

The $(g-2)_\mu$ in 2HDMs

Eung Jin Chun

In collaboration with A. Broggio, M. Passera, K.M. Patel, S.K. Vempati, arXiv:1409.3199
Z. Kang, M. Takeuchi, Y.L.S. Tsai, arXiv:1507.08067

Introduction

- “Can the muon $g-2$ be accounted for in 2HDMs?”

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

less studied in 2HDMs: Ex.) Dedes, Haber, 0102297 in Type I & II,
Cheung, Chou, Kong, 0103183, etc.
Cao, et.al, 0909.5148 (Type X)

- Revisit the question with updated experimental inputs: [arXiv:1409.3199](#)

- Constraints from the **125 GeV Higgs** data at LHC.
- Extra Higgs spectrum constrained by **EWPD, vacuum stability & perturbativity**.
- Important new inputs from $\bar{B} \rightarrow X_s \gamma$, $B_s \rightarrow \mu^+ \mu^-$, & **lepton universality tests**.

Wang, Han, [arXiv:1412.4874](#); Abe, et.al, [1504.07059](#)

- Predicted tau-rich signatures need to be searched for. [arXiv:1507.08067](#)

Two-Higgs-Doublet-Model (2HDM)

- The most general Higgs potential and Yukawa couplings with two Higgs doublets

$$\begin{aligned} V_{2\text{HDM}} = & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] + \frac{1}{2} \lambda_1 \left(\Phi_1^\dagger \Phi_1 \right)^2 + \frac{1}{2} \lambda_2 \left(\Phi_2^\dagger \Phi_2 \right)^2 \\ & + \lambda_3 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_2^\dagger \Phi_2 \right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_1 \right) + \left\{ \frac{1}{2} \lambda_5 \left(\Phi_1^\dagger \Phi_2 \right)^2 + \left[\lambda_6 \left(\Phi_1^\dagger \Phi_1 \right) \right. \right. \\ & \left. \left. + \lambda_7 \left(\Phi_2^\dagger \Phi_2 \right) \right] \left(\Phi_1^\dagger \Phi_2 \right) + \text{h.c.} \right\}. \end{aligned}$$

$$\mathcal{L}_Y = y_{ij}^{u1,2} \tilde{\Phi}_{1,2} q_i u_j^c + y_{ij}^{d1,2} \Phi_{1,2} q_i d_j^c + y_{ij}^{e1,2} \Phi_{1,2} l_i e_j^c + \text{h.c.}$$

Two-Higgs-Doublet-Model (2HDM)

- 4 mass + 2 angle parameters:

$$\Phi_{1,2} = (\phi_{1,2}^+, \frac{1}{\sqrt{2}} [v_{1,2} + \rho_{1,2} + i \eta_{1,2}]) \rightarrow h(125), H, A, H^\pm; \quad t_\beta = \frac{v_2}{v_1}$$

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

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

- Gauge couplings: $\mathcal{L}_g = g_V m_V (s_{\beta-\alpha} h + c_{\beta-\alpha} H) VV + \dots$
- Yukawa couplings: FCNC if Mass $\neq$ Yukawa

$$\mathcal{L}_Y = y_{ij}^{u1,2} \tilde{\Phi}_{1,2} q_i u_j^c + y_{ij}^{d1,2} \Phi_{1,2} q_i d_j^c + y_{ij}^{e1,2} \Phi_{1,2} l_i e_j^c + h.c.$$

$$\rightarrow (y_{ij}^{f1} c_\beta + y_{ij}^{f2} s_\beta) \frac{v}{\sqrt{2}} f_i f_j^c \quad \text{vs.} \quad (y_{ij}^{f1} c_\alpha - y_{ij}^{f2} s_\alpha) h f_i f_j^c + \dots$$

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
 $y_{ij}^1 \sim y_{ij}^2$

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

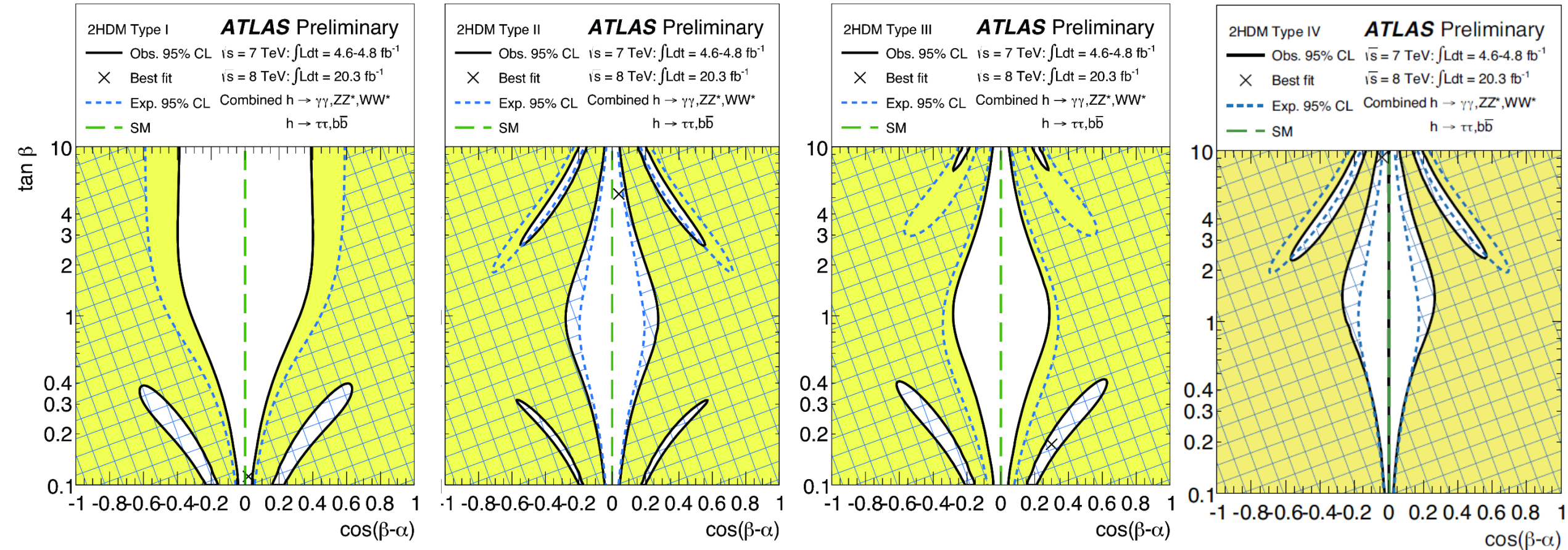
Model	u_R^i	d_R^i	e_R^i		y_u^A	y_d^A	y_l^A	y_u^H	y_d^H	y_l^H	y_u^h	y_d^h	y_l^h
Type I	Φ_2	Φ_2	Φ_2	Type I	$\cot \beta$	$-\cot \beta$	$-\cot \beta$	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\sin \beta}$
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	$\cot \beta$	$\tan \beta$	$-\cot \beta$	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\cos \beta}$	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\sin \beta}$	$-\frac{\sin \alpha}{\cos \beta}$	$\frac{\cos \alpha}{\sin \beta}$

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

125 GeV

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

ATLAS-CONF-2014-010



Aligned/decoupled 2HDMs

$$V_{2\text{HDM}} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}] + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\ + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) + \left\{ \frac{1}{2} \lambda_5 (\Phi_1^\dagger \Phi_2)^2 + [\cancel{\lambda_6 (\Phi_1^\dagger \Phi_1)} \right. \\ \left. + \cancel{\lambda_7 (\Phi_2^\dagger \Phi_2)}] (\Phi_1^\dagger \Phi_2) + \text{h.c.} \right\}.$$

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	$\cot \beta$	$\tan \beta$	$-\cot \beta$	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\cos \beta}$	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\sin \beta}$	$-\frac{\sin \alpha}{\cos \beta}$	$\frac{\cos \alpha}{\sin \beta}$

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

125 GeV

± 1

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

Muon g-2 from an extra Higgs?

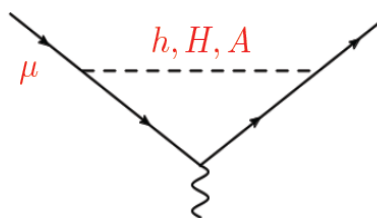
- One-loop with light H and large $y_\mu^H \approx t_\beta$ (II, X):

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

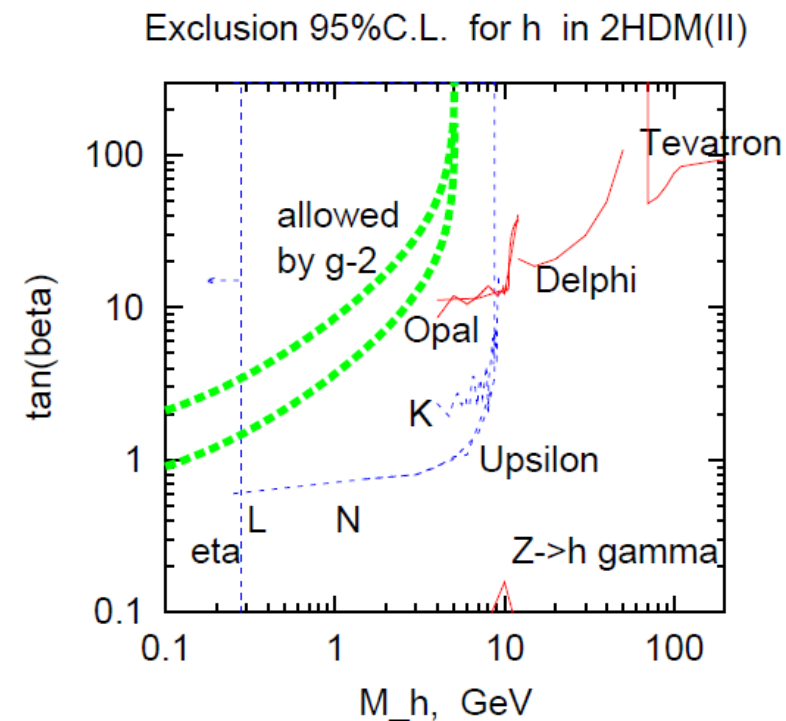
For $r_\mu^j = m_\mu^2/M_j^2 \ll 1$:

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

roughly scales with m_μ^4 !



- Requires H below 5GeV $\rightarrow$ Excluded!



Krawczyk, 0208076

Muon g-2 from an extra Higgs?

- Two-loop Barr-Zee with a light A and large $y_{\mu,f}^A \approx t_\beta$ (II, X):

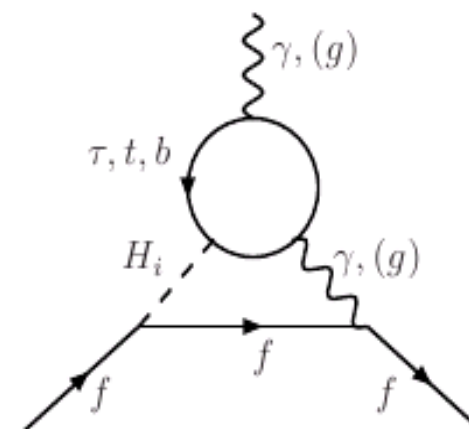
$$\delta a_\mu^{2\text{HDM}}(2\text{loop} - \text{BZ}) = \frac{G_F m_\mu^2}{4\pi^2 \sqrt{2}} \left(\frac{\alpha_{\text{em}}}{\pi} \right) \sum_{f; i=h,H,A} N_f^c Q_f^2 y_\mu^i y_f^i r_f^i g_i(r_f^i)$$

$$g_{h,H}(r) < 0$$

$$g_A(r) > 0$$

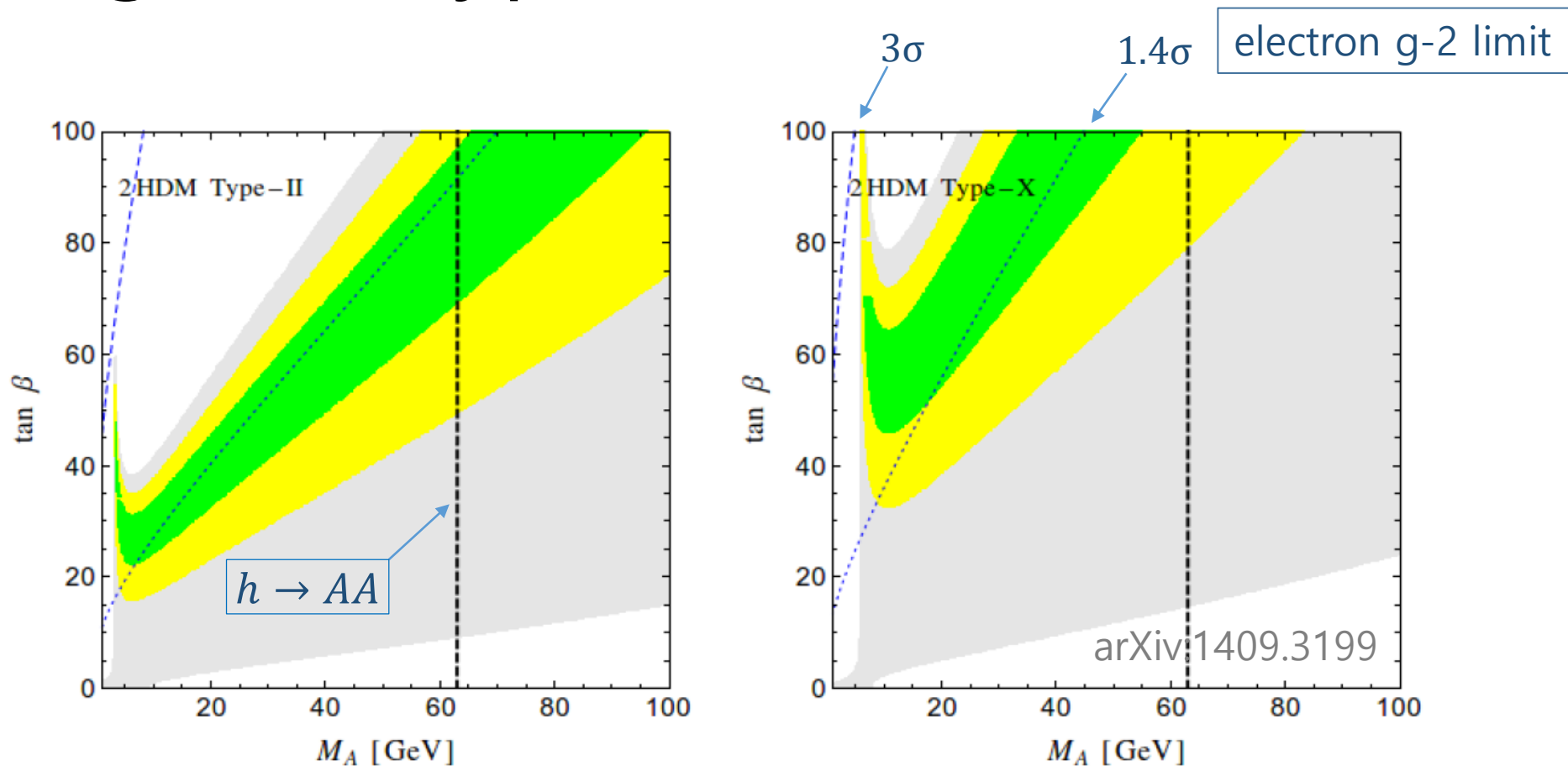
$$m_f^2/m_\mu^2$$

	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



- light A and large $t_\beta \rightarrow$ B, tau decays (LU) & LHC searches.

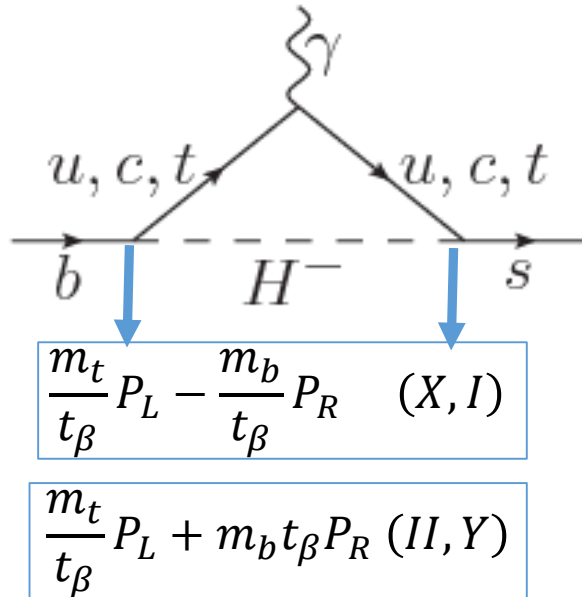
Muon $g-2$ in Type II & X



$$m_h (m_H) = 125 (200) \text{ GeV}$$

Constraints from B decays

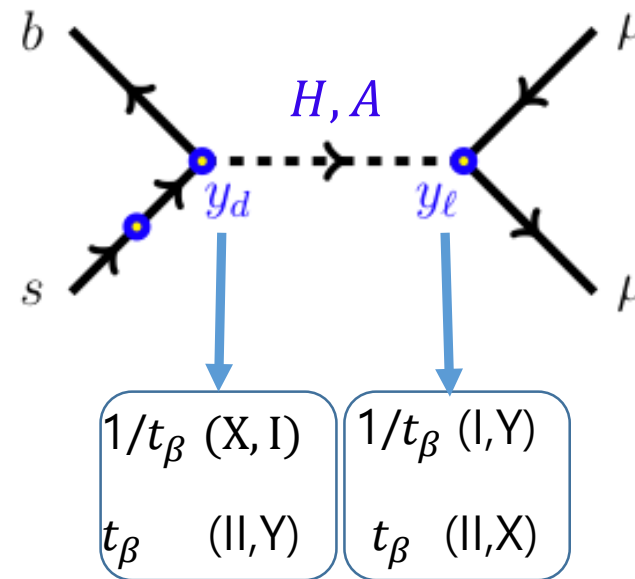
- $\bar{B} \rightarrow X_s \gamma$



$$\propto t_\beta^2 / m_{H^\pm}^2 \quad (II)$$

$$\propto 1 / m_{H^\pm}^2 \quad (X)$$

- $B_s \rightarrow \mu^+ \mu^-$

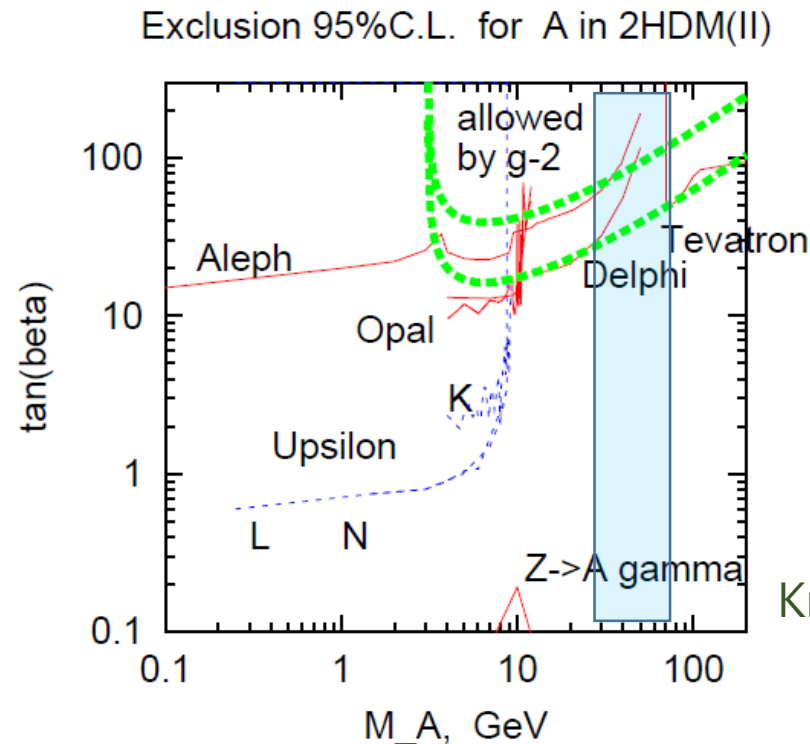


$$\propto t_\beta^2 / m_A^2 \quad (II)$$

$$\propto 1 / m_A^2 \quad (X)$$

In 2HDM-II,

- $\bar{B} \rightarrow X_s \gamma$ puts a strong limit of $m_{H^\pm} > 480 \text{ GeV}$. Misiak, et.al., 1503.01789
- $B_s \rightarrow \mu^+ \mu^-$ excludes the muon g-2 region.



$$Br(B_s \rightarrow \mu^+ \mu^-) = (2.9 \pm 0.7) \times 10^{-9} \text{ @ LHC}$$

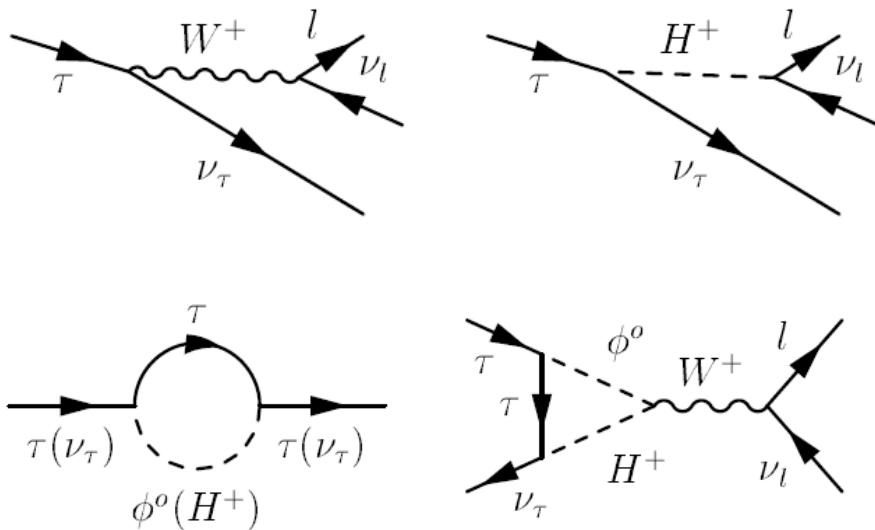
$$Br(B_s \rightarrow \mu^+ \mu^-) \propto t_\beta^4 / m_A^4$$

→ Excludes $t_\beta \gtrsim 7$ for $m_A \lesssim 70 \text{ GeV}$.

Krawczyk, 0208076

In 2HDM-X,

- $\bar{B} \rightarrow X_s \gamma$ puts no bound on $m_{H^\pm}$ for $t_\beta > 2$.
- $B_s \rightarrow \mu^+ \mu^-$ not affected if $m_A \gtrsim 15 \text{ GeV}$.
- Type X at large t_β , being hadro-phobic, is elusive at LHC.
- Strong limits on $t_\beta/m_{H^\pm}$ from Lepton Universality tests: Abe, et.al., 1504.07059
Cao, et.al, 0909.5148



$$G_{\tau \rightarrow l} = G_F(1 + \delta_{tree} + \delta_{loop}) \quad \text{Krawczyk, Temes, 0410248}$$

$$\delta_{tree} = \frac{m_\tau^2 m_l^2}{8 m_{H^\pm}^4} t_\beta^4 - \frac{m_l^2}{m_{H^\pm}^2} t_\beta^2 \kappa(m_l^2/m_\tau^2)$$

$$\delta_{loop} = \frac{G_F m_\tau^2 t_\beta^2}{16\sqrt{2} \pi^2} \left(3 + \frac{1}{2} \left[G\left(\frac{m_A}{m_{H^\pm}}\right) + s_{\beta-\alpha}^2 G\left(\frac{m_H}{m_{H^\pm}}\right) + c_{\beta-\alpha}^2 G\left(\frac{m_h}{m_{H^\pm}}\right) \right] \right)$$

Lepton Universality tests

HFAG, 1412.7515

- From pure leptonic processes: $l \rightarrow l' \nu \nu$

Note) Only two ratios are independent

$$\left(\frac{g_\tau}{g_\mu}\right) = 1.0011 \pm 0.0015, \quad \left(\frac{g_\tau}{g_e}\right) = 1.0029 \pm 0.0015, \quad \left(\frac{g_\mu}{g_e}\right) = 1.0018 \pm 0.0014$$

- From semi-hadronic processes: $\frac{(\tau \rightarrow \nu \pi / K)}{(\pi / K \rightarrow \mu \nu)}$

$$\left(\frac{g_\tau}{g_\mu}\right)_\pi = 0.9963 \pm 0.0027, \quad \left(\frac{g_\tau}{g_\mu}\right)_K = 0.9858 \pm 0.0071$$

- Combining the three in (g_τ/g_μ) : $\left(\frac{g_\tau}{g_\mu}\right)_{\tau+\pi+K} = 1.0001 \pm 0.0014$

LU constraining the muon g-2 region

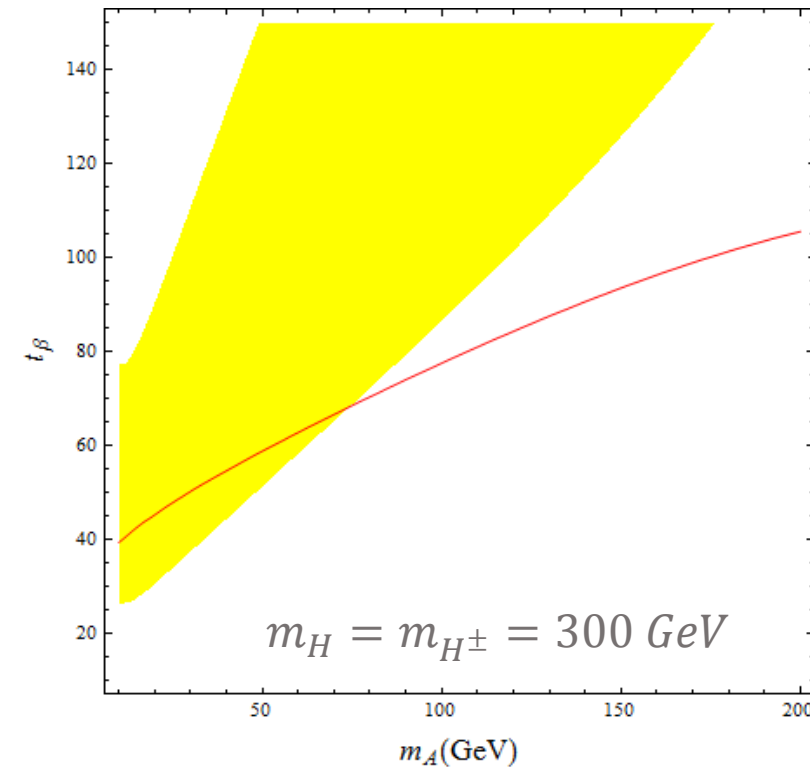
- Two independent leptonic data and the combined data lead to

$$\sqrt{\frac{3}{2}}\delta_{tree} = 0.0022 \pm 0.0017$$

$$\delta_{loop} = 0.0001 \pm 0.0014$$

$$\sqrt{\frac{1}{2}}\delta_{tree} + \sqrt{2}\delta_{loop} = 0.0028 \pm 0.0019$$

- Limiting the region below
 $m_A \lesssim 70\text{GeV}$ & $t_\beta \lesssim 60$.



Constraints from EWPD

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

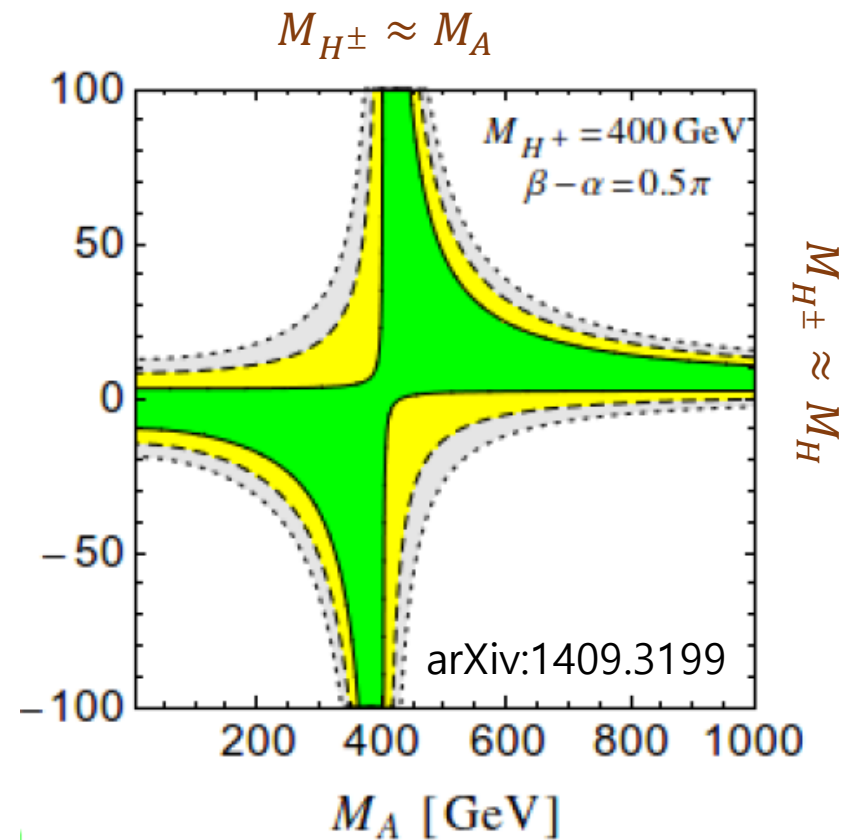
$$\sin^2 \theta_{\text{eff}}^{\text{lept}} = k_l (M_Z^2) \sin^2 \theta_W$$

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

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

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

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



Vacuum stability & perturbativity

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

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

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

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

In the limit of $\tan \beta \gg 1$ & $\sin(\beta - \alpha) \approx 1$,

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

$$\lambda_3 v^2 \approx 2M_{H^\pm}^2 - (1 + s_{\beta-\alpha} y_\tau) M_H^2 + s_{\beta-\alpha} y_\tau M_h^2$$

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

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



$$\lambda_{hAA} \propto \lambda_5 - \lambda_3 - \lambda_4 \approx (1 + s_{\beta-\alpha} y_\tau) M_H^2 - 2M_A^2 - s_{\beta-\alpha} y_\tau M_h^2 < \sqrt{\lambda_1} v M_h$$

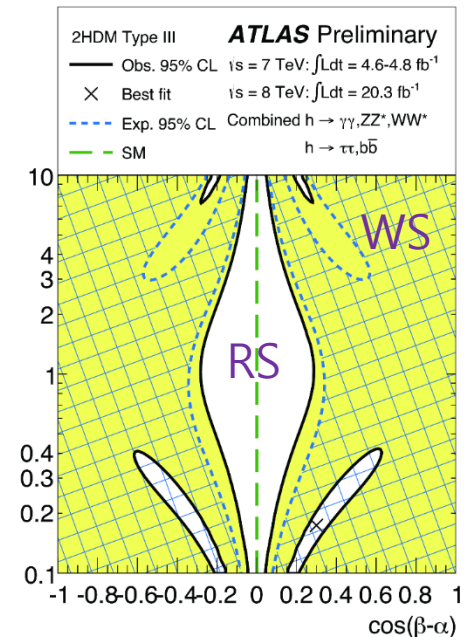
Right & wrong sign limit of Yukawas

- Tau/b-quark Yukawa coupling to h(125) can be negative in 2HDMs:

$$y_\tau = -\frac{s_\alpha}{c_\beta} = s_{\beta-\alpha} - t_\beta c_{\beta-\alpha} \approx \pm 1$$

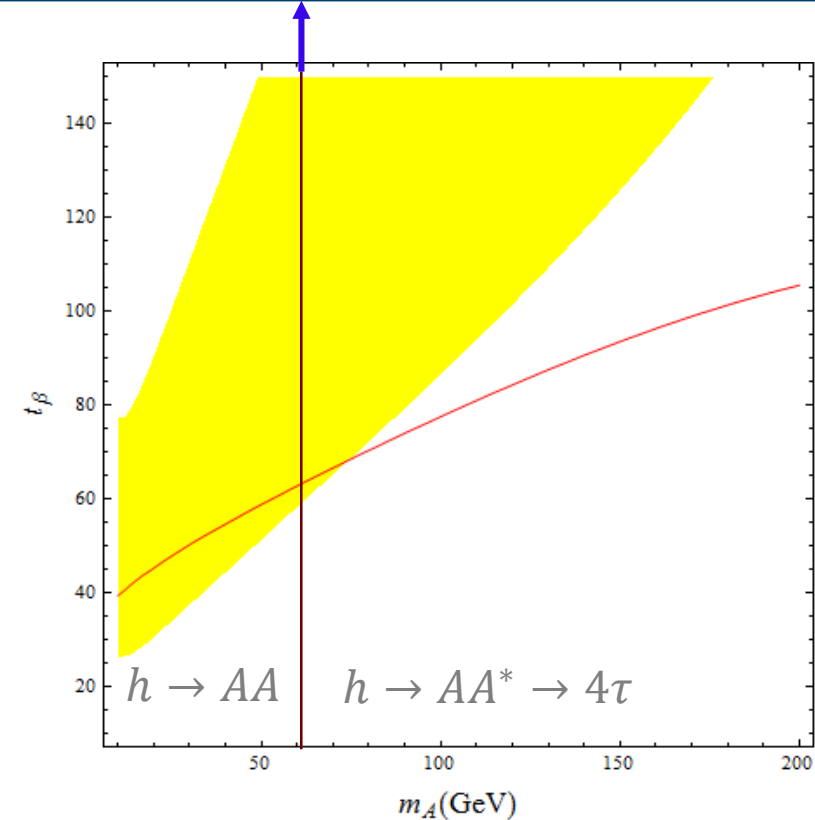
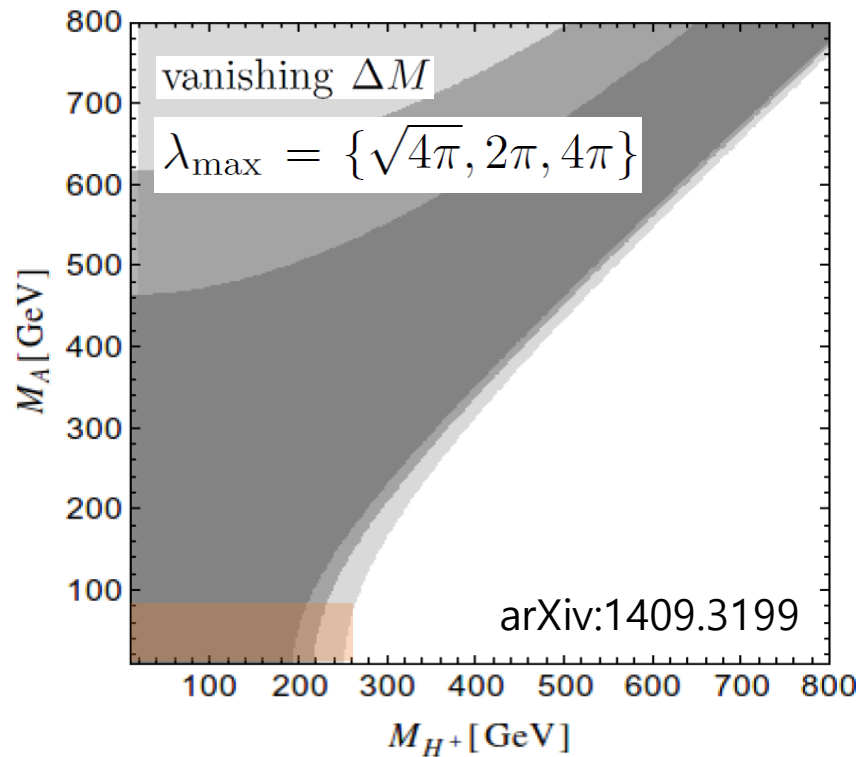
RS (SM) limit: $y_\tau \approx +1$ with $s_{\beta-\alpha} \gg t_\beta c_{\beta-\alpha}$
WS limit: $y_\tau \approx -1$ with $t_\beta c_{\beta-\alpha} \approx 2$

Ferreira, et.al, 1403.4736
1410.1926



Type X in the right-sign limit ($y_\tau s_{\beta-\alpha} \approx +1$)

$$\lambda_{hAA} v \approx -(1 + s_{\beta-\alpha} y_\tau) M_H^2 + 2M_A^2 + s_{\beta-\alpha} y_\tau M_h^2$$



$$63 \text{ GeV} \lesssim M_A \ll M_H \approx M_{H^\pm} \lesssim 250 \text{ GeV}, \text{ or } M_A \sim M_h \sim M_H$$

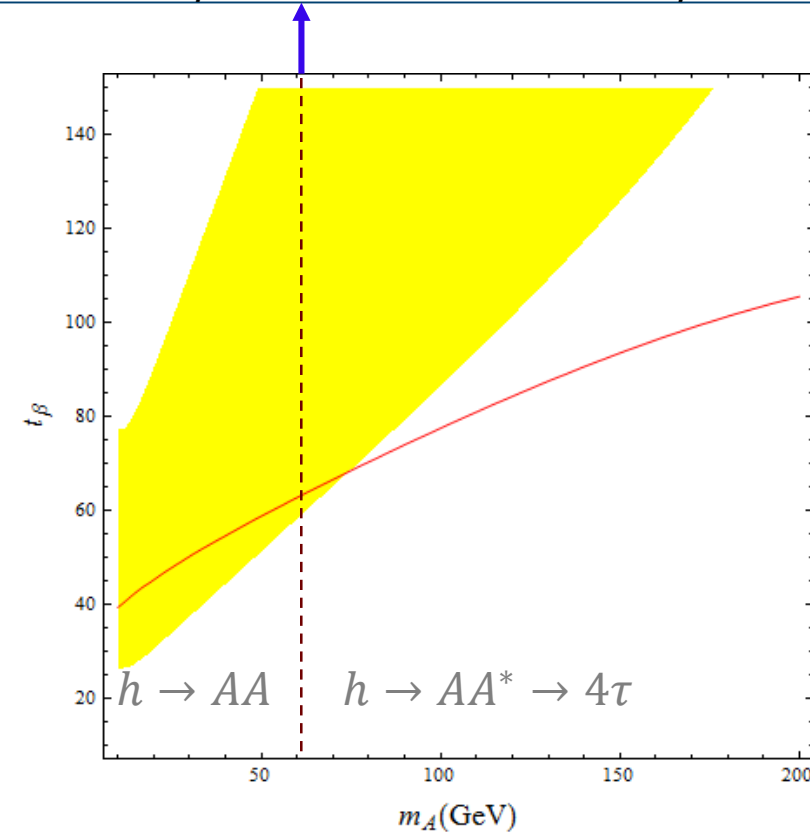
Type X in the wrong-sign limit ($y_\tau s_{\beta-\alpha} \approx -1$)

$$\lambda_{hAA} \approx -(1 + s_{\beta-\alpha} y_\tau) M_H^2 + 2M_A^2 + s_{\beta-\alpha} y_\tau M_h^2 \rightarrow 0$$

- $h \rightarrow AA$ can be arbitrarily suppressed even for $M_h \ll M_H$ allowed up to the perturbativity limit.

Wang, Han, arXiv:1412.4874

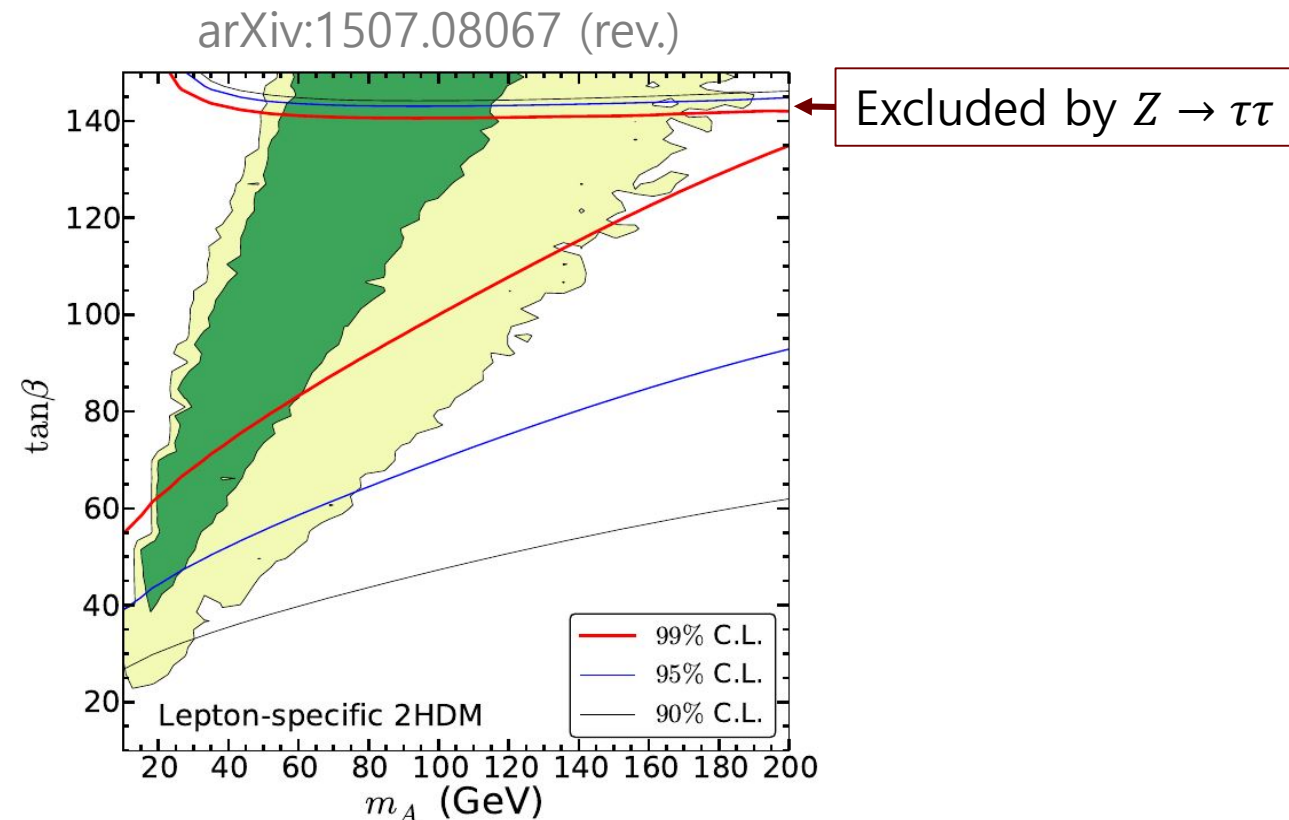
$$10 \text{ GeV} \lesssim m_A \ll m_H \approx m_{H^\pm} \lesssim \sqrt{4\pi} v$$

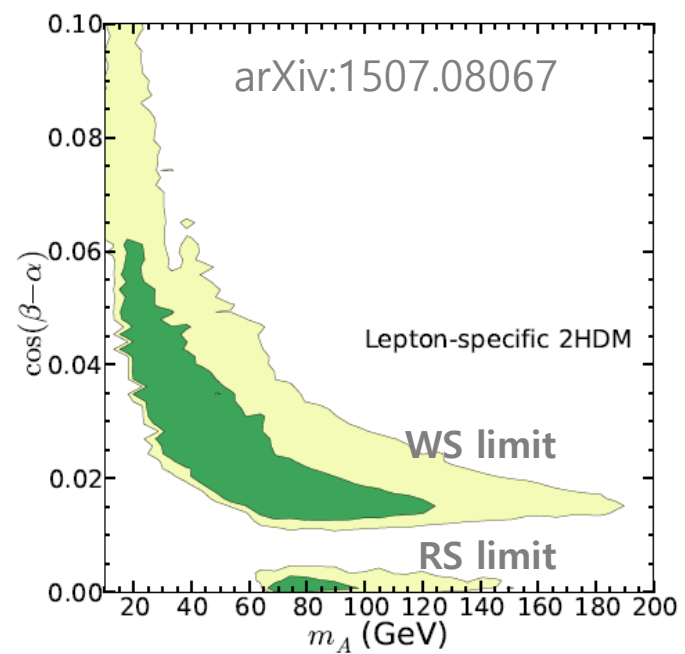
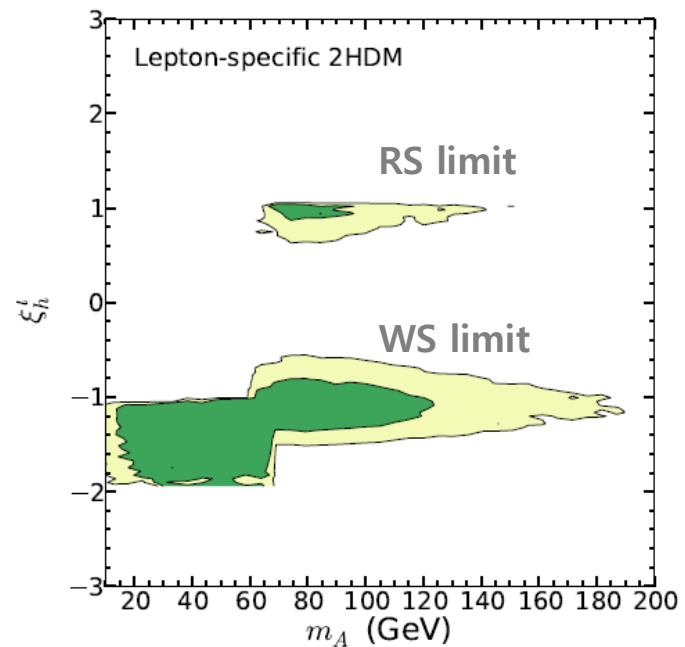
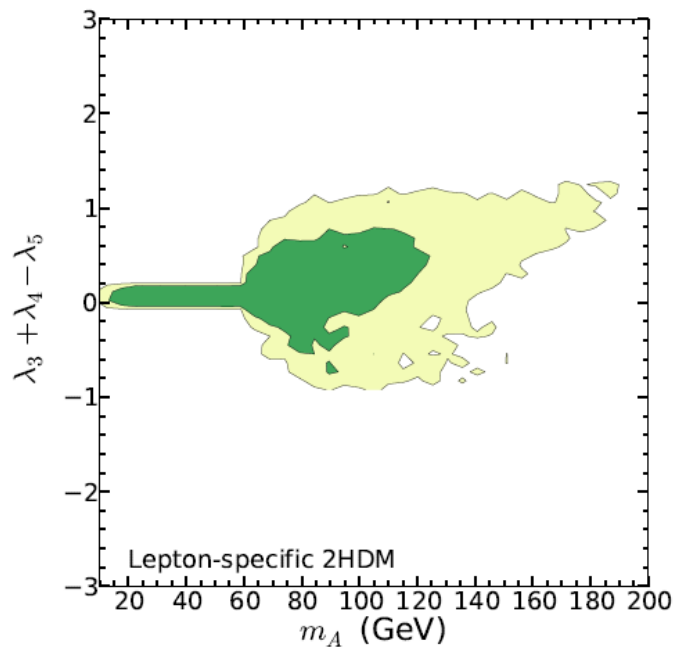
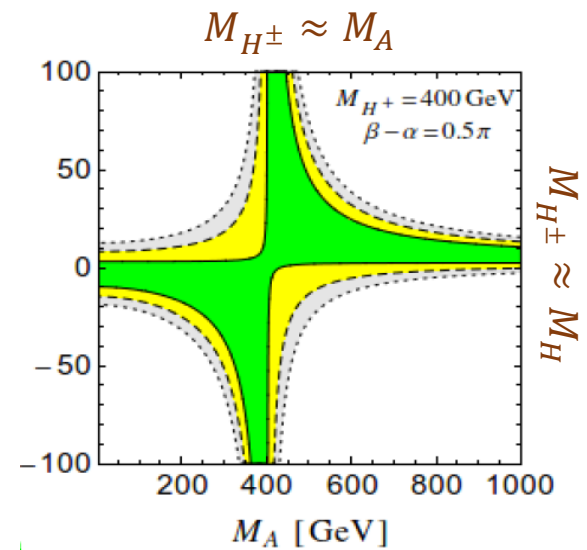
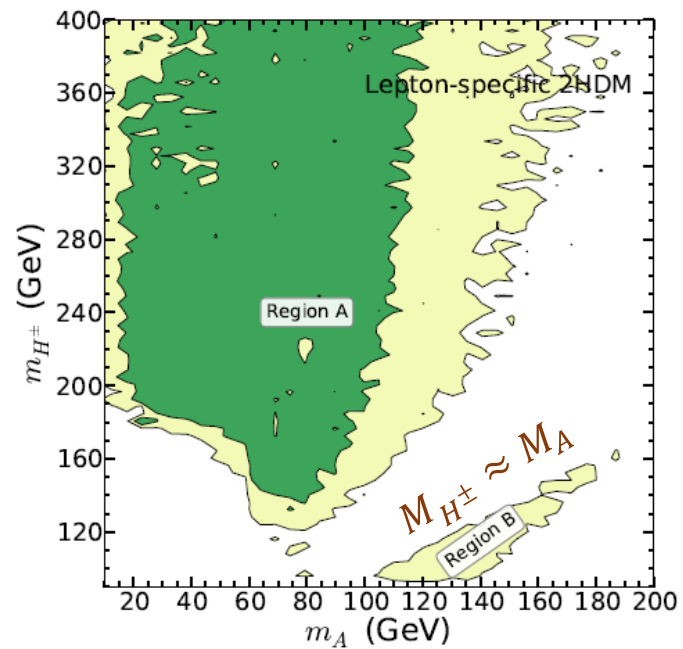
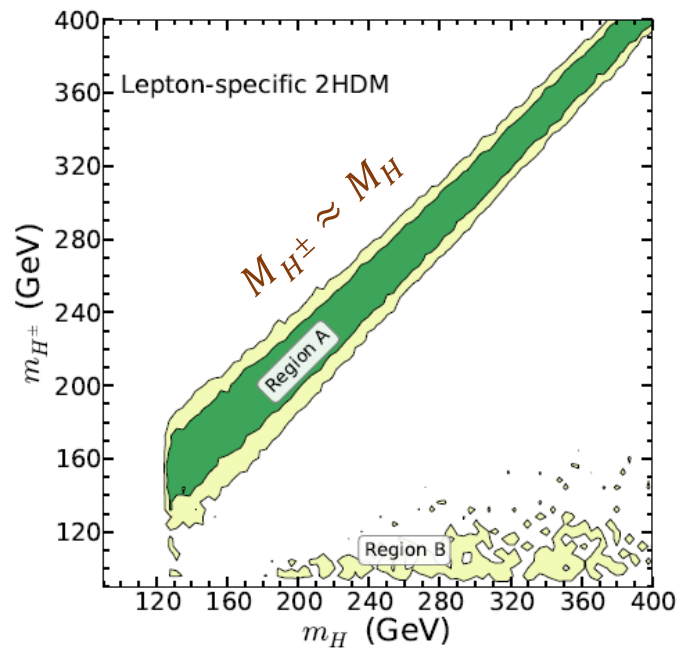


Profile likelihood analysis

- Scanning through all the parameter space combining the h(125) data, muon g-2, EWPD, theoretical constraints, and the relevant LEP, B decay and LU limits.

2HDM parameter	Range
Scalar Higgs mass (GeV)	$125 < m_H < 400$
Pseudoscalar Higgs mass (GeV)	$10 < m_A < 400$
Charged Higgs mass (GeV)	$94 < m_{H^\pm} < 400$
$c_{\beta-\alpha}$	$0.0 < c_{\beta-\alpha} < 0.1$
$\tan \beta$	$10 < \tan \beta < 150$
λ_1	$0.0 < \lambda_1 < 4\pi$

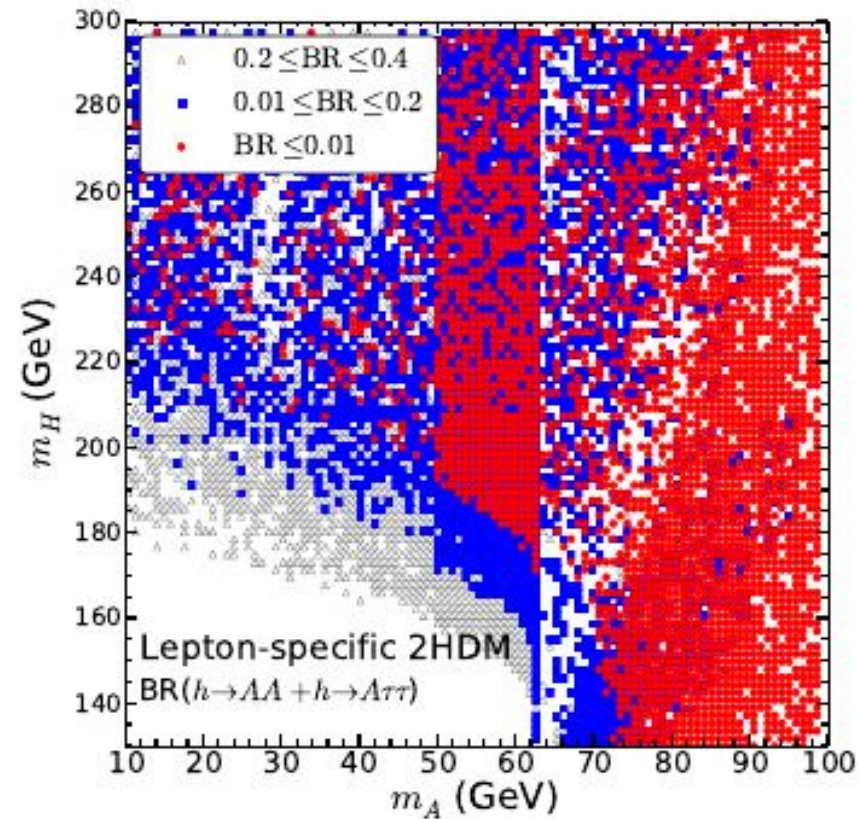




Tau-rich signatures at LHC

- $h(125) \rightarrow AA \rightarrow 4 \text{ tau}$

arXiv:1507.08067



Tau-rich signatures at LHC

- EW production of extra Higgses

$$pp \rightarrow W^{\pm*} \rightarrow H^{\pm} A \rightarrow (\tau^{\pm} \nu)(\tau^+ \tau^-),$$

$$pp \rightarrow Z^*/\gamma^* \rightarrow H A \rightarrow (\tau^+ \tau^-)(\tau^+ \tau^-),$$

$$pp \rightarrow W^{\pm*} \rightarrow H^{\pm} H \rightarrow (\tau^{\pm} \nu)(\tau^+ \tau^-),$$

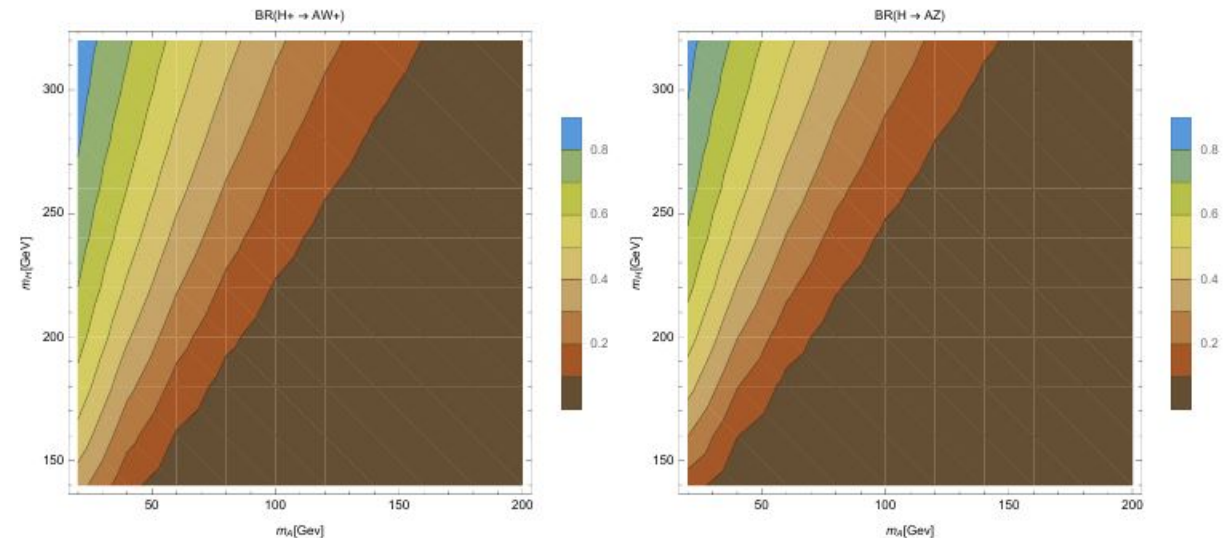
$$pp \rightarrow Z^*/\gamma^* \rightarrow H^+ H^- \rightarrow (\tau^+ \nu)(\tau^- \bar{\nu}).$$

$$\tan \beta = 1.25 \left(\frac{m_A}{\text{GeV}} \right) + 25.$$

Region A: $m_{H^{\pm}} = m_H + 15 \text{ GeV}$

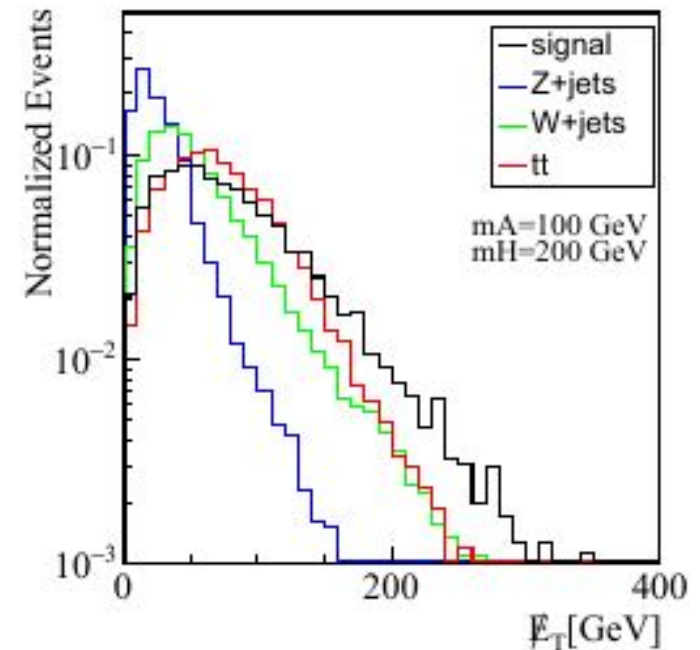
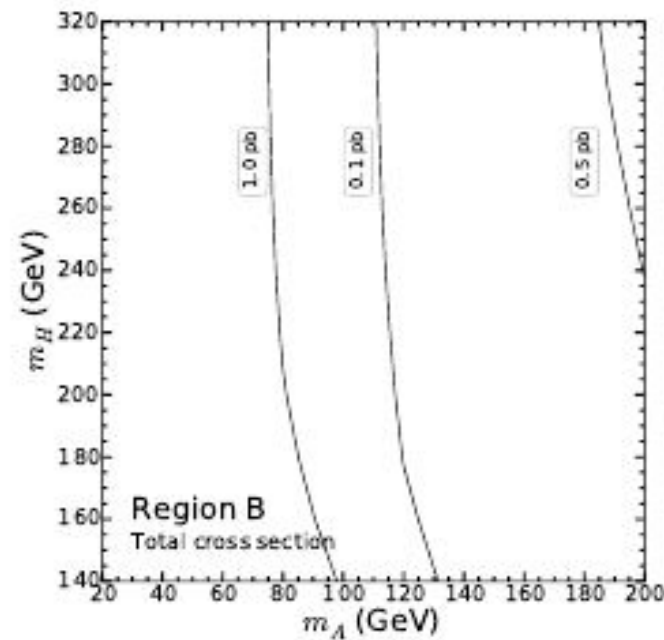
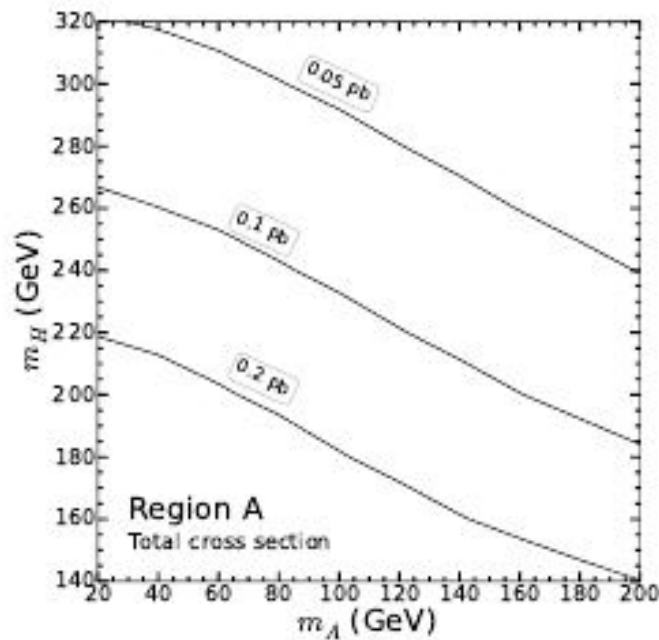
Region B: $m_{H^{\pm}} = \max(90 \text{ GeV}, 0.8m_A + 10 \text{ GeV})$

$$\begin{array}{ll} H^{\pm} \rightarrow A W^{\pm} & \text{vs. } \nu \tau^{\pm} \\ H \rightarrow A Z & \text{vs. } \tau^+ \tau^- \end{array}$$



LHC14 perspective

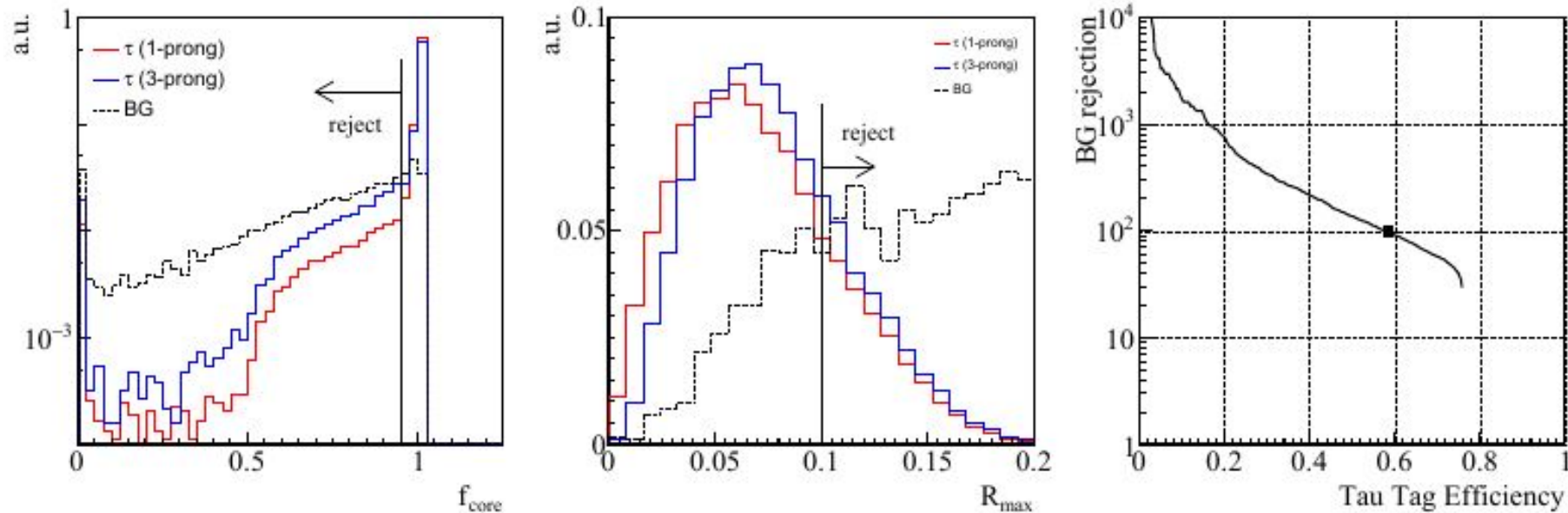
- Production X-section & missing signature:



Tau identification and reconstruction

- Our working point: $R_{max}^{cut} = 0.1, \epsilon_{BG-jets} \approx 1\% \rightarrow \epsilon_{\tau} \approx 60\%$

$$R_{max} = \max_{\text{tracks}} \Delta R(p_j, p_i) \quad \text{and} \quad f_{core} = \frac{\sum_{R < 0.1} E_T^{calo}}{\sum_{R < 0.2} E_T^{calo}},$$



Event selection cuts

ex) $m_A = 100 \text{ GeV}$ & $m_H = 200 \text{ GeV}$

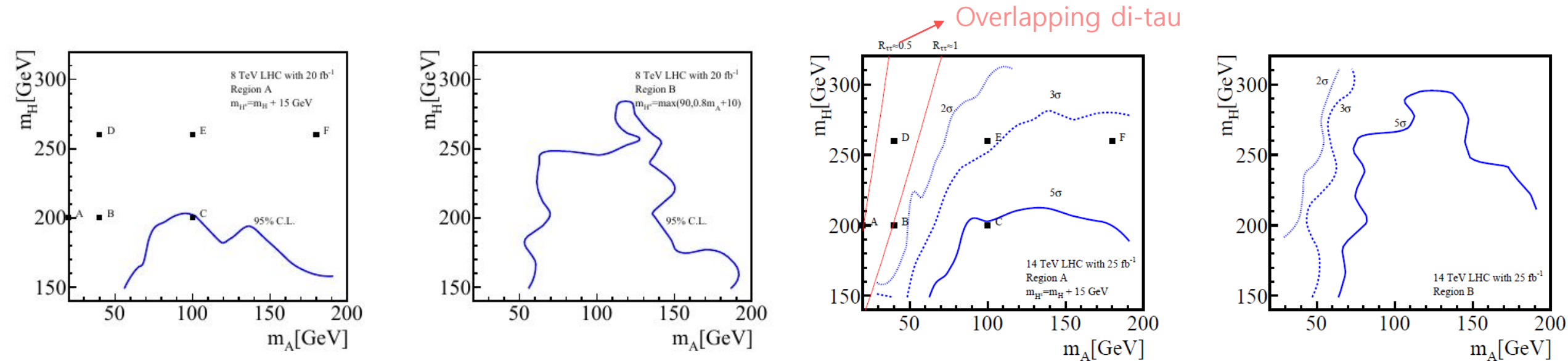
selection cuts	point C	$t\bar{t}$	$W+\text{jets}$	$Z+\text{jets}$	WW	WZ	ZZ	total BG	S/B	$S/\sqrt{B}_{25\text{fb}^{-1}}$
total σ_{gen} [fb]	153.580	$102 \cdot 10^3$	$1365 \cdot 10^3$	$714 \cdot 10^3$	8125	942	112	$2190 \cdot 10^3$	-	-
$n_\ell \geq 3$	21.713	273.27	138.59	3412.84	6.495	88.937	26.965	3947.1	-	1.7
$n_\tau \geq 3$	4.386	5.837	13.776	91.324	0.070	0.343	0.174	111.52	0.04	2.1
$\cancel{E}_T > 100 \text{ GeV}$	1.179	1.482	0.232	1.244	0.000	0.018	0.003	2.980	0.4	3.4
$n_b = n_j = 0$	0.857	0.163	0.000	0.505	0.000	0.017	0.003	0.688	1.2	5.2

Benchmark study of significance at 25/fb

	point A	point B	point C	point D	point E	point F
m_A [GeV]	20	40	100	40	100	180
m_H [GeV]	200	200	200	260	260	260
total σ_{gen} [fb]	270.980	241.830	153.580	100.430	71.271	44.163
$n_\ell \geq 3$	6.606	16.681	21.713	7.110	11.962	8.822
$n_\tau \geq 3$	0.894	2.602	4.386	0.888	2.346	1.971
$E_T > 100$ GeV	0.201	0.547	1.179	0.209	0.765	0.926
$n_b = n_j = 0$	0.098	0.314	0.857	0.121	0.479	0.631
S/B	0.1	0.5	1.2	0.2	0.7	0.9
$S/\sqrt{B}_{25\text{fb}^{-1}}$	0.6	1.9	5.2	0.7	2.9	3.8

Current limits & future perspective

- LHC8 constraints mostly from chargino-neutralino searches.
- Challenges to probe lighter A producing softer taus, and heavy $H^\pm/H$ producing boosted $A(\tau\tau)$.



Conclusion

- 2HDM-X is still a viable option for muon $g-2$.
- The LU tests strongly limit the allowed region (at 2σ):
$$m_A \approx 10 - 75 \text{ GeV} \text{ \& } t_\beta \approx 25 - 60.$$
- The SM (RS) limit requires $63 \text{ GeV} \lesssim m_A \ll m_H \approx m_{H^\pm} \lesssim 250 \text{ GeV}$.
- The WS limit, allowing $10 \text{ GeV} \lesssim m_A \ll m_H \approx m_{H^\pm} \lesssim \sqrt{4\pi}v$, is more preferable.
- The exotic Higgs decay $h \rightarrow AA^{(*)} \rightarrow 4\tau$ would provide a hint.
- Tau-rich signals should be searched for with a more care, in particular, to probe a light A .