KIAS KOREA INSTITUTE FOR ADVANCED STUDY

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The Muon g-2 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

"Can the muon g-2 be explained in 2HDMs?"

- Back in 2001, right after the BNL announcement:

In SUSY, 0102145, 146, 147, ...
In 2HDM, Dedes, Haber, 0102297 (Type I & II)
Cheung, Chou, Kong, 0103183, and a few more
Cao, et.al, 0909.5148 (Type X)

- Improved theoretical and experimental inputs over the years:

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

Revisit the issue with updated inputs

- The SM-like **125 GeV Higgs** at LHC. arXiv:1409.3199
- Extra Higgs spectrum constrained by

  EWPD, vacuum stability & perturbativity.
- New results on

  $\bar{B} \to X_s \gamma$, $B_s \to \mu^+ \mu^-$, **& lepton universality tests**.

Wang,Han, arXiv:1412.4874; Abe,Sato,Yagyu 1504.07059

✓ LHC can probe it from the tau-righ signatures arXiv:1507.08067

On two-Higgs-Doublet-Model (2HDM)

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

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

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

4 mass & 2 angle parameters in 2HDM

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

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

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

Couplings of extra Higgses

- Gauge couplings: $\mathcal{L}_g = g_V m_V \left(s_{\beta-\alpha} h + c_{\beta-\alpha} H\right) VV + \cdots$

- Yukawa couplings: FCNC if Mass $\not\approx$ Yukawa

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

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

4 types of 2HDMs with natural flavor conservation

Impose Z_2 to couple only one Higgs to each Yukawa type (d, e)

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

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

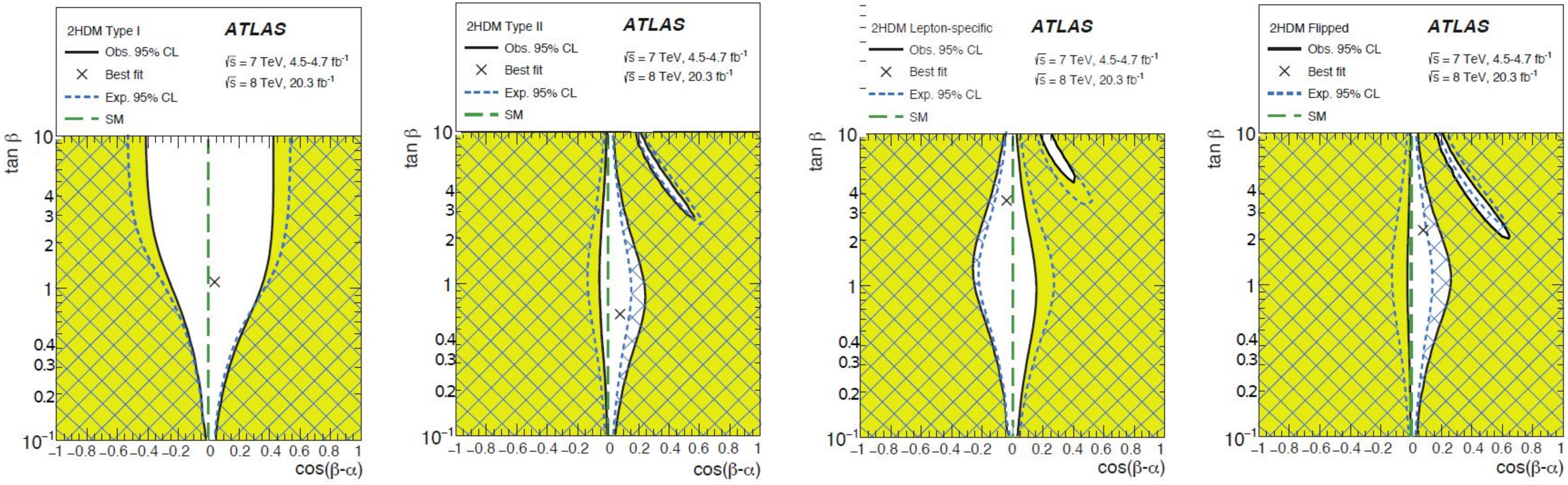
$$-\mathcal{L}_{\rm Yukawa}^{\rm 2HDMs} = \sum_{f=u,d,l} \frac{m_f}{v}\left(y_f^h h\bar{f}f + y_f^H H\bar{f}f - i y_f^A A\bar{f}\gamma_5 f\right)$$

125 GeV

$$+\left[\sqrt{2}V_{ud}H^+\bar{u}\left(\frac{m_u}{v}y_u^A P_L + \frac{m_d}{v}y_A^d P_R\right)d + \sqrt{2}\frac{m_l}{v}y_l^A H^+\bar{\nu}P_R l + h.c.\right]$$

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

ATLAS 1509.00672



Aligned/decoupled 2HDMs

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

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 RS WS

$$-\mathcal{L}_{\text{Yukawa}}^{\text{2HDMs}} = \sum_{f=u,d,l}\frac{m_f}{v}\left(y_f^h h\bar{f}f + y_f^H H\bar{f}f - iy_f^A A\bar{f}\gamma_5 f\right)$$

125 GeV

$$+\left[\sqrt{2}V_{ud}H^+\bar{u}\left(\frac{m_u}{v}y_u^A P_L + \frac{m_d}{v}y_A^d P_R\right)d + \sqrt{2}\frac{m_l}{v}y_l^A H^+\bar{\nu}P_R l + h.c.\right]$$

"Muon g-2 from an extra Higgs?"

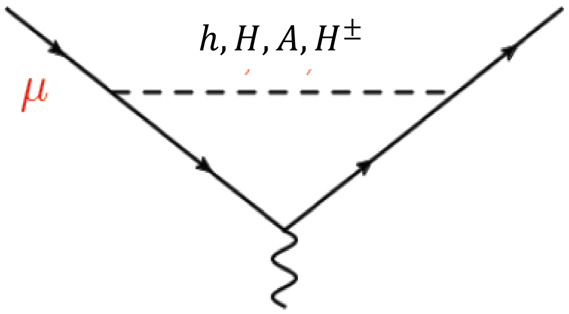
- One-loop with a light H and large $y_\mu^H \approx t_\beta$ (II, X):

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

roughly scales with m_μ^4!

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

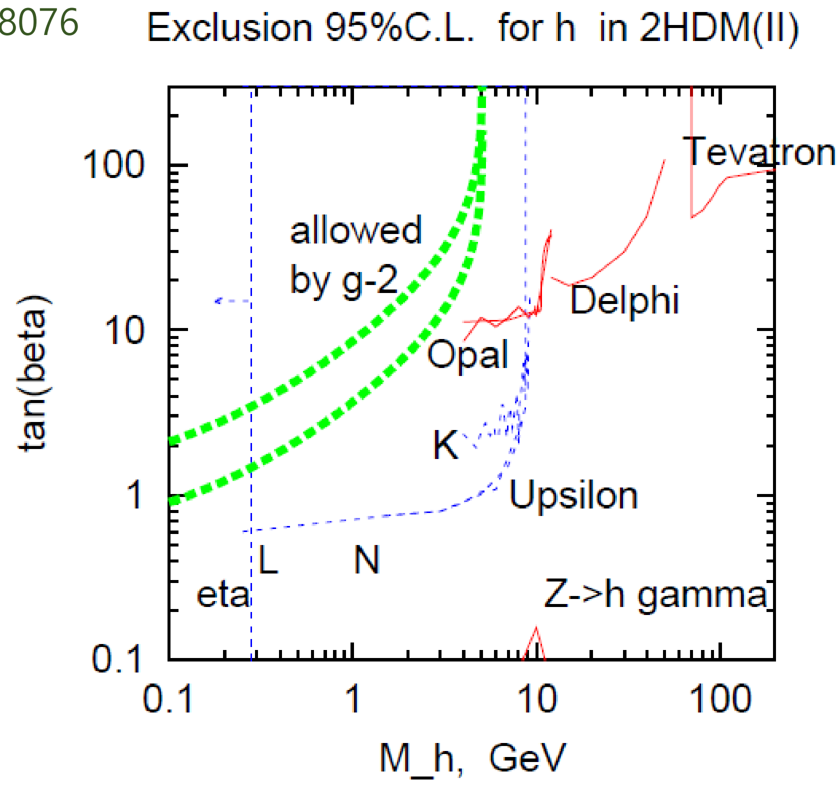
$$\begin{aligned} f_{h,H}(r) &\sim -\ln r - 7/6 + O(r) > 0 \\ f_A(r) &\sim +\ln r + 11/6 + O(r) < 0 \\ f_{H^\pm}(r) &\sim -1/6 + O(r) < 0 \end{aligned}$$



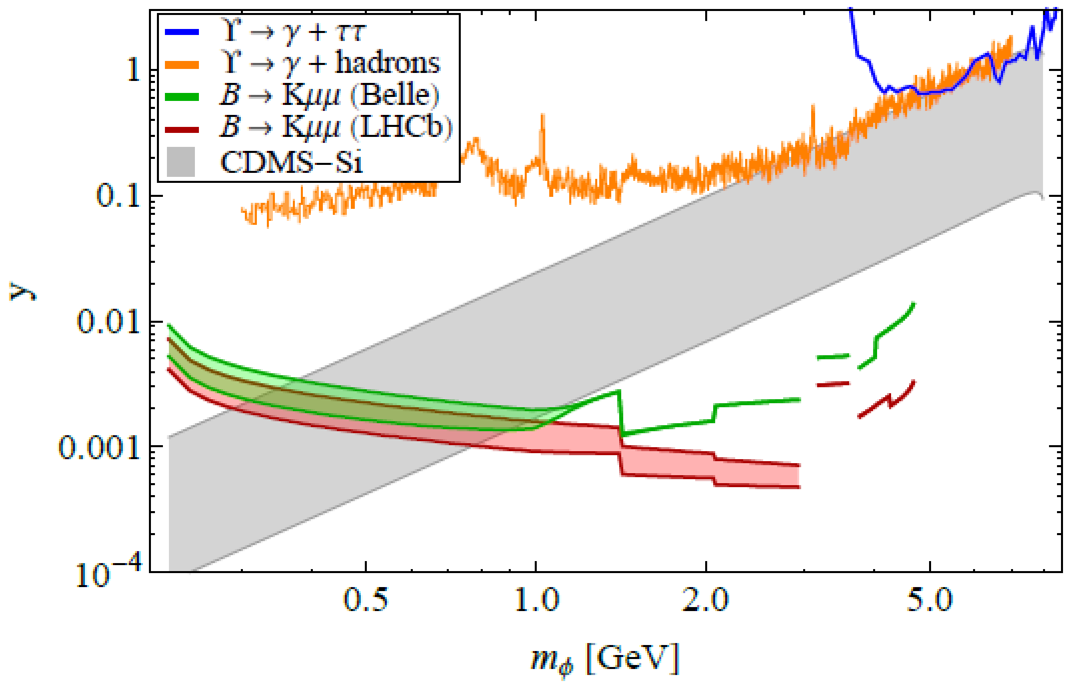
One-loop solution excluded!

- Muon g-2 requires H below 5GeV, but in contradiction with $\Upsilon \to \gamma + X, B \to K\mu\mu$ (& $B_s \to \mu\mu$).

Krawczyk, 0208076



Schumidt-Horberg, et.al., 1310.6752



"Muon g-2 from an extra Higgs?"

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

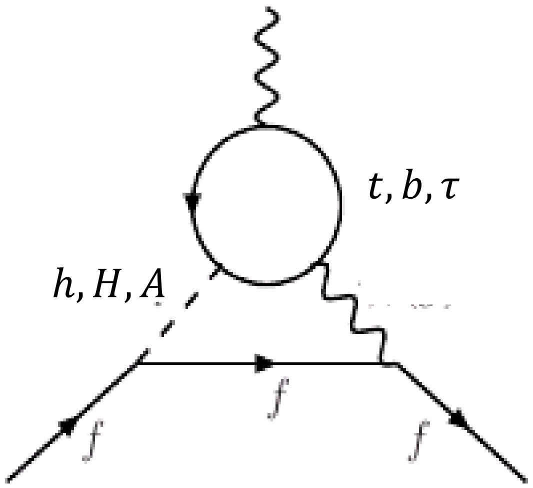
$$\delta a_\mu^{\rm 2HDM}(2{\rm loop} - {\rm BZ}) = \frac{G_F\, m_\mu^2}{4\pi^2\sqrt{2}} \frac{\alpha_{\rm em}}{\pi} \sum_{f;\, i=h,H,A} N_f^c\, Q_f^2\, y_\mu^i\, y_f^i\, r_f^i\, g_i(r_f^i)$$

$r_f^i \to m_f^2/m_\mu^2$

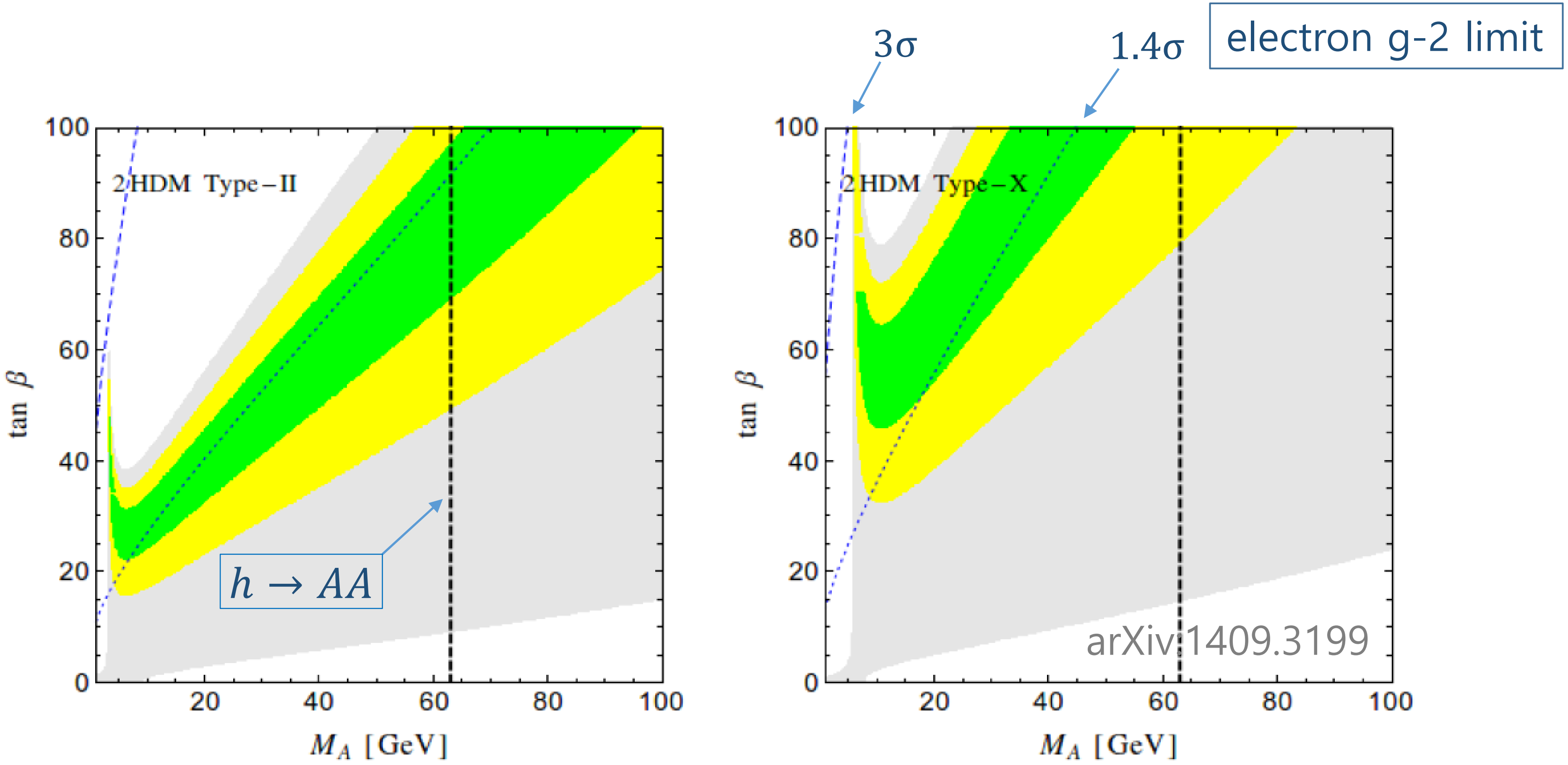
$g_{h,H}(r) < 0$

$g_A(r) > 0$

	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



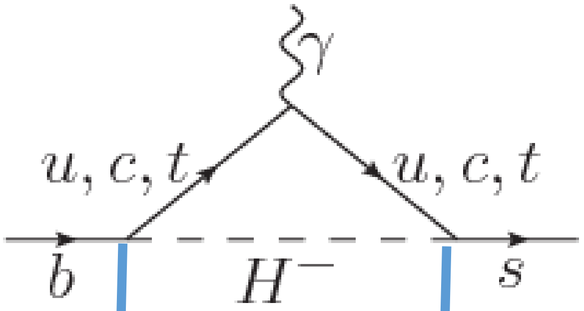
Muon g-2 at 2-loop in Type II & X



$$m_h\ (m_H) = 125\ (200)\ GeV$$

Constraints from B decays

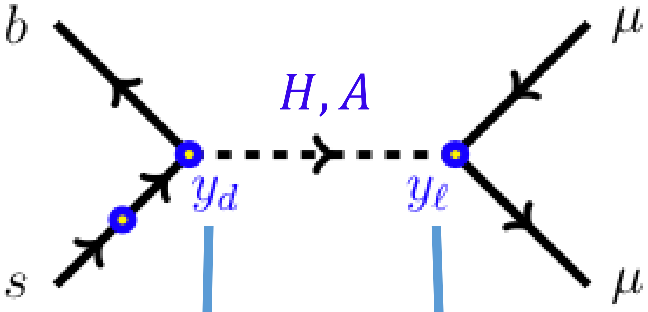
- $\bar{B} \to X_s \gamma$



$\frac{m_t}{t_\beta} P_L - \frac{m_b}{t_\beta} P_R \quad (X, I)$ $\quad \propto \frac{t_\beta^2}{m_{H^\pm}^2}$ (II)

$\frac{m_t}{t_\beta} P_L + m_b t_\beta P_R \; (II, Y)$ $\quad \propto \frac{1}{t_\beta^2 m_{H^\pm}^2}$ (X)

- $B_s \to \mu^+ \mu^-$



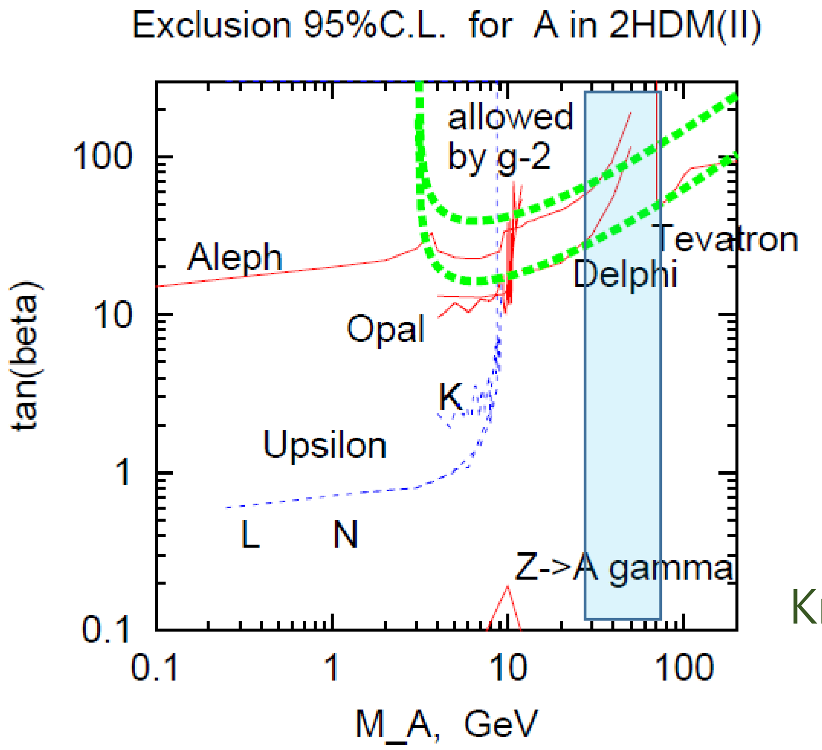
y_d		y_ℓ	
$1/t_\beta$	(X, I)	$1/t_\beta$	(I,Y)
t_β	(II,Y)	t_β	(II,X)

$\propto \frac{t_\beta^2}{m_{H,A}^2}$ (II)

$\propto \frac{1}{m_{H,A}^2}$ (X)

In Type II,

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



Krawczyk, 0208076

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

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

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

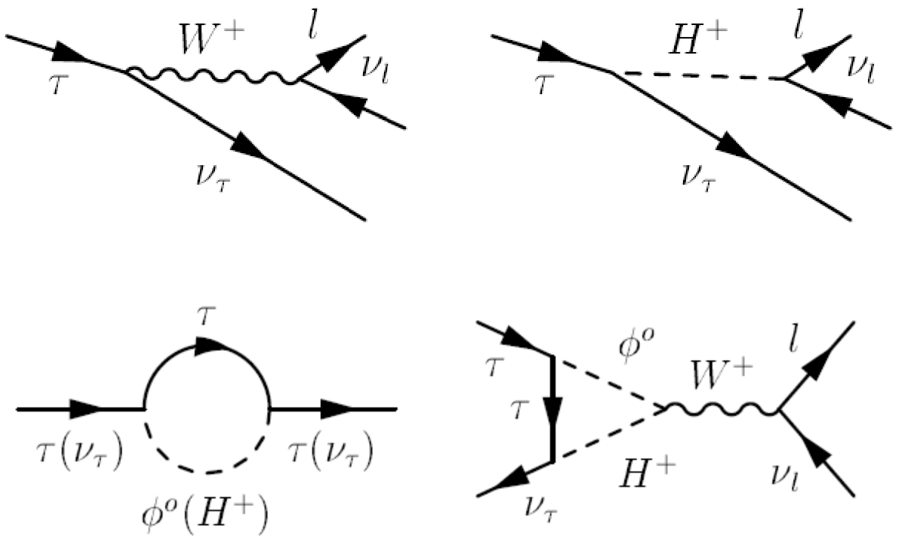
In Type X,

- $\bar{B} \to X_s \gamma$ puts no bound on $m_{H^\pm}$ for $t_\beta > 2$.
- $B_s \to \mu^+ \mu^-$ not affected if $m_A \gtrsim 15\ GeV$.
- Type X at large t_β, being hadro-phobic, is elusive at LHC.
- Strong limits from precision leptonic observables like lepton universality in $Z \to ll,\ l \to l' \nu\nu'$.

Abe, et.al., 1504.07059
Cao, et.al., 0909.5146

Lepton universality & τ decay

- Tree-level contribution from $H^{\pm}$.
- One-loop corrections mediated by $A, H, H^{\pm}$.



$$G_{\tau\to l} = G_F(1+\delta_{tree}+\delta_{loop})$$

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

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

Krawczyk, Temes, 0410248

Lepton Universality test by HFAG

HFAG, 1412.7515

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

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: $\frac{(\tau \to \nu\pi/K)}{(\pi/K \to \mu\nu)}$

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

- 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

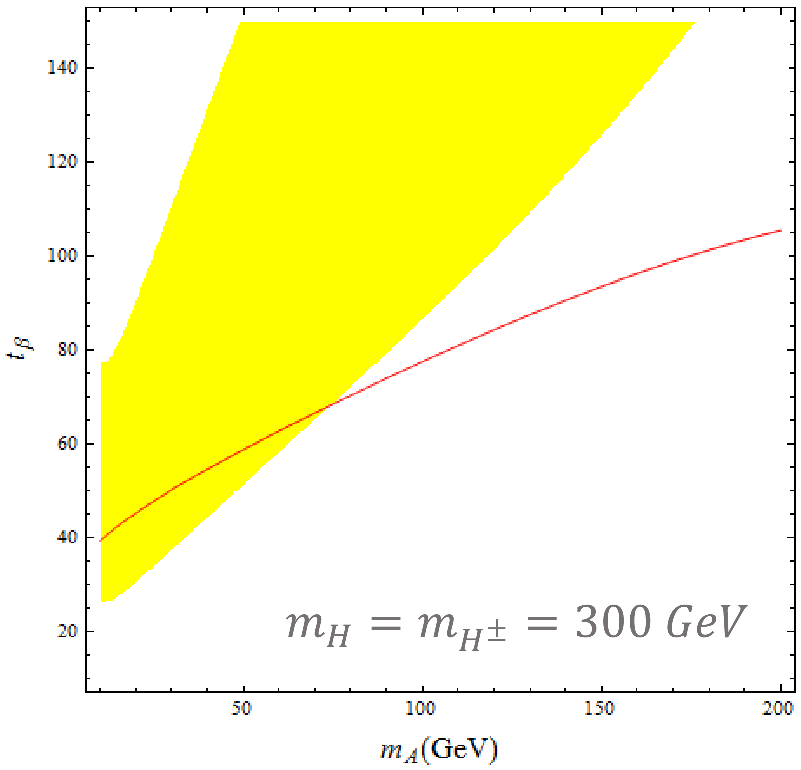
- Two independent leptonic data and the combined data lead to

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

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

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

- The muon g-2 favoured region is strongly limited:



Constraints from EWPD

- Such a light A with heavier $H/H^{\pm}$ strongly onstrained by the "ρ" parameter bound:

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

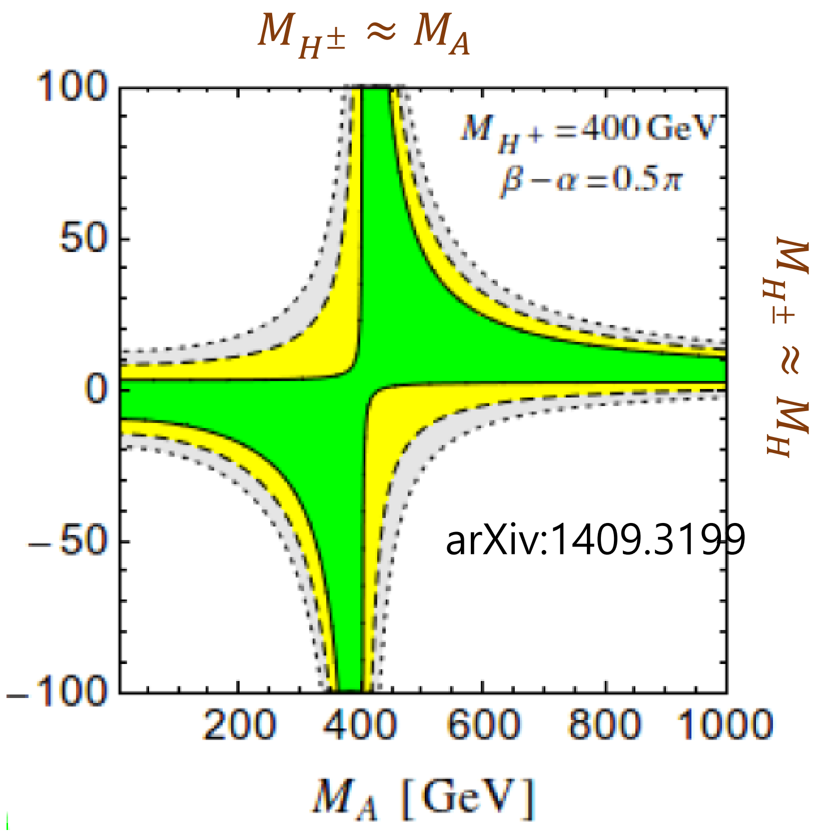
$$\sin^2\theta_{\rm eff}^{\rm lept} = k_l\left(M_Z^2\right)\sin^2\theta_W$$

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

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

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

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



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 $\tan\beta \gg 1$ & $\sin(\beta-\alpha) \approx 1$,

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

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

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

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

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

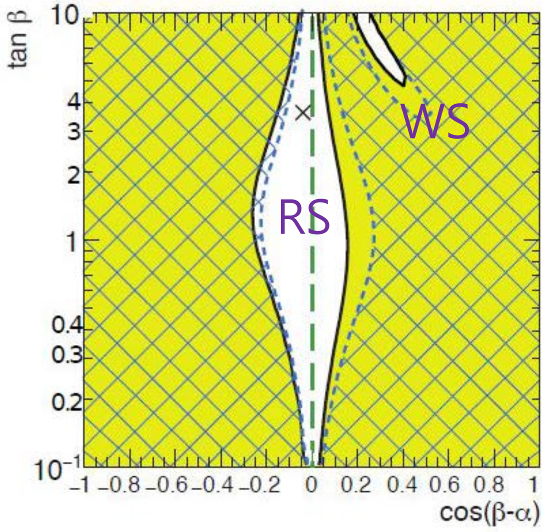
Right & wrong sign limit of Yukawas

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

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

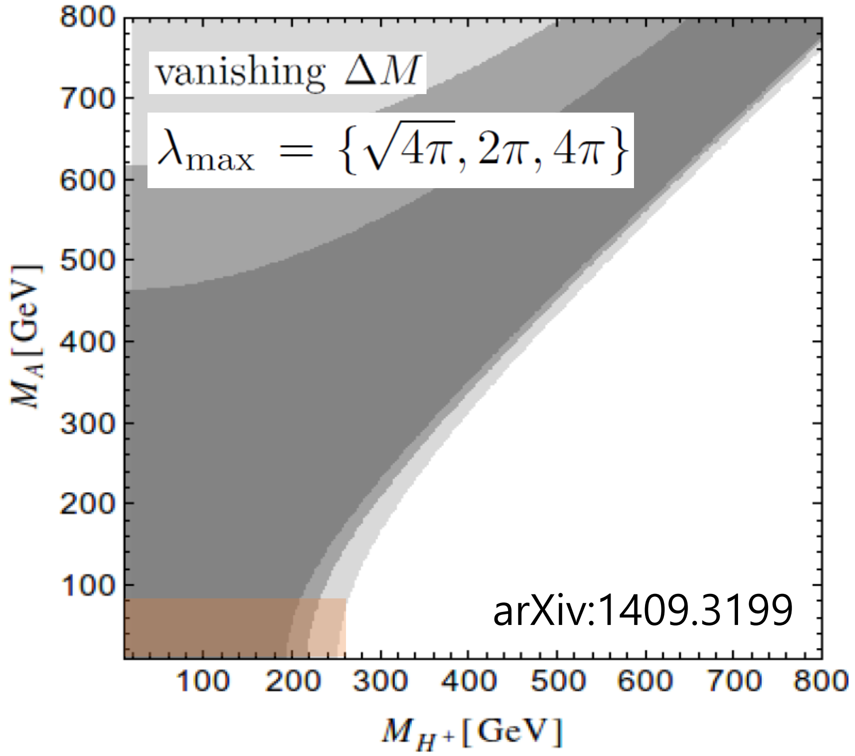
RS limit: $y_\tau \approx +1$ with $s_{\beta-\alpha} \gg t_\beta c_{\beta-\alpha}$
WS limit: $y_\tau \approx -1$ with $t_\beta c_{\beta-\alpha} \approx 2$

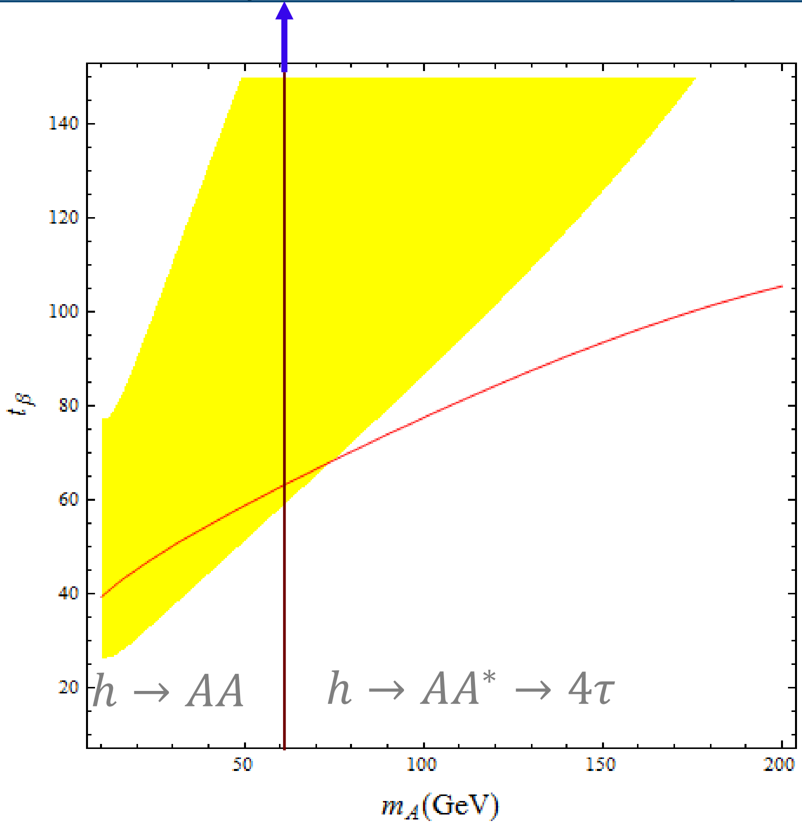
Ferreira, et.al, 1403.4736
1410.1926



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

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





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

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

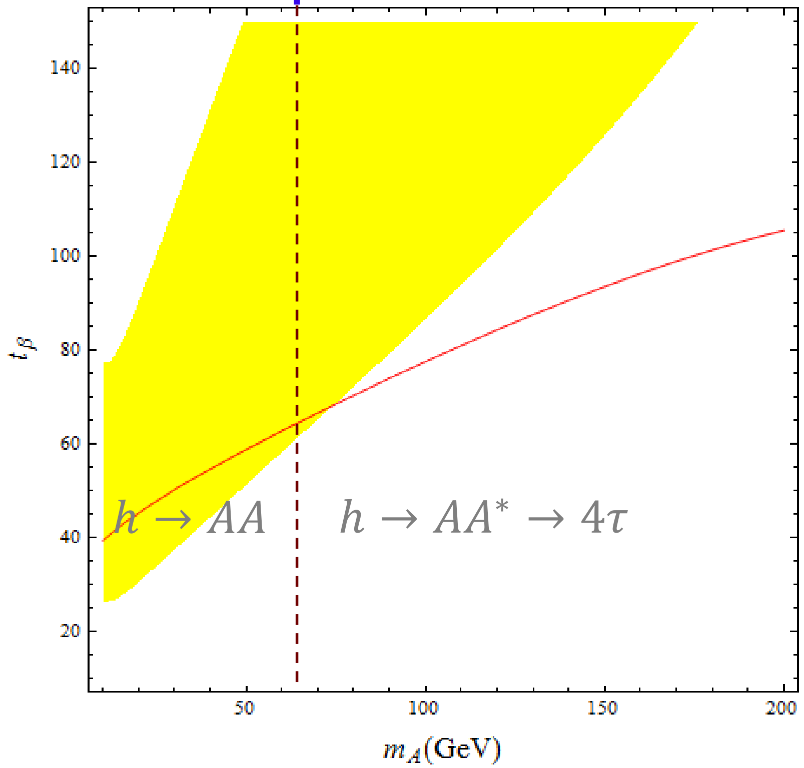
$$\lambda_{hAA} v \approx -(1 + s_{\beta-\alpha} y_\tau) M_H^2 + 2 M_A^2 + s_{\beta-\alpha} y_\tau M_h^2 \to \mathbf{0}$$

$$y_\tau \approx -\frac{M_H^2 - 2\,M_A^2 - \lambda_{hAA} v}{M_H^2 - M_h^2}$$

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

Wang, Han, arXiv:1412.4874

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

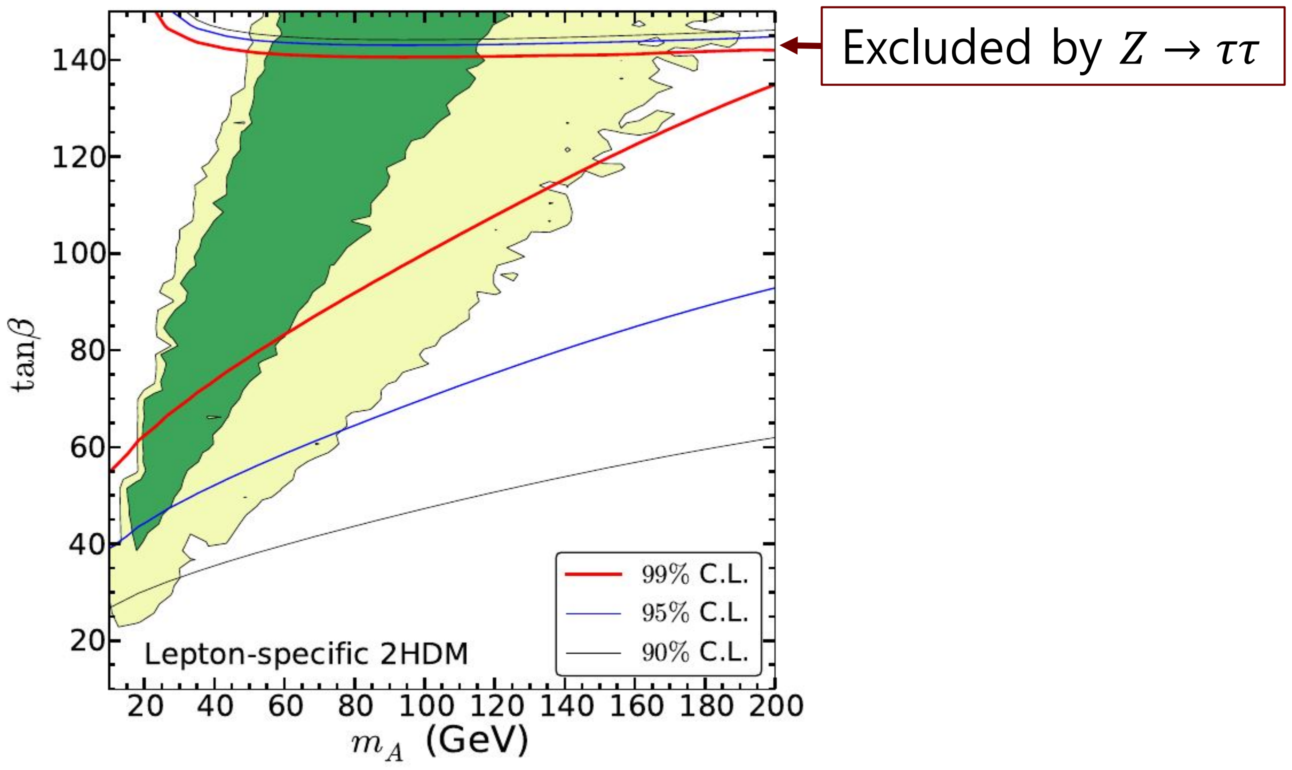


Profile likelihood analysis

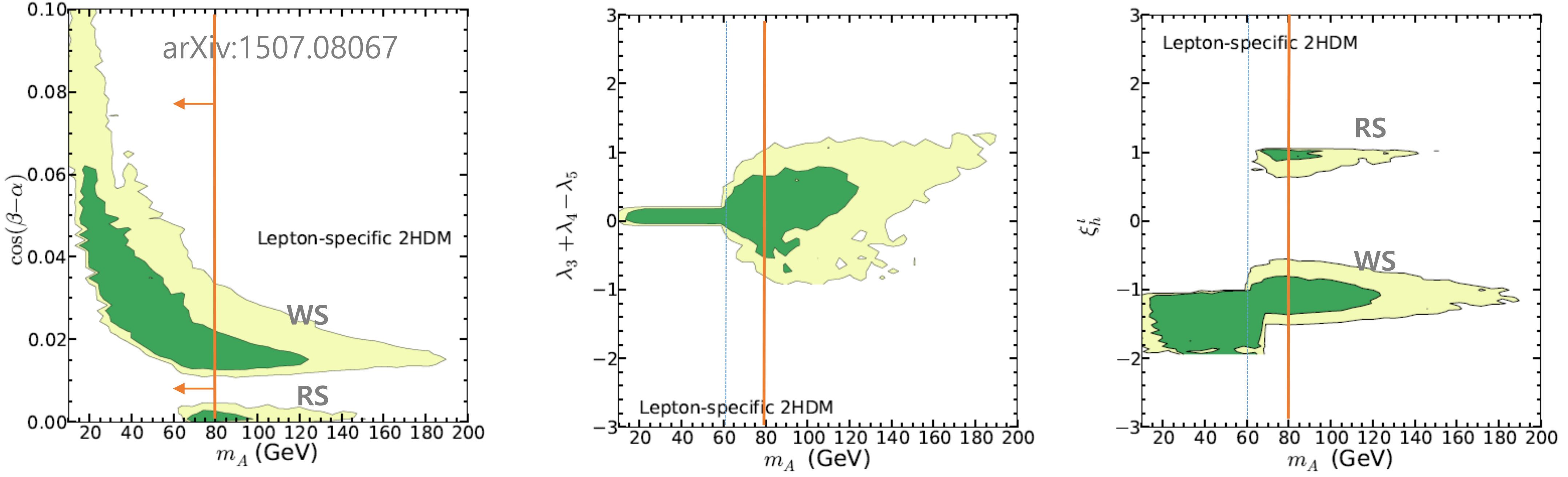
- Scanning through all the parameter space combining the h(125) data, muon g-2, EWPD, theoretical constraints, and the relevant LEP, B decay and LU limits.

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	$0.0 < \lambda_1 < 4\pi$

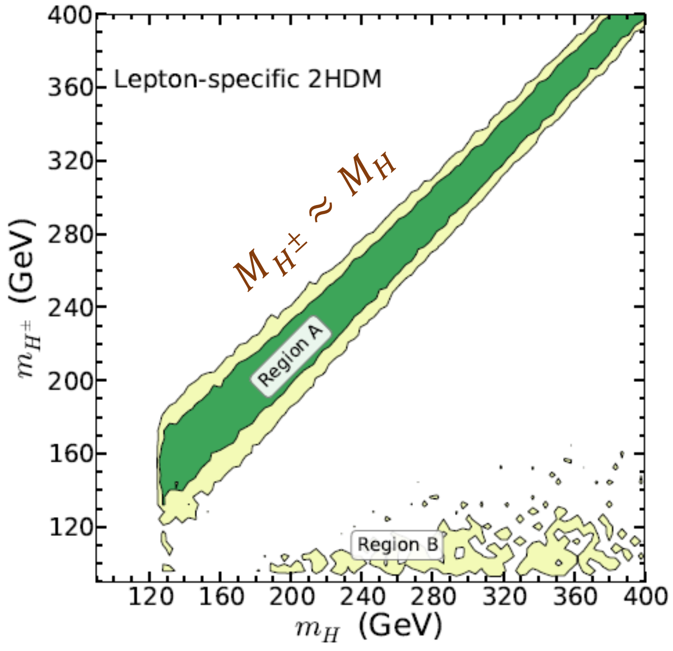
arXiv:1507.08067 (rev.)

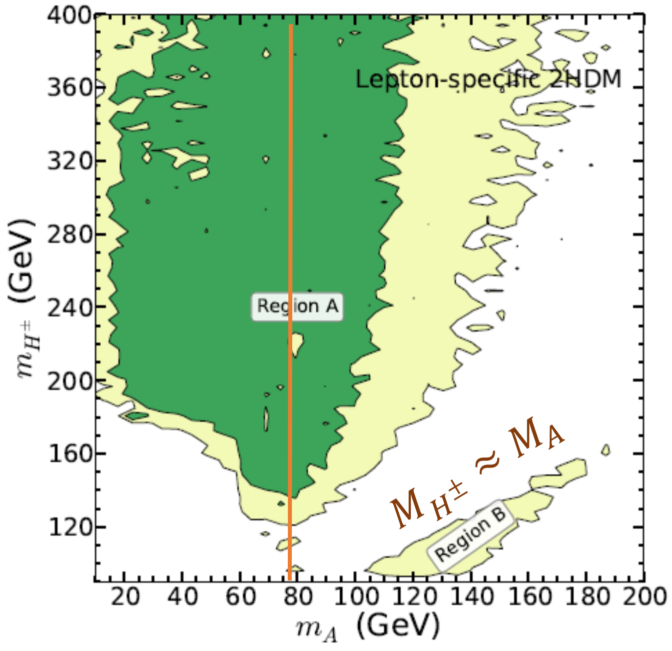


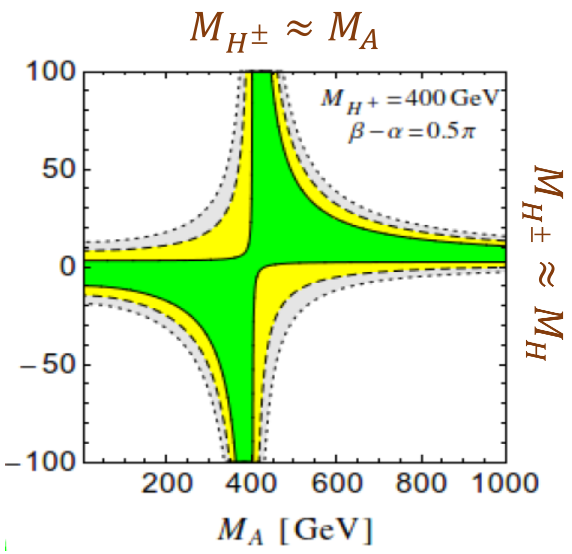
The RS vs. WS domain



Mass distribution



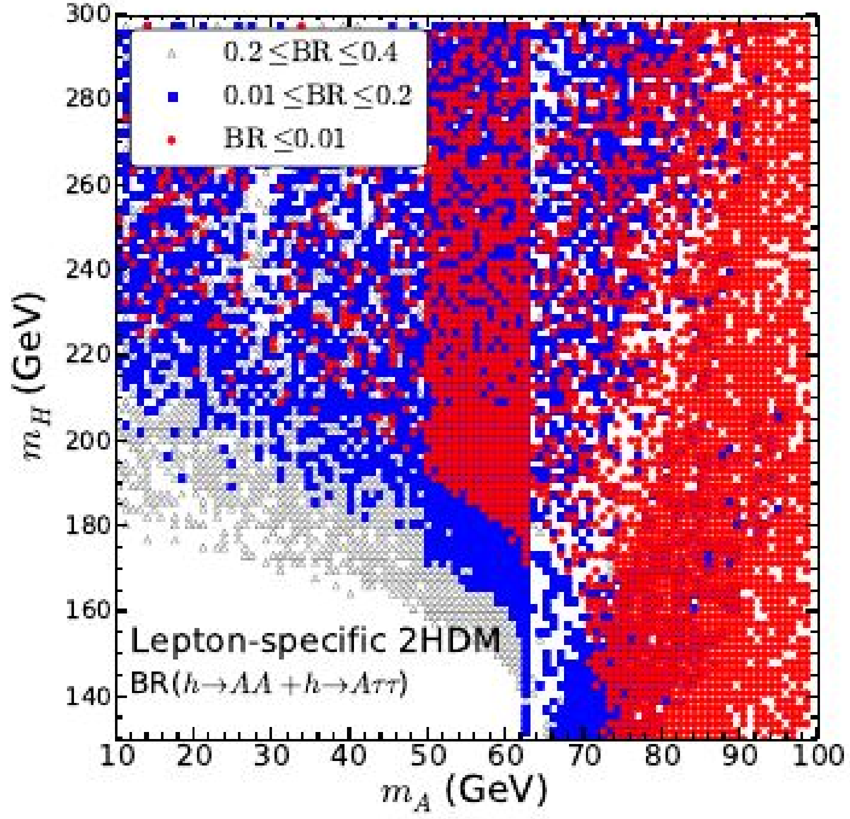




Tau-rich signatures at LHC

- h(125) → AA → 4 tau

arXiv:1507.08067



Tau-rich signatures at LHC

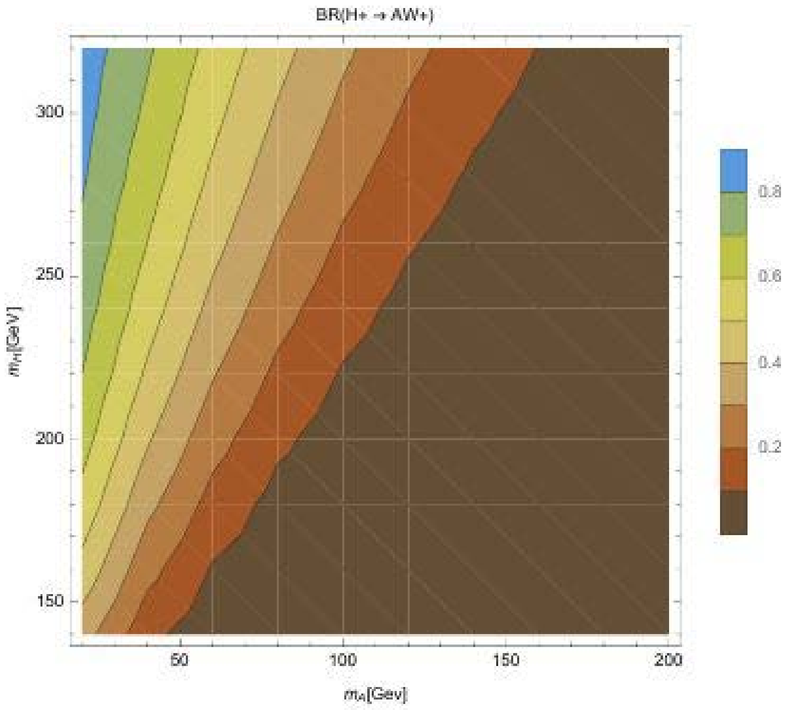
- EW production of extra Higges

$$pp \to W^{\pm *} \to H^{\pm} A \to (\tau^{\pm}\nu)(\tau^{+}\tau^{-}),$$
$$pp \to Z^{*}/\gamma^{*} \to HA \to (\tau^{+}\tau^{-})(\tau^{+}\tau^{-}),$$
$$pp \to W^{\pm *} \to H^{\pm} H \to (\tau^{\pm}\nu)(\tau^{+}\tau^{-}),$$
$$pp \to Z^{*}/\gamma^{*} \to H^{+}H^{-} \to (\tau^{+}\nu)(\tau^{-}\bar{\nu}).$$

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

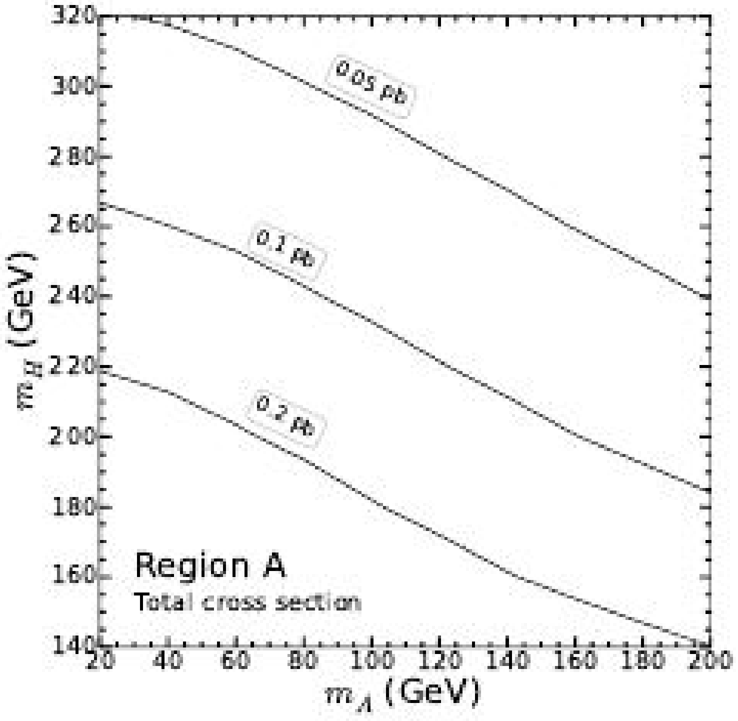
Region A: $m_{H^\pm} = m_H + 15$ GeV

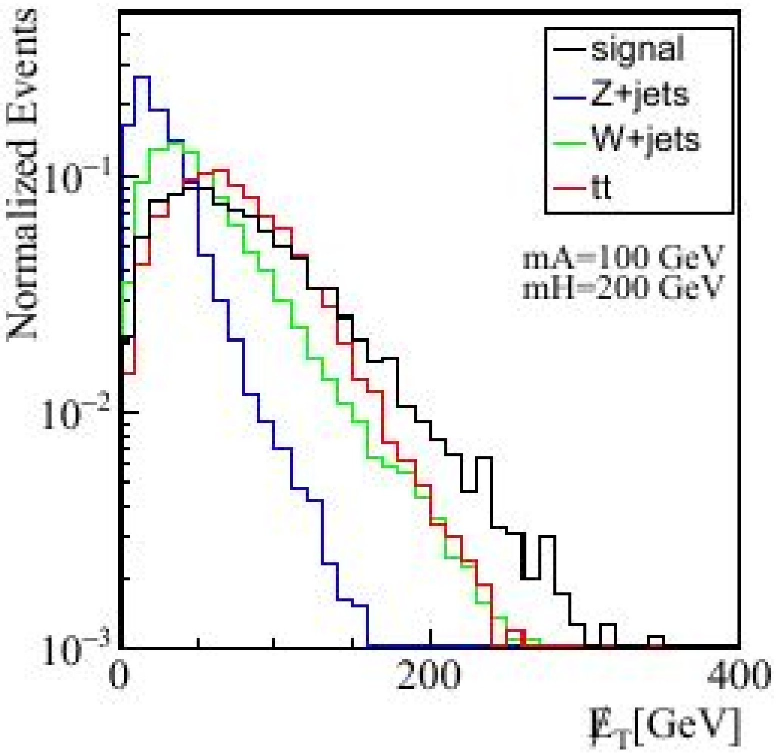
$$H^{\pm} \to A\,W^{\pm} \quad vs. \quad \nu\,\tau^{\pm}$$
$$H \quad \to \quad A\,Z \quad vs. \quad \tau^{+}\tau^{-}$$



LHC14 perspective

- Production X-section & missing signature:

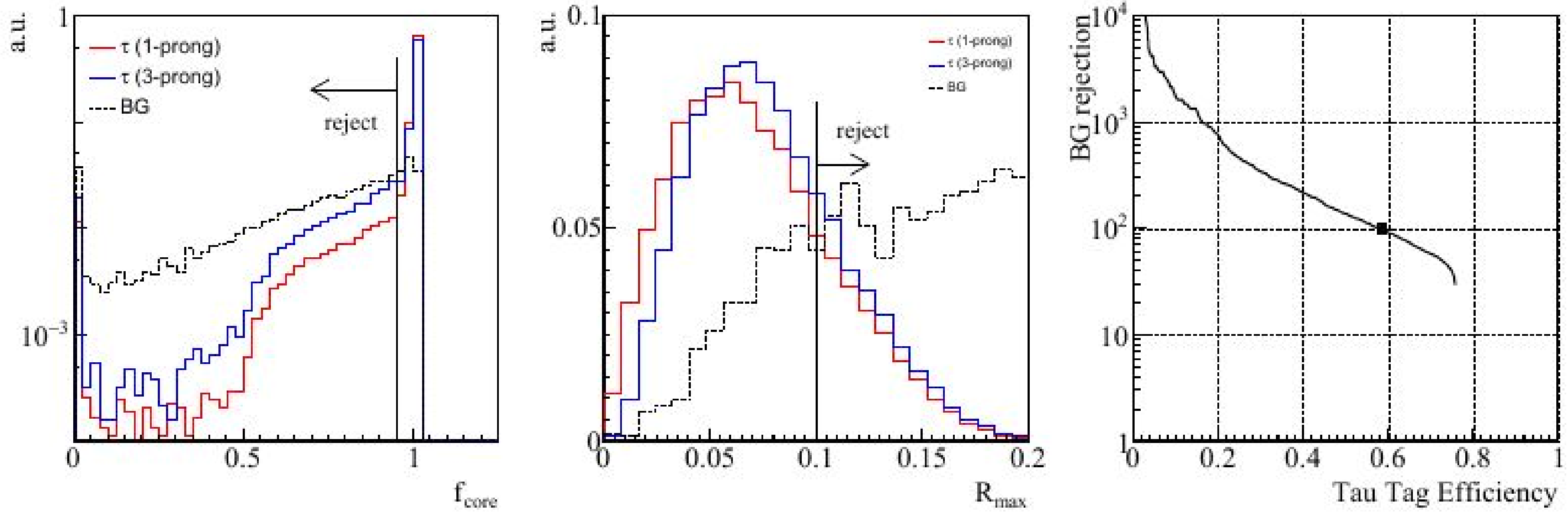




Tau identification and reconstruction

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

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



Event selection cuts

$ex)\ m_A = 100\ GeV\ \&\ m_H = 200\ GeV$

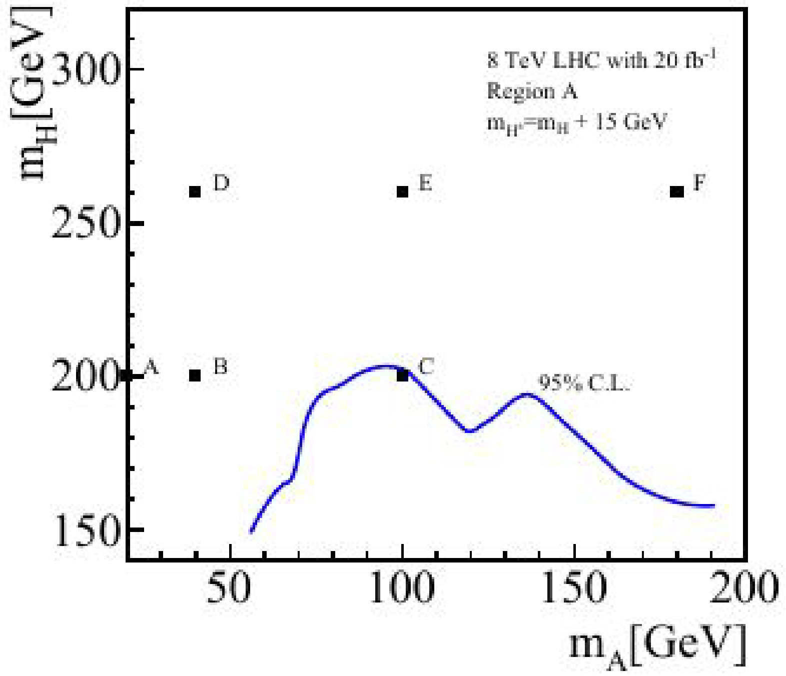
selection cuts	point C	$t\bar{t}$	W+jets	Z+jets	WW	WZ	ZZ	total BG	S/B	$S/\sqrt{B}_{25\text{fb}^{-1}}$
total σ_{gen} [fb]	153.580	$102 \cdot 10^3$	$1365 \cdot 10^3$	$714 \cdot 10^3$	8125	942	112	$2190 \cdot 10^3$	-	-
$n_\ell \geq 3$	21.713	273.27	138.59	3412.84	6.495	88.937	26.965	3947.1	-	1.7
$n_\tau \geq 3$	4.386	5.837	13.776	91.324	0.070	0.343	0.174	111.52	0.04	2.1
$\not{E}_T > 100$ 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

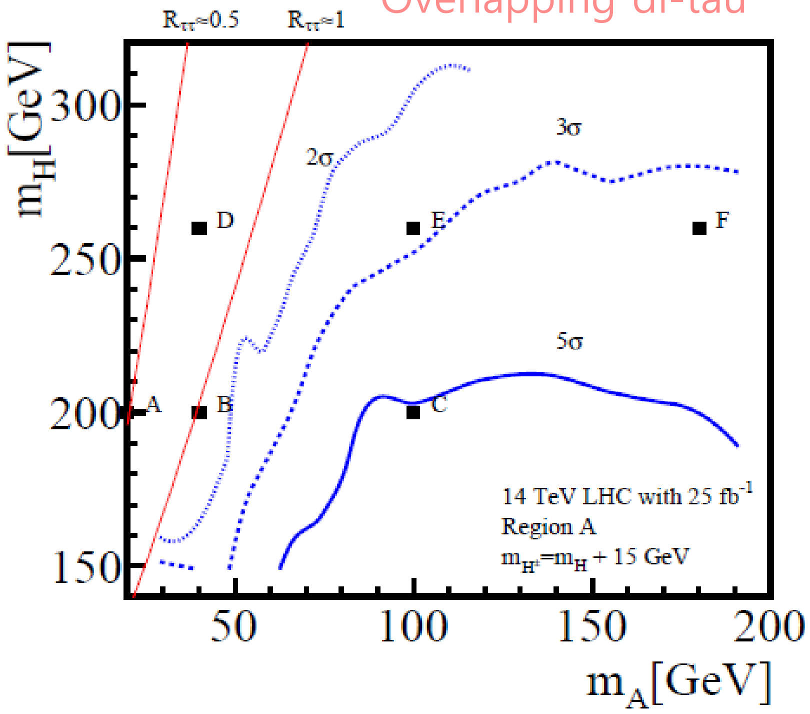
Benchmark study of significance at 25/fb

	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
$\not{E}_T > 100$ 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-neuralino 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 most strong constraint comes from the lepton universality tests strongly limit the allowed region (at 2σ):

$$m_A \approx 10 - 80\, GeV\ \&\ t_\beta \approx 25 - 60.$$

- The RS limit requires $63GeV \lesssim m_A \ll m_H \approx m_{H^\pm} \lesssim 250GeV$.
- The WS limit, allowing $10\, GeV \lesssim m_A \ll m_H \approx m_{H^\pm} \lesssim \sqrt{4\pi}v$, is more preferable.
- The exotic Higgs decay $h \to AA^{(*)} \to 4\tau$ would provide a hint.
- Tau-rich signals should be searched for with a more care, in particular, to probe a light A.