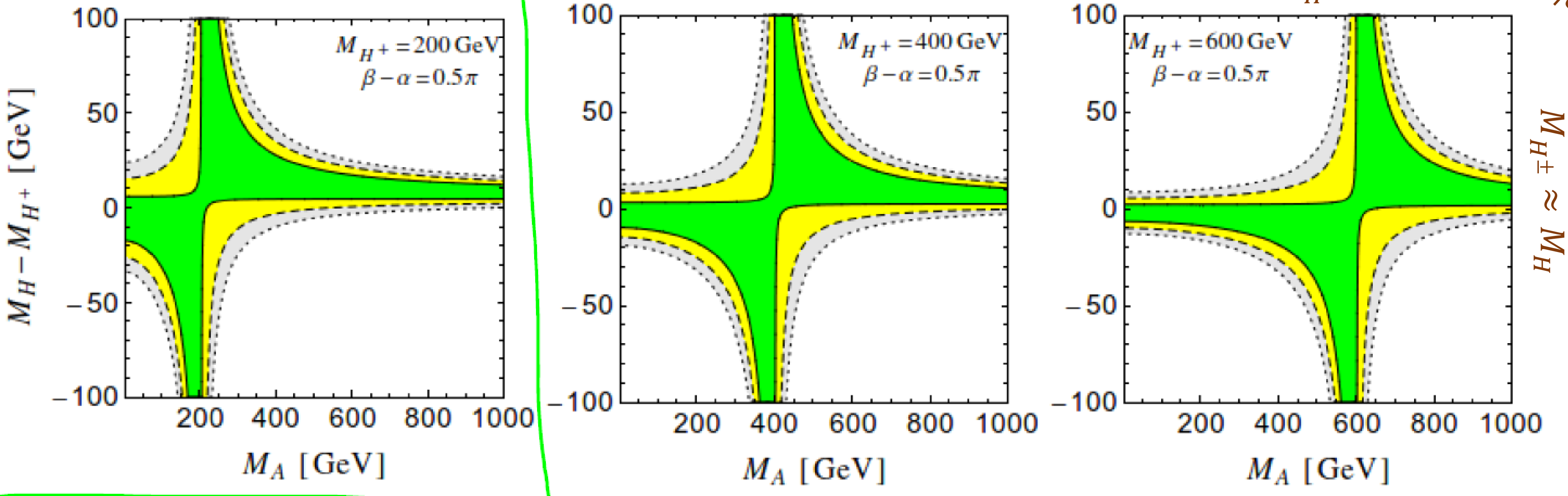
$$M_W^{\rm exp} = 80.385 \pm 0.015\ {\rm GeV},$$
$$\sin^2\theta_{\rm eff}^{\rm lept,\ exp} = 0.23153 \pm 0.00016.$$

$$\Delta r^{\rm 2HDM} = \Delta\alpha^{\rm 2HDM} - \frac{\cos^2\theta_W}{\sin^2\theta_W}\Delta\rho^{\rm 2HDM} + \ldots,$$
$$\Delta k_l^{\rm 2HDM} = +\frac{\cos^2\theta_W}{\sin^2\theta_W}\Delta\rho^{\rm 2HDM} + \ldots,$$

Twisted custodial symmetry:
Gerard-Herquet, 0703051

$M_{H^\pm} \approx M_A$

$M_{H^\pm} \approx M_H$



Vacuum stability & perturbativity

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

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

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

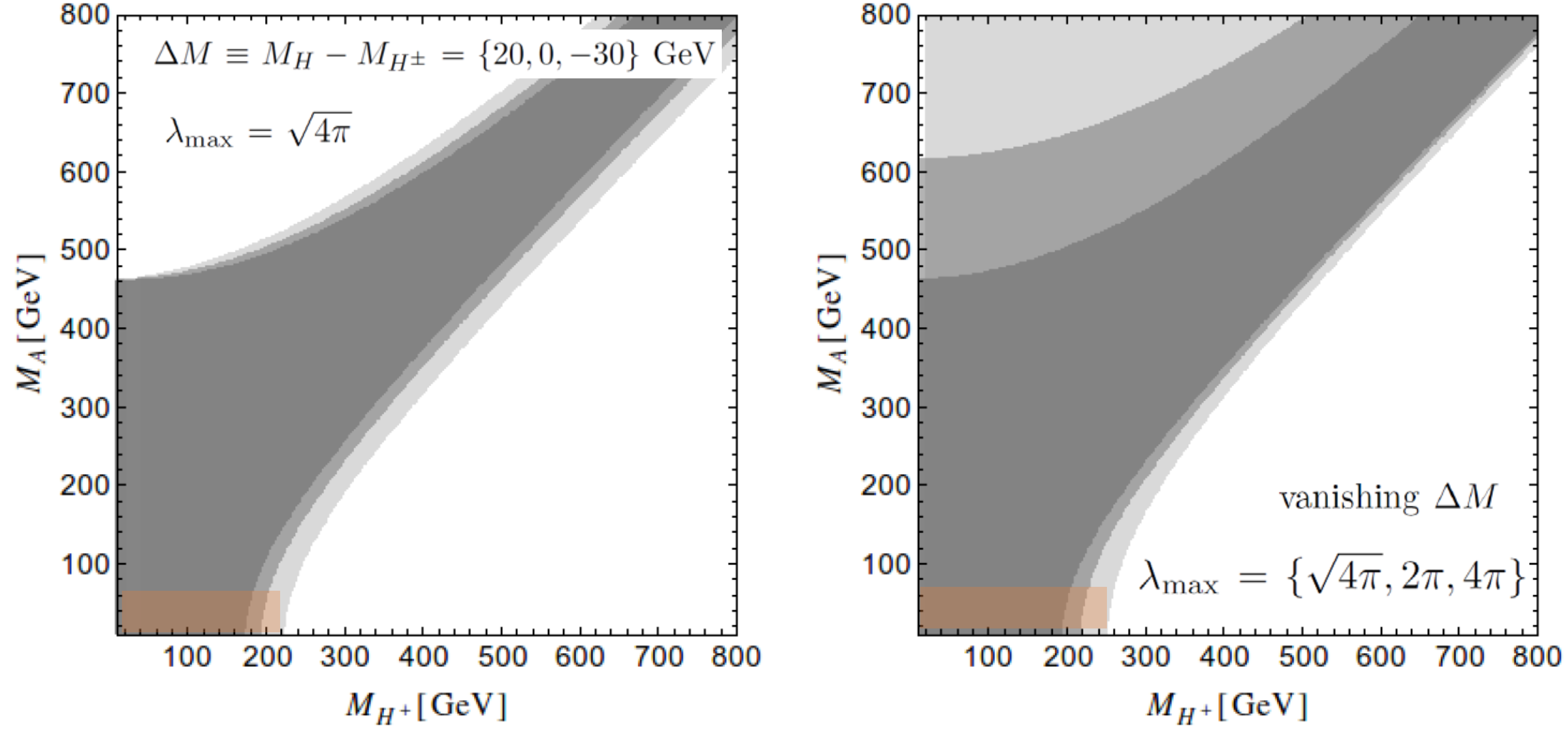
$$M_{H^\pm}^2 = M_A^2 + \frac{1}{2}v^2(\lambda_5 - \lambda_4).$$

For $\tan\beta \gg 1$ in the SM limit: $\sin(\beta - \alpha) = 1$,

$$\lambda_2 v^2 \simeq M_h^2 + \lambda_1 v^2/\tan^4\beta,$$
$$\lambda_3 v^2 \simeq 2M_{H^\pm}^2 - 2M_H^2 + M_h^2 + \lambda_1 v^2/\tan^2\beta,$$
$$m_{12}^2 \simeq M_H^2/\tan\beta + (M_h^2 - \lambda_1 v^2)/\tan^3\beta\,.$$

$$\lambda_2 v^2 \approx M_h^2$$
$$\lambda_3 v^2 \approx 2M_{H^\pm}^2 - 2M_H^2 + M_h^2$$
$$\lambda_4 v^2 \approx M_H^2 - 2M_{H^\pm}^2 + M_A^2$$
$$\lambda_5 v^2 \approx M_H^2 - M_A^2$$

Vacuum stability & perturbativity



In the SM limit: $\sin(\beta - \alpha) = 1$

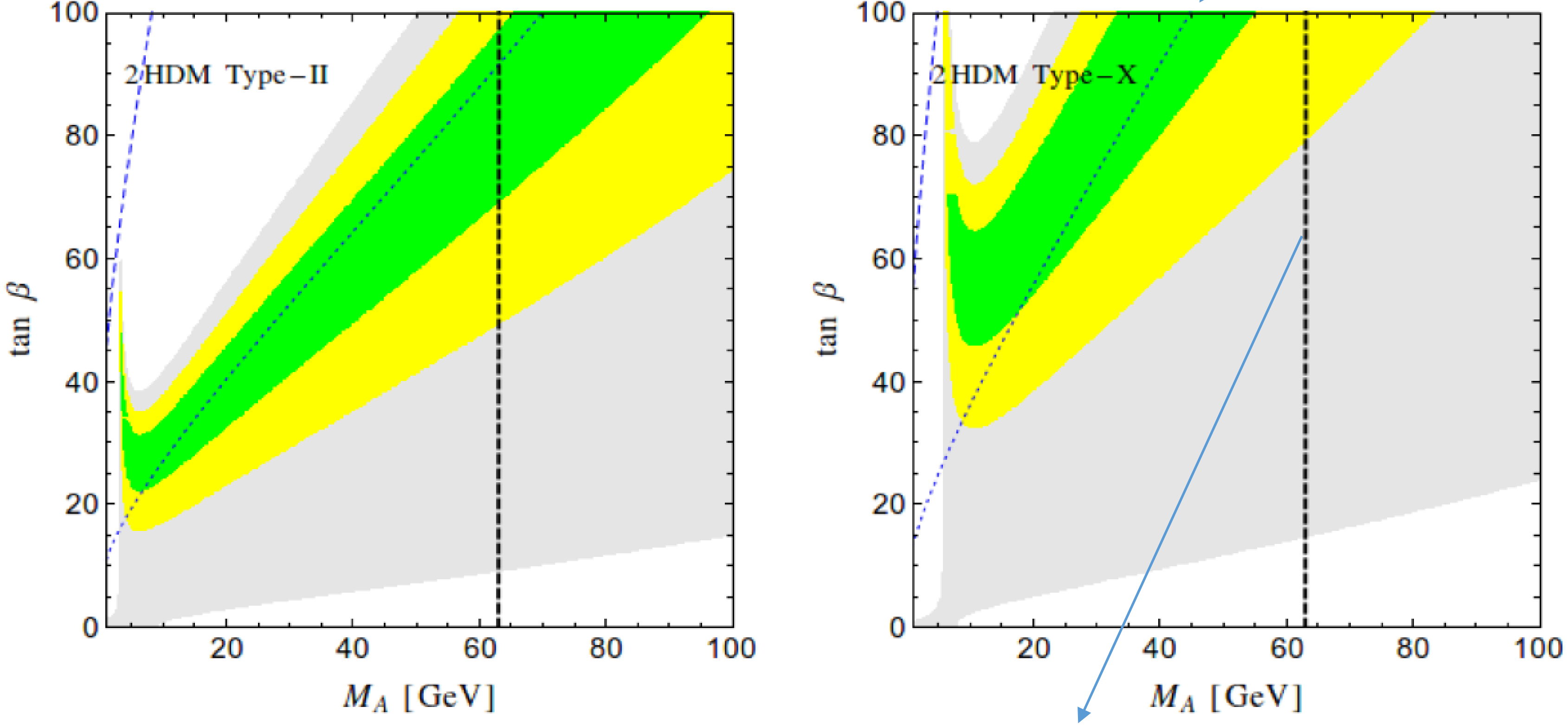
Results

$h \to AA$

electron g-2 limit

3σ

1.4σ



$m_h \ (m_H) = 126 \ (200) \ GeV$

$\lambda_{hAA} v \approx 2M_H^2 - M_h^2 - 2M_A^2 \gtrsim 0.13 \ v^2$ (in the SM limit)

Type X in the wrong-sign limit

$$\mathcal{L}_{\rm Yukawa}^{\rm 2HDM} = -\frac{m_f}{v}\left(\xi_h^f \overline{f} h f + \xi_H^f \overline{f} H f - i\xi_A^f \overline{f}\gamma_5 A f\right) - \left\{\frac{\sqrt{2}V_{ud}}{v}\overline{u}\left(m_u\xi_A^u P_L + m_d\xi_A^d P_R\right)H^+ d + \frac{\sqrt{2}m_l}{v}\xi_A^l \overline{v}_L H^+ l_R + \text{H.C.}\right\}$$

$$\xi_h^u = \xi_h^d = \frac{\cos\alpha}{\sin\beta},\ \xi_h^l = -\frac{\sin\alpha}{\cos\beta},$$
$$\xi_H^u = \xi_H^d = \frac{\sin\alpha}{\sin\beta},\ \xi_H^l = \frac{\cos\alpha}{\cos\beta},$$
$$\xi_A^u = -\xi_A^d = \cot\beta,\ \xi_A^l = \tan\beta.$$

$$\Rightarrow$$

$$\xi_h^q = \frac{c_\alpha}{s_\beta} = s_{\beta-\alpha} + \frac{c_{\beta-\alpha}}{t_\beta} \approx\ 1$$

$$\xi_h^l = -\frac{s_\alpha}{c_\beta} = s_{\beta-\alpha} - t_\beta\, c_{\beta-\alpha} \approx\ \pm 1$$

Ferreira, et.al., 1403.4736

Suppressing $h \to AA(\tau\tau)$ by $\xi_h^\tau \approx -1$

$$\lambda_1 = \frac{m_H^2 c_\alpha^2 + m_h^2 s_\alpha^2 - m_{12}^2 t_\beta}{v^2 c_\beta^2},$$

$$\lambda_2 = \frac{m_H^2 s_\alpha^2 + m_h^2 c_\alpha^2 - m_{12}^2 t_\beta^{-1}}{v^2 s_\beta^2},$$

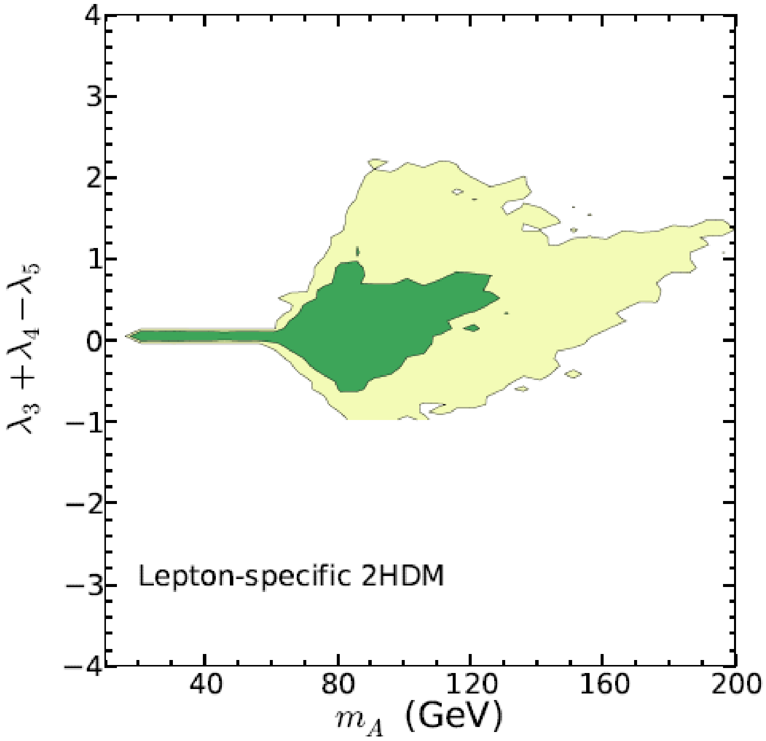
$$\lambda_3 = \frac{(m_H^2 - m_h^2) c_\alpha s_\alpha + 2 m_{H\pm}^2 s_\beta c_\beta - m_{12}^2}{v^2 s_\beta c_\beta},$$

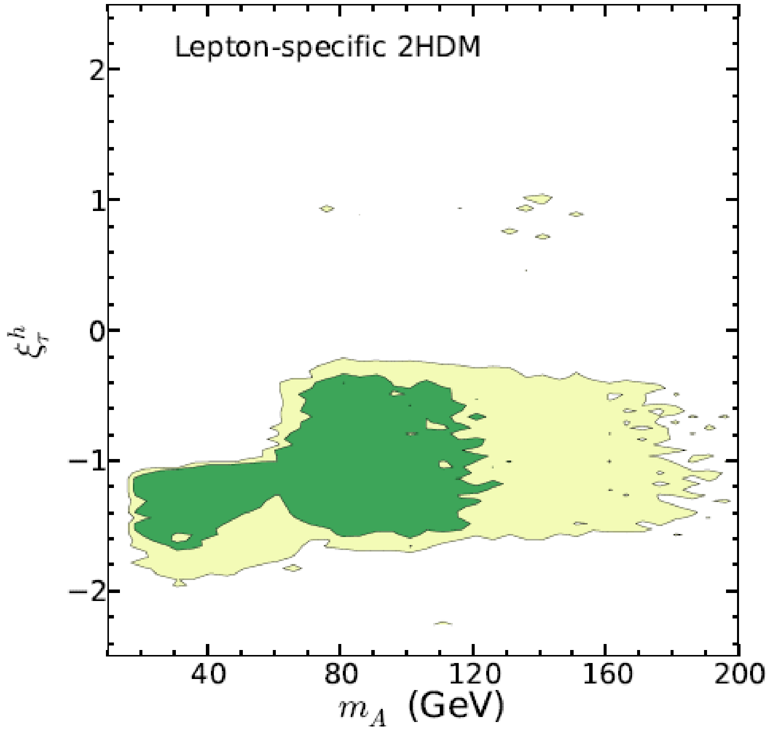
$$\lambda_4 = \frac{(m_A^2 - 2 m_{H\pm}^2) s_\beta c_\beta + m_{12}^2}{v^2 s_\beta c_\beta},$$

$$\lambda_5 = \frac{m_{12}^2 - m_A^2 s_\beta c_\beta}{v^2 s_\beta c_\beta}.$$

$$\lambda_{hAA} v \approx (\lambda_3 + \lambda_4 - \lambda_5) v^2$$
$$\approx (1 + \xi_h^\tau) m_H^2 - \xi_h^\tau m_h^2 - 2 m_A^2$$

$$\xi_h^\tau \approx -\frac{m_H^2 - 2 m_A^2 + \lambda_{hAA} v^2}{m_H^2 - m_h^2}$$

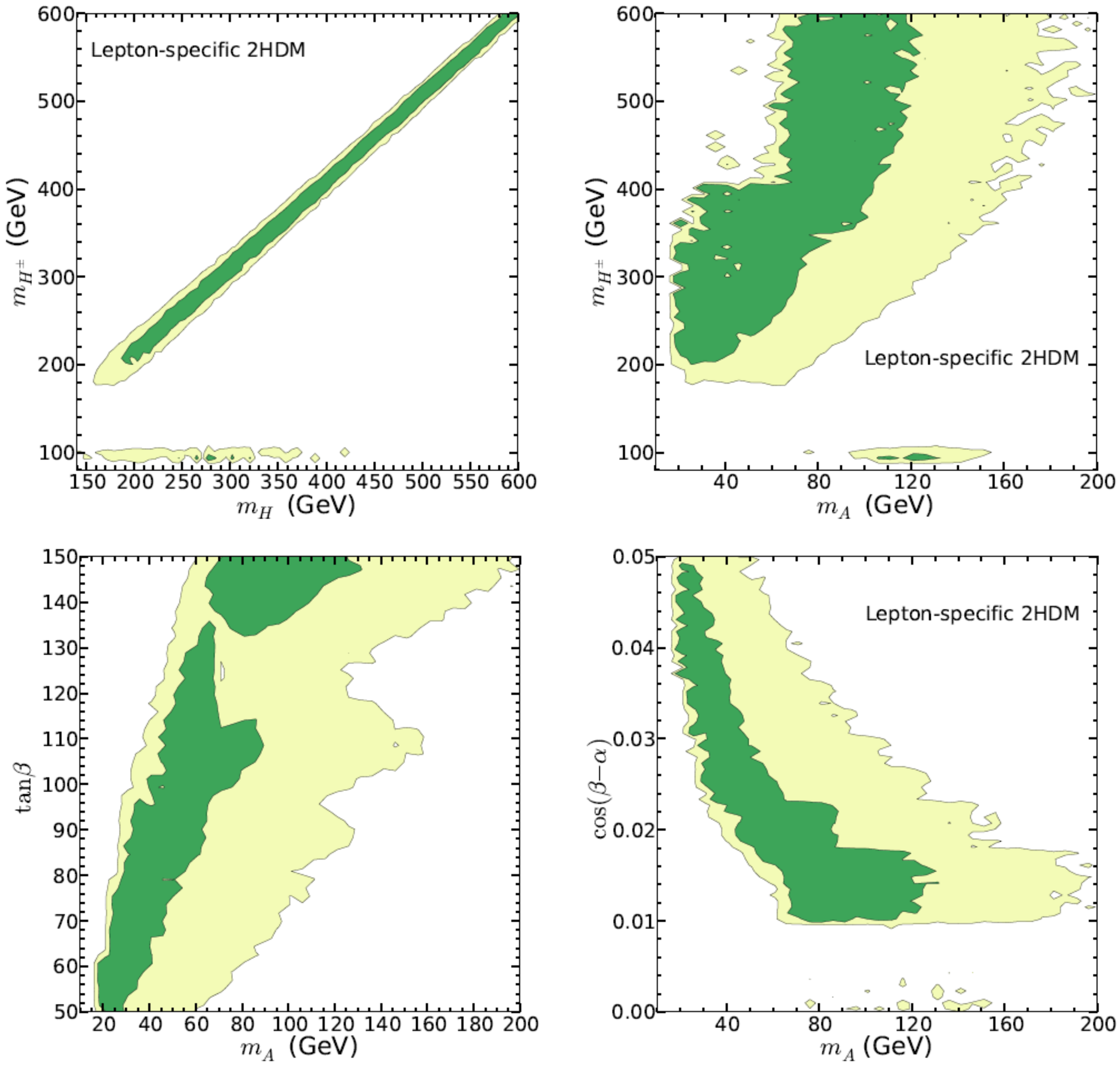




Parameter scan

Measurement	central value μ	Error: $(\sigma,\, \tau)$	Distribution
$\delta\,(g-2)_\mu \times 10^{11}$	262.0	85.0, 0%	Gaussian
BR(h $\to$ EXO)	40%	0.0, 0%	hard-cut
$S,\, T,\, U$	see Ref. [?]	see Ref. [?]	Gaussian
BR($\tau \to \mu\bar{\nu}\nu$)	17.42%	0.04%, 0.07%	Gaussian
$R(h \to \tau\tau)_{\mathrm{ATLAS}}$	1.43	0.4, 0.00%	Gaussian
$R(h \to \tau\tau)_{\mathrm{CMS}}$	0.91	0.28, 0.00%	Gaussian
Higgs bounds	see Ref. [?]	see Ref. [?]	hard cut

2HDM Parameter	Range	Prior distribution
Scenario I: $m_h = 126\,\mathrm{GeV}$		
Scalar Higgs mass (GeV)	$126 < m_H < 600$	Flat
Pseudoscalar Higgs mass (GeV)	$10 < m_A < 400$	Flat
Charged Higgs mass (GeV)	$94 < m_{H^\pm} < 600$	Log
$c_{\beta-\alpha}$	$0.0 < c_{\beta-\alpha} < 0.05$	Flat
t_β	$10 < t_\beta < 150$	Flat
λ_1	$0.0 < \lambda_1 < 4\pi$	Log
Scenario II: $m_H = 126\,\mathrm{GeV}$		
Scalar Higgs mass (GeV)	$40 < m_h < 126$	Flat
Pseudoscalar Higgs mass (GeV)	$10 < m_A < 400$	Flat
Charged Higgs mass (GeV)	$94 < m_{H^\pm} < 600$	Log
$c_{\beta-\alpha}$	$0.0 < s_{\beta-\alpha} < 0.05$	Flat
t_β	$10 < t_\beta < 150$	Flat
λ_1	$0.0 < \lambda_1 < 4\pi$	Log



$$m_H^2 \approx \frac{\xi_h^\tau m_h^2 + 2m_A^2 + \lambda_{hAA} v}{1+\xi_h^\tau}$$

Conclusion

- Imposing the muon g-2 singles out Type X 2HDM in a specific parameter region provable at the LHC2.
- The SM limit is allowed only at 2σ due to large $h \to AA(\tau\tau)$.
- In the wrong-sign limit, the region of $t_\beta > 50$, $m_A = 20 - 80\ GeV, m_H \sim m_{H^\pm} = 200 - 600\ GeV$, is viable with a tuned $\frac{\lambda_{hAA}}{v} \ll 1$.
- LHC13 prospect under investigation:

$$pp \to h, Z, W \to AA, AH, AH^\pm \to 4\tau, 3\tau + \nu.$$