KOREA INSTITUTE FOR ADVANCED STUDY


# LHC probe of Lepto-filic 2HDM for muon g-2

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
(J.S. Kim, work in progress)

# “Can a 2HDM explain muon g-2?”

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

- Only in Lepton-specific (Type X) 2HDM through Barr-Zee two-loop with a light pseudoscalar $A$ and large $t_\beta$. arXiv:1409.3199

- The parameter space limited by EWPD, vacuum stability & perturbativity, $h(126)$, and $B_s \to \mu\mu$.
- Stronger constraints on loop corrections to tau vertices from the lepton universality in $l \to l'\nu\nu$ & $Z \to ll$. (arXiv:1605.xxxxx)

- LHC probe of the model: a light $A$ mainly decaying to $\tau\tau$. arXiv:1507.08067

$$pp \to h \to AA^{(*)} \to 4\tau; \quad pp \to H^{0,\pm} A \to AA + Z/W \to 4\tau + Z/W$$

# 4 types of 2HDM with natural flavor conservation

Impose $Z_2$ to couple only one Higgs to each down-type Yukawa

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

| Model | $u_R^i$ | $d_R^i$ | $e_R^i$ |
|---|---|---|---|
| Type I | $\Phi_2$ | $\Phi_2$ | $\Phi_2$ |
| Type II | $\Phi_2$ | $\Phi_1$ | $\Phi_1$ |
| Lepton-specific | $\Phi_2$ | $\Phi_2$ | $\Phi_1$ |
| Flipped | $\Phi_2$ | $\Phi_1$ | $\Phi_2$ |

| | $y_u^A$ | $y_d^A$ | $y_l^A$ | $y_u^H$ | $y_d^H$ | $y_l^H$ | $y_u^h$ | $y_d^h$ | $y_l^h$ |
|---|---|---|---|---|---|---|---|---|---|
| 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 | $\cot\beta$ | $\tan\beta$ | $-\cot\beta$ | $\frac{\sin\alpha}{\sin\beta}$ | $\frac{\cos\alpha}{\cos\beta}$ | $\frac{\sin\alpha}{\sin\beta}$ | $\frac{\cos\alpha}{\sin\beta}$ | $-\frac{\sin\alpha}{\cos\beta}$ | $\frac{\cos\alpha}{\sin\beta}$ |

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

# Aligned/decoupled limit: $\sin(\beta-\alpha)\to 1$

$$\mathcal{L}_{gauge} = g_V m_V (s_{\beta-\alpha} h + c_{\beta-\alpha} H) VV + \cdots$$

| Model | $u_R^i$ | $d_R^i$ | $e_R^i$ |
|---|---|---|---|
| Type I | $\Phi_2$ | $\Phi_2$ | $\Phi_2$ |
| Type II | $\Phi_2$ | $\Phi_1$ | $\Phi_1$ |
| Lepton-specific | $\Phi_2$ | $\Phi_2$ | $\Phi_1$ |
| Flipped | $\Phi_2$ | $\Phi_1$ | $\Phi_2$ |

| | $y_u^A$ | $y_d^A$ | $y_l^A$ | $y_u^H$ | $y_d^H$ | $y_l^H$ | $y_u^h$ | $y_d^h$ | $y_l^h$ |
|---|---|---|---|---|---|---|---|---|---|
| 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 | $\cot\beta$ | $\tan\beta$ | $-\cot\beta$ | $\frac{\sin\alpha}{\sin\beta}$ | $\frac{\cos\alpha}{\cos\beta}$ | $\frac{\sin\alpha}{\sin\beta}$ | $\frac{\cos\alpha}{\sin\beta}$ | $-\frac{\sin\alpha}{\cos\beta}$ | $\frac{\cos\alpha}{\sin\beta}$ |

≈

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

RS
WS

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

125 GeV

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

# Muon g-2 from Barr-Zee 2-loop

- Needs a light $A$ and large $y^A_{\mu,f} \approx t_\beta$:

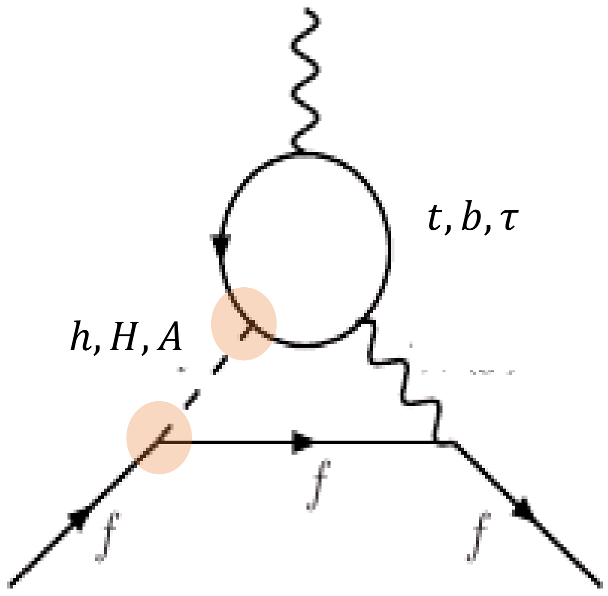
$$\delta a_\mu^{\rm 2HDM}(2{\rm loop}-{\rm BZ}) = \frac{G_F\, m_\mu^2}{4\pi^2\sqrt{2}} \frac{\alpha_{\rm em}}{\pi} \sum_{f;\, i=h,H,A} N_f^c\, Q_f^2\, y_\mu^i\, y_f^i\, r_f^i\, g_i(r_f^i)$$

$y_\mu^i y_f^i \to t_\beta^2$, $r_f^i \to m_f^2/m_{h,H,A}^2$

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

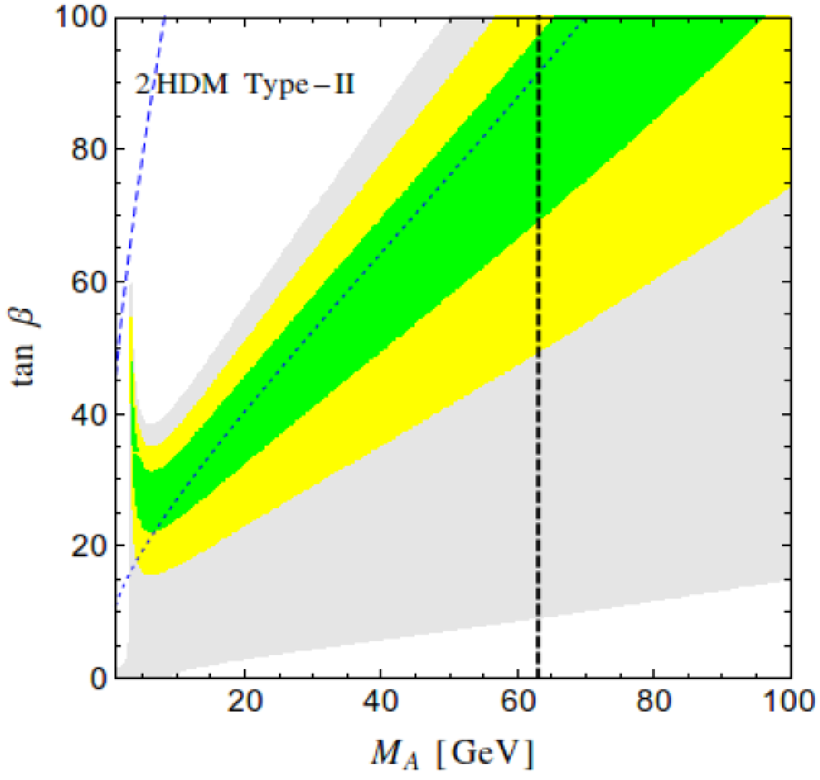
$g_A(r) > 0$

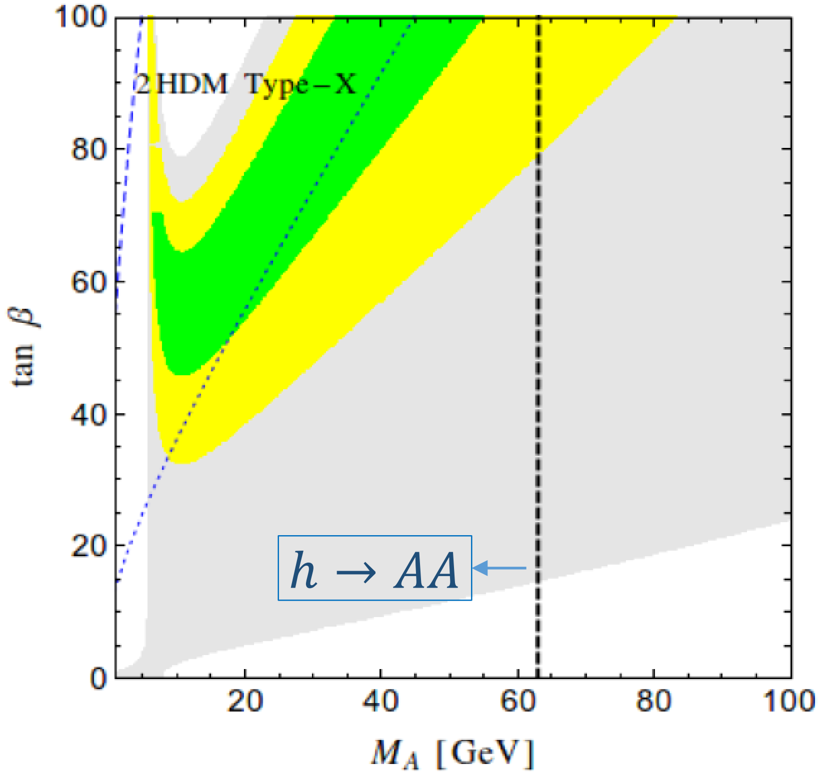
| | $\tau$ | $t$ | $b$ |
|---|---|---|---|
| I | $1/t_\beta^2$ | $-1/t_\beta^2$ | $1/t_\beta^2$ |
| II | $t_\beta^2$ | 1 | $t_\beta^2$ |
| X | $t_\beta^2$ | 1 | -1 |
| Y | $1/t_\beta^2$ | $-1/t_\beta^2$ | -1 |



# Muon g-2 in Type II & X

arXiv:1409.3199




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

# EWPD requires $m_A \ll m_H \approx m_{H^\pm}$

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

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

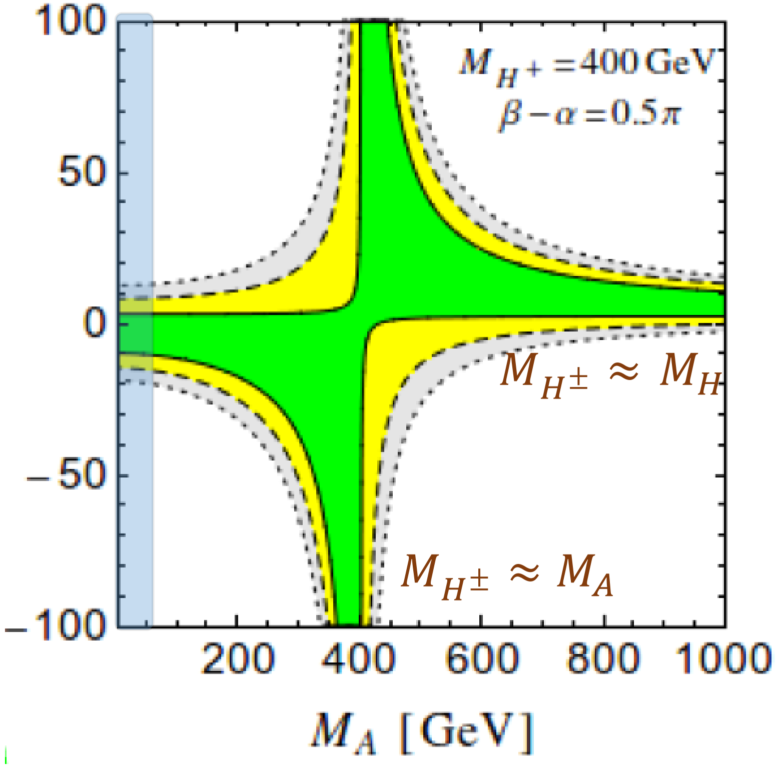
$$\Delta r^{\rm 2HDM} = \Delta\alpha^{\rm 2HDM} - \frac{\cos^2\theta_W}{\sin^2\theta_W}\Delta\rho^{\rm 2HDM} + \ldots ,$$

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

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

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

arXiv:1409.3199




Generalized custodial symmetry
Gerard-Herquet, 0703051

# Vacuum stability & perturbativity

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

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

$$|\lambda_i| < 4\pi$$

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

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

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

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

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

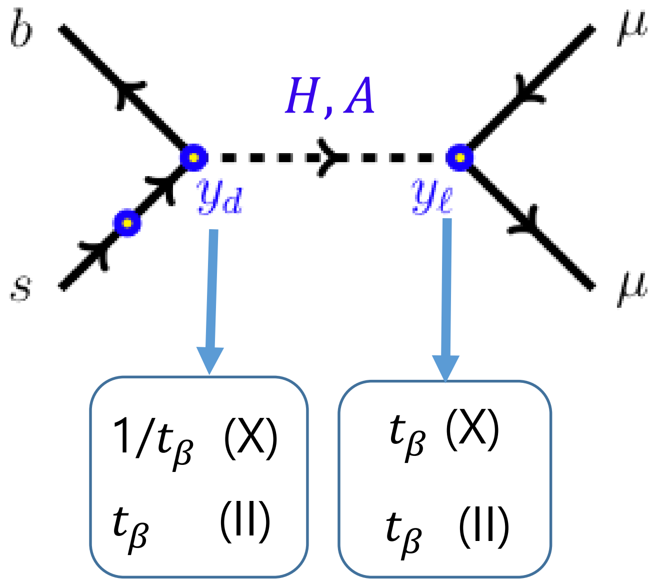
$$\lambda_4 v^2 \approx -2M_{H^\pm}^2 + M_H^2 + M_A^2$$

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

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

$s_{\beta-\alpha}y_\tau = \pm 1$ RS / WS

# $B_s \to \mu^+\mu^-$ requires heavy $A$ and low $t_\beta$




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

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

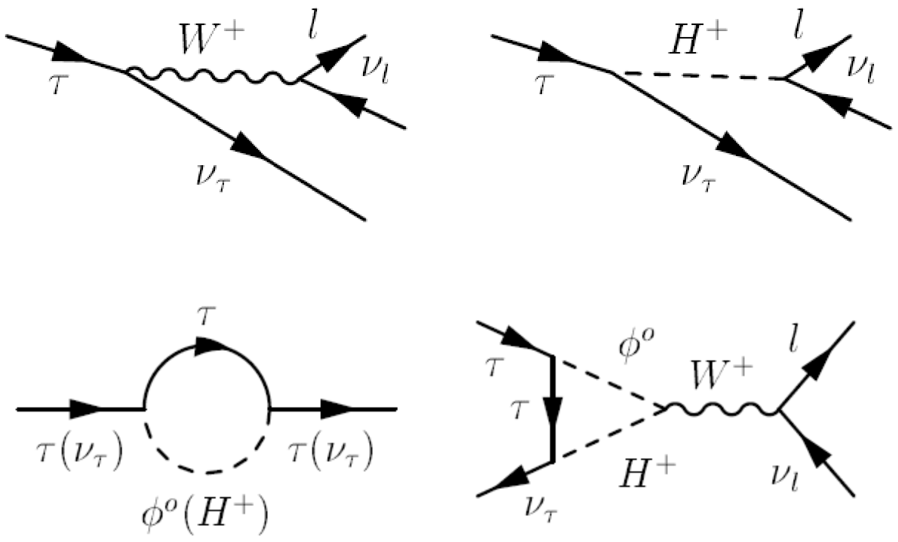
Type II excluded

Type X with $m_A \gtrsim 10$ GeV

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

# Lepton universality in $\tau$ 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
Abe, et.al., 1504.07059

# LU constraining the muon g-2 region

- Two independent data from $l \to l'\nu\nu$ and the combined data from $\tau \to \nu\pi/K$ leads to

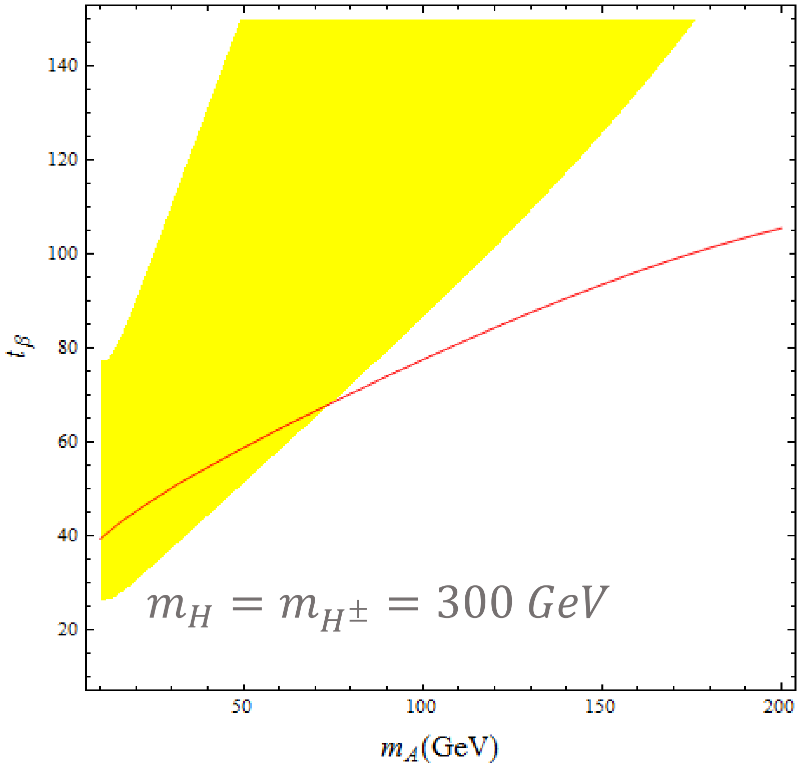
$$\sqrt{\frac{3}{2}}\delta_{tree} = 0.0022 \pm 0.0017$$

HFAG, 1412.7515

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

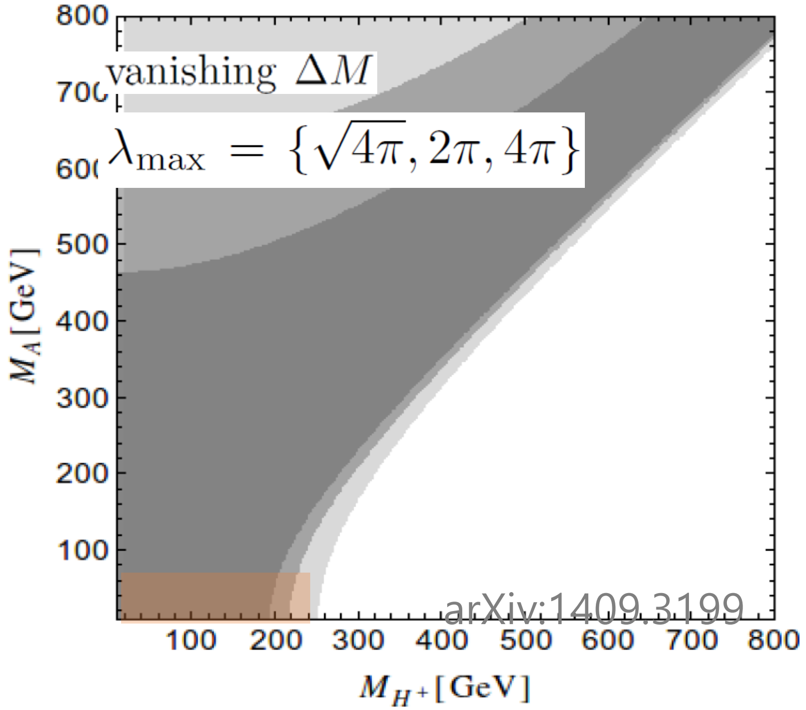
$$\sqrt{\frac{1}{2}}\delta_{tree} + \sqrt{2}\delta_{loop} = 0.0028 \pm 0.0019$$

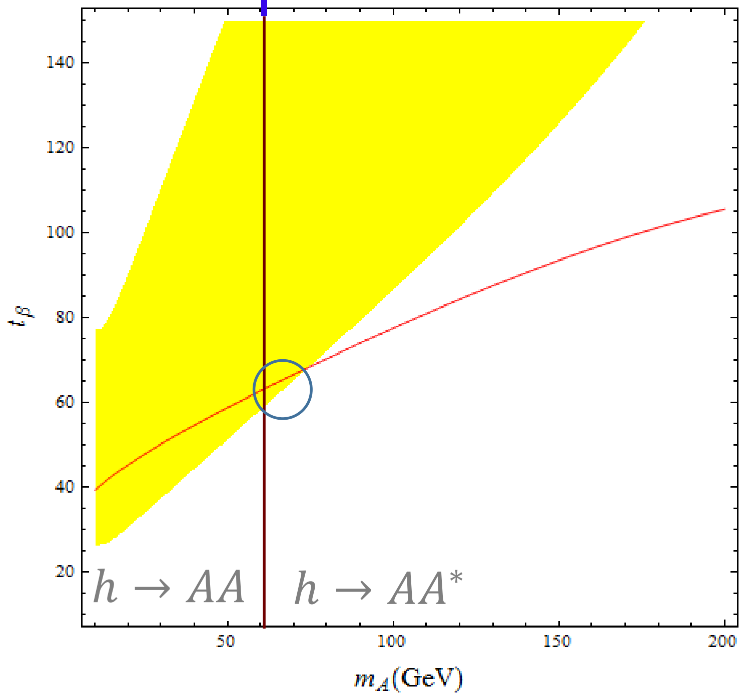
- The muon g-2 favoured region is strongly limited:



# L2HDM in the right-sign limit $(y_\tau s_{\beta-\alpha} \approx +1, c_{\beta-\alpha} \approx 0)$

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




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

# L2HDM in the wrong-sign limit $(y_\tau\, s_{\beta-\alpha} \approx -1, c_{\beta-\alpha} \approx \frac{2}{t_\beta})$

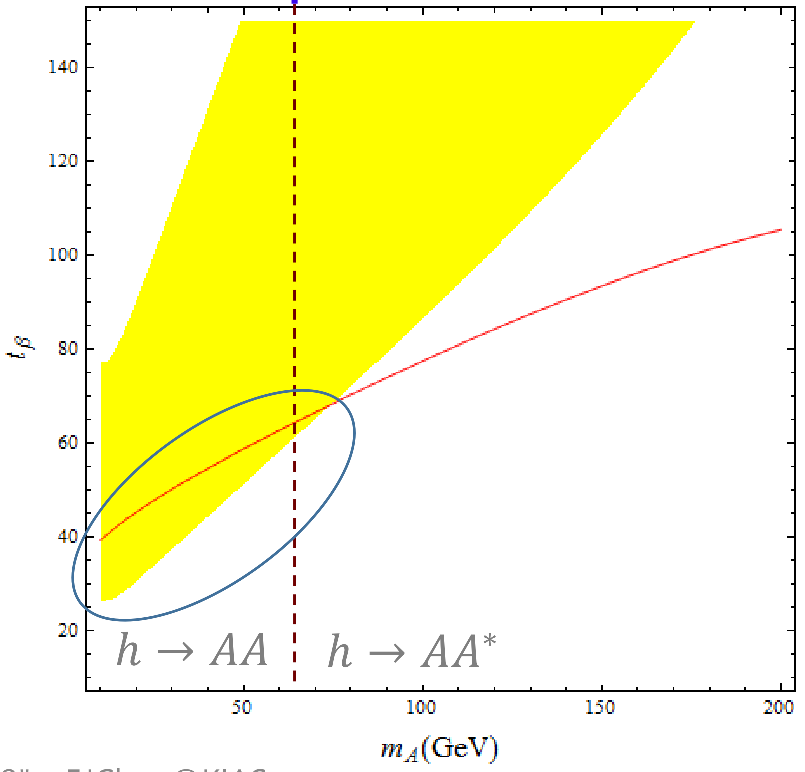
$$\lambda_{hAA} v \approx -(1 + s_{\beta-\alpha} y_\tau) M_H^2 + 2M_A^2 + s_{\beta-\alpha} y_\tau M_h^2 \rightarrow \mathbf{0}$$

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

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

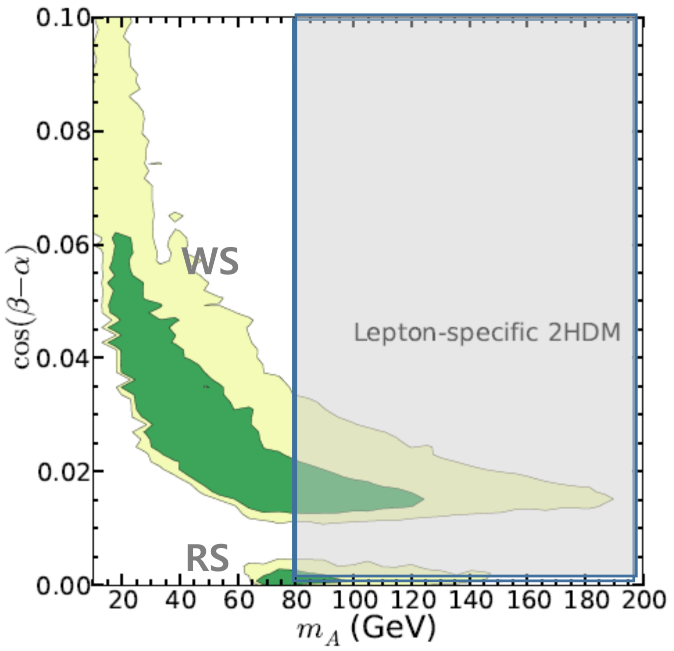
Wang, Han, arXiv:1412.4874

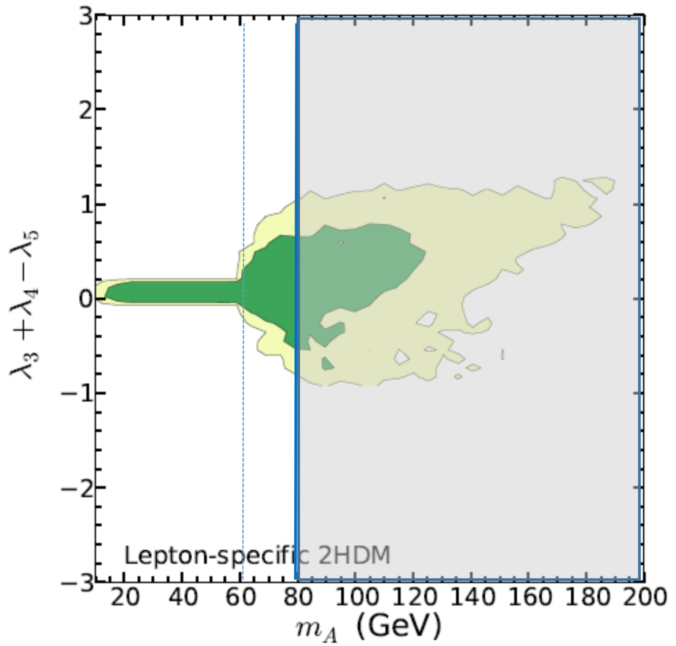
$$10\ GeV \lesssim m_A \ll m_H \approx m_{H^\pm} \lesssim \sqrt{4\pi} v$$

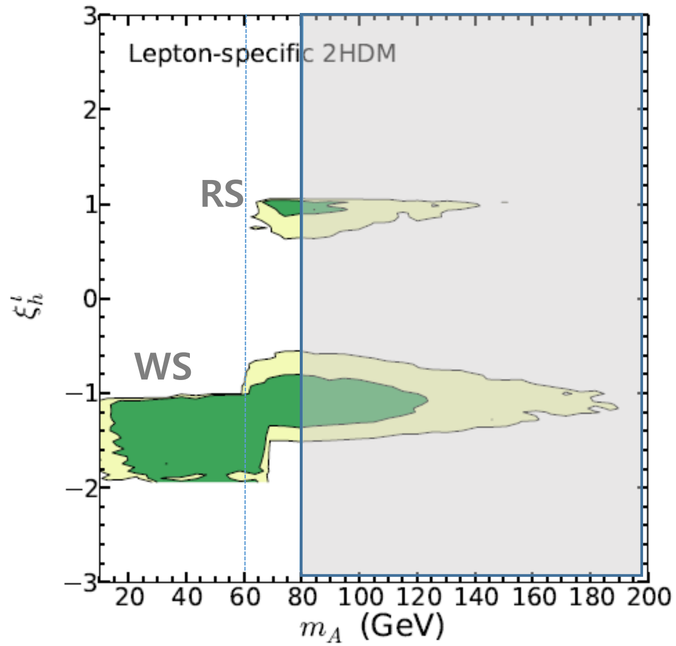


# Allowed parameter space

arXiv:1507.08067




$\cos(\beta-\alpha)$

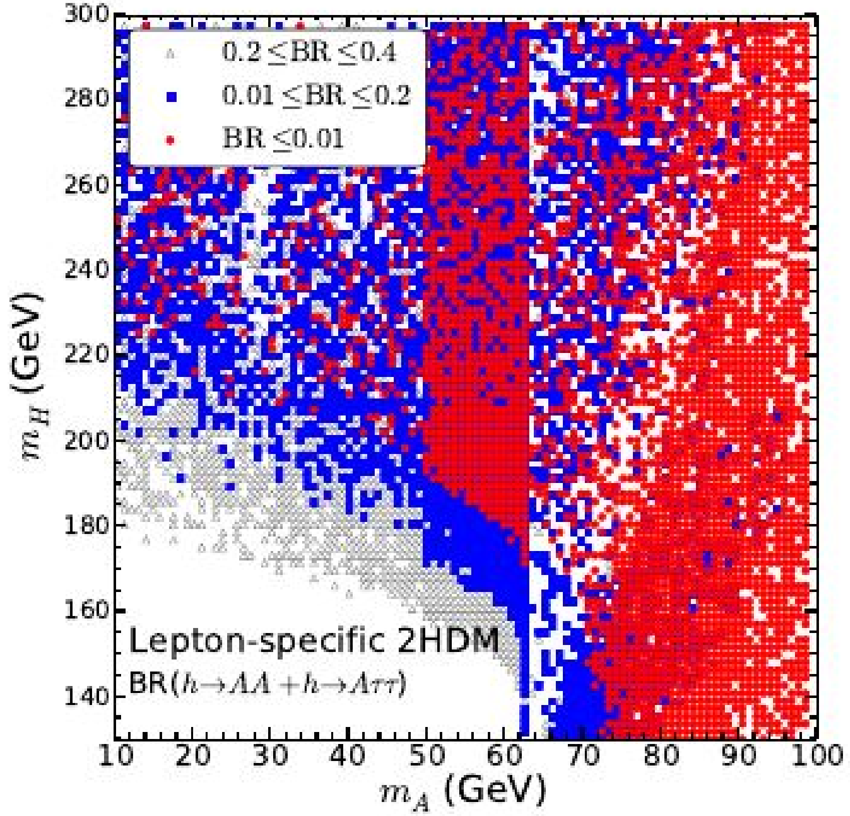
$\lambda_{hAA} \propto \lambda_3 + \lambda_4 - \lambda_5$

Assuming $BR(h \to AA) < 40\%$

$y_\tau$

# LHC signatures from $h \to AA^{(*)} \to 4\tau$ ?

arXiv:1507.08067



# LHC signatures from $pp \to H^{0,\pm} A \to 3\tau/4\tau$

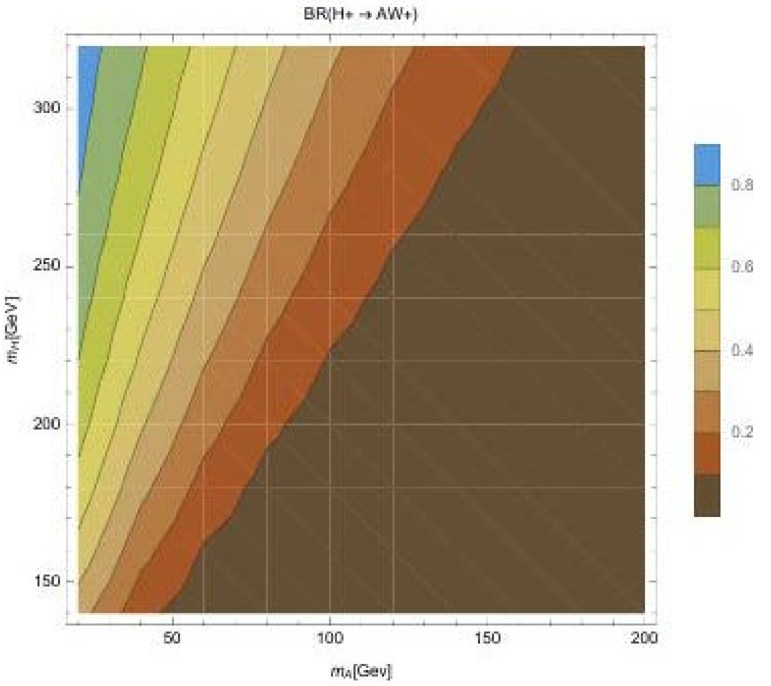
- EW production of extra Higges decaying mainly to taus

$$pp \to H^{\pm} A \to AA + W^{\pm} \to 4\tau + W$$
$$pp \to H^{\pm} A \to 3\tau + \nu$$
$$pp \to H^{0} A \to AA + Z \to 4\tau + Z$$
$$pp \to H^{0} A \to 4\tau$$

➢ Signal selection: $3\tau + MET, 0b, 0j$

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

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

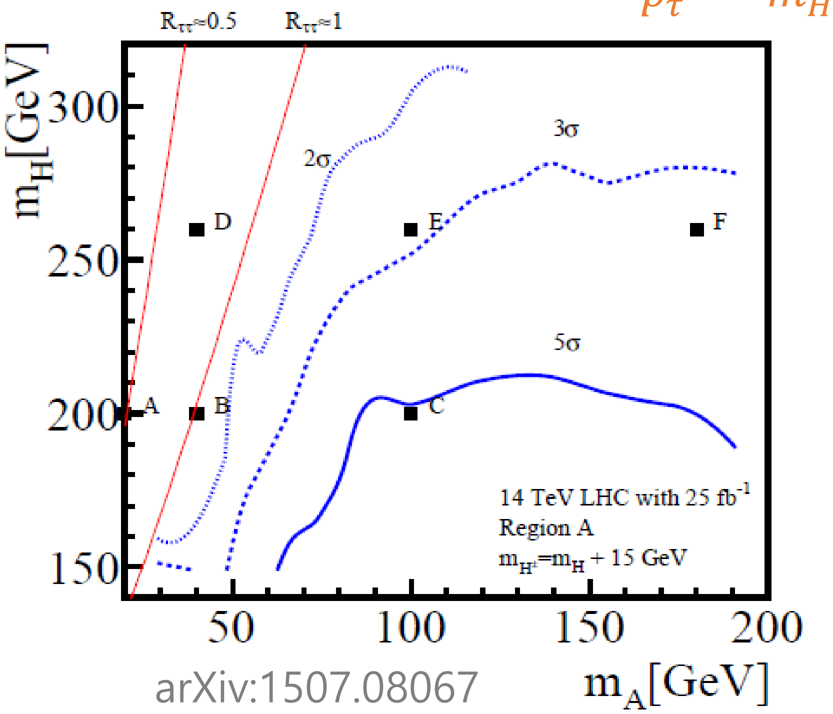


# LHC14 perspective with 25/fb

- Challenges to probe lighter $A$ producing softer $\tau\tau$, and heavy $H^{\pm}/H$ producing boosted $A(\tau\tau)$.
- Needs HL-LHC.

| | 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 $\sigma_{\text{gen}}$ [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 |

Overlapping di-tau $R_{\tau\tau} \sim \frac{2m_\tau}{p_\tau} \sim \frac{4m_\tau}{m_H}$

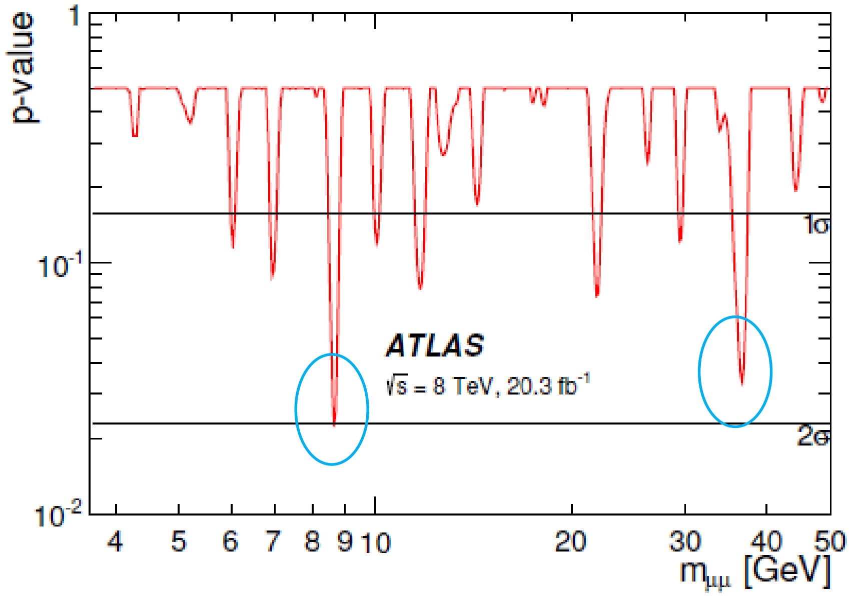


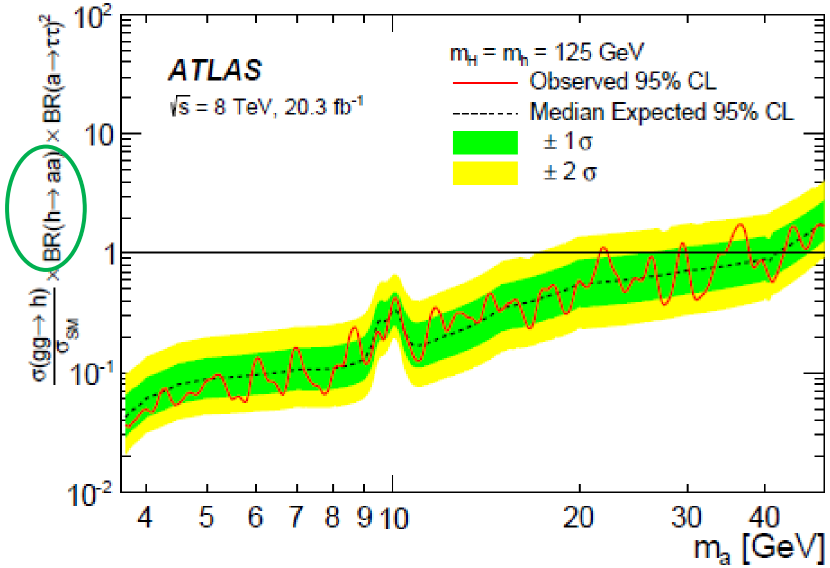

arXiv:1507.08067

# LHCski discussion

✓ Search for $h \to A\, A \to \mu\mu\, \tau\tau$

ATLAS, 1505.01609




✓ Also for $pp \to H^{0,\pm} A \to \mu\mu\, \tau(\tau) + X$ ?

# Conclusion

- 2HDM-X is still a viable option for muon $g$-2.
- The most strong constraint comes from the lepton universality tests strongly limiting the allowed region (at $2\sigma$):

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

in the RS limit: $63GeV \lesssim m_A \ll m_H \approx m_{H^\pm} \lesssim 250GeV$

in the WS limit: $10\ GeV \lesssim m_A \ll m_H \approx m_{H^\pm} \lesssim \sqrt{4\pi}v$

- LHC can search for $A \to \tau\tau\ (\mu\mu)$ through $pp \to h \to AA^{(*)} \to 4\tau\ (\mu\mu\tau\tau)$, or $pp \to H^{0,\pm}A \to 4\tau + X\ (\mu\mu\tau\tau + X)$.
- Challenge to probe a light $A$ : more data and/or further studies on boosted di-tau tagging.

# Back up

# Muon g-2 from 1-loop

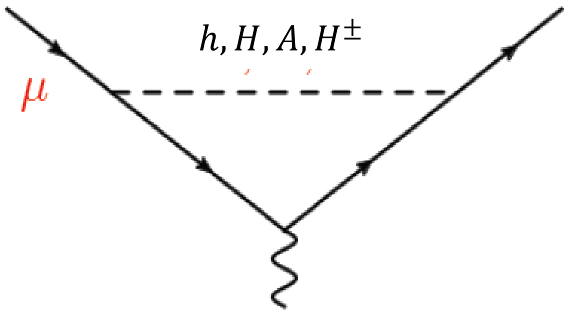
- For a light $H$ and large $y_\mu^H \approx t_\beta$ (II, X):

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

roughly scales with $m_\mu^4$!

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

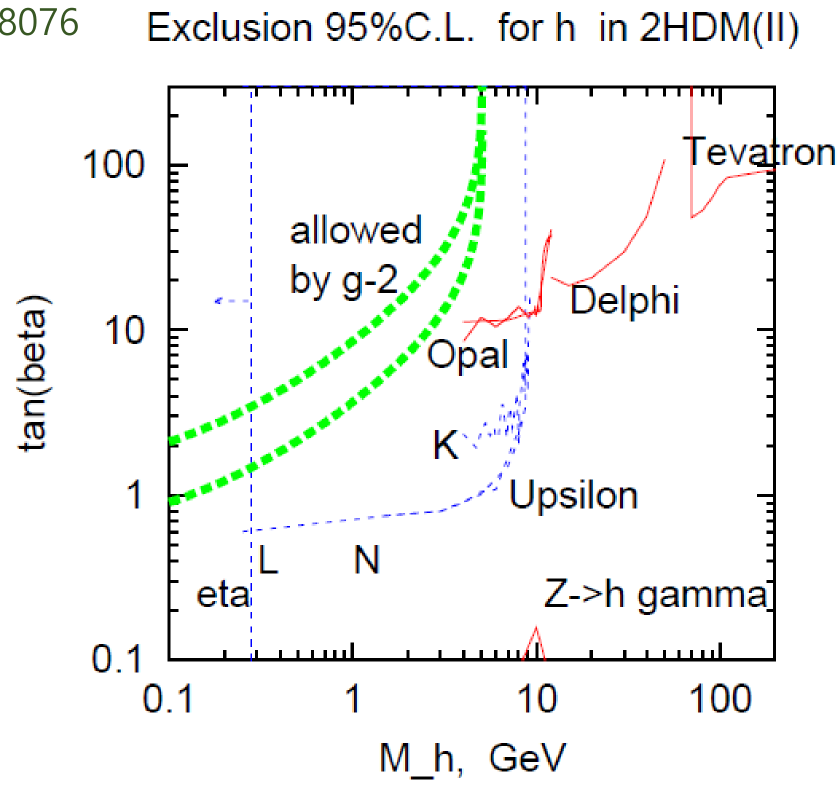
$$\begin{aligned} f_{h,H}(r) &\sim -\ln r - 7/6 + O(r) > 0 \\ f_A(r) &\sim +\ln r + 11/6 + O(r) < 0 \\ f_{H^\pm}(r) &\sim -1/6 + O(r) < 0 \end{aligned}$$



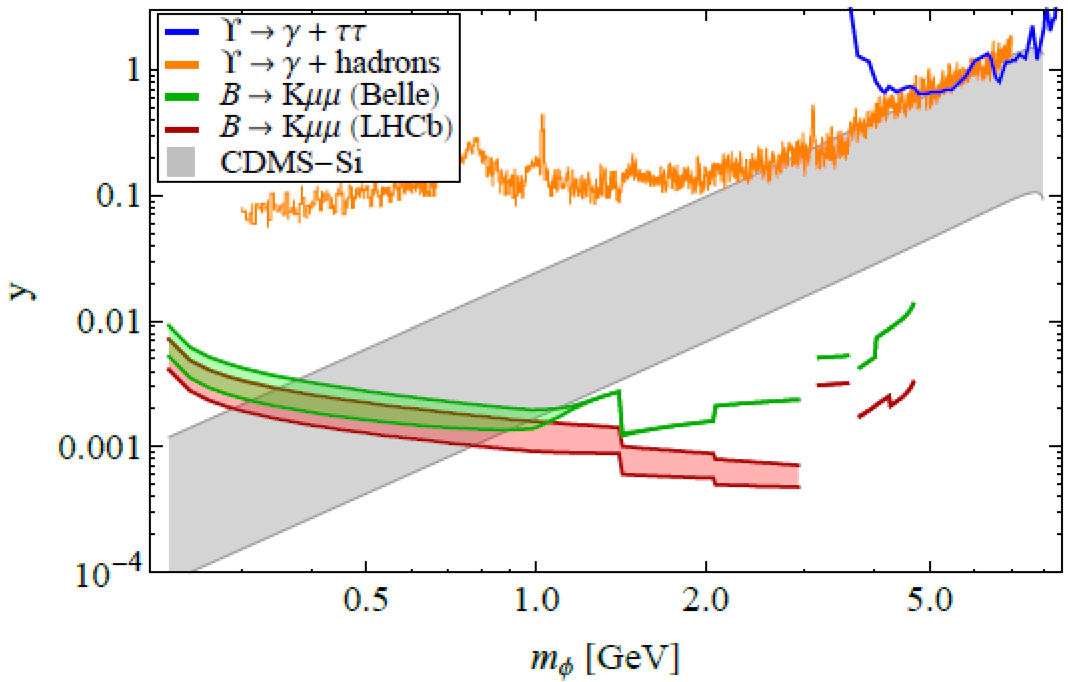
# One-loop solution excluded!

- 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



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

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

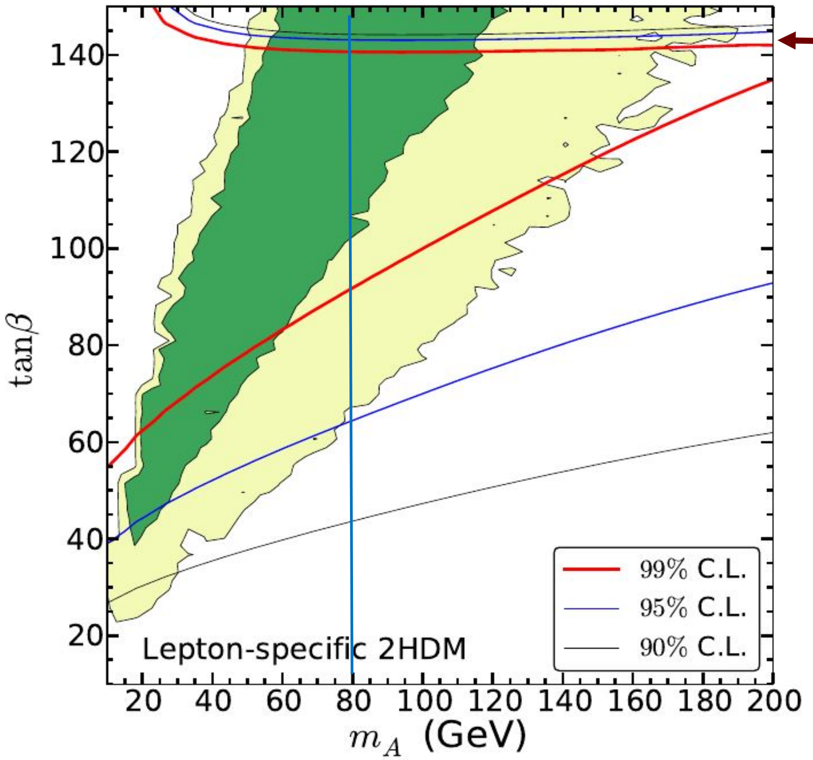
- Combining the three in $(g_\tau/g_\mu)$: $\left(\frac{g_\tau}{g_\mu}\right)_{\tau+\pi+K} = 1.0001 \pm 0.0014$

# 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) | $94 < m_{H^\pm} < 400$ |
| $c_{\beta-\alpha}$ | $0.0 < c_{\beta-\alpha} < 0.1$ |
| $\tan\beta$ | $10 < \tan\beta < 150$ |
| $\lambda_1$ | $0.0 < \lambda_1 < 4\pi$ |

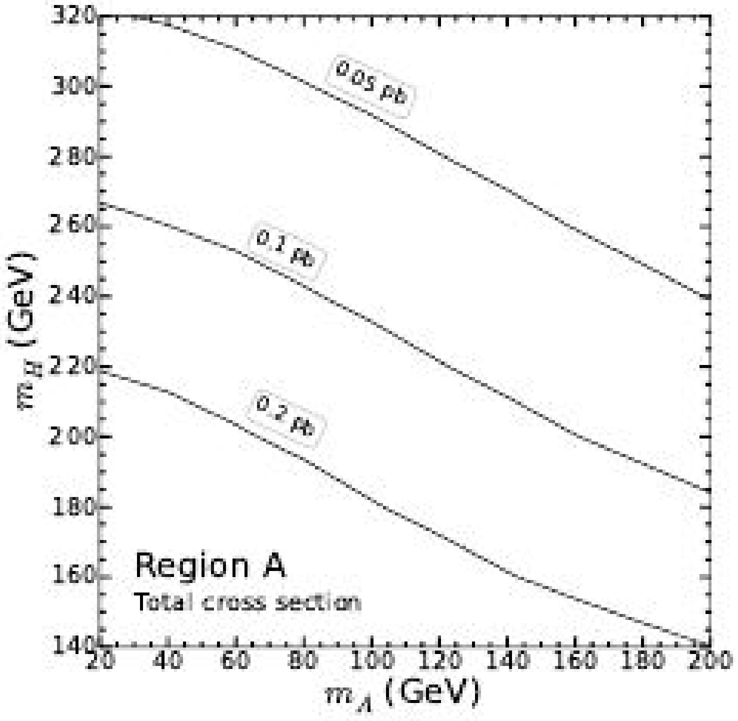
arXiv:1507.08067 (rev.)

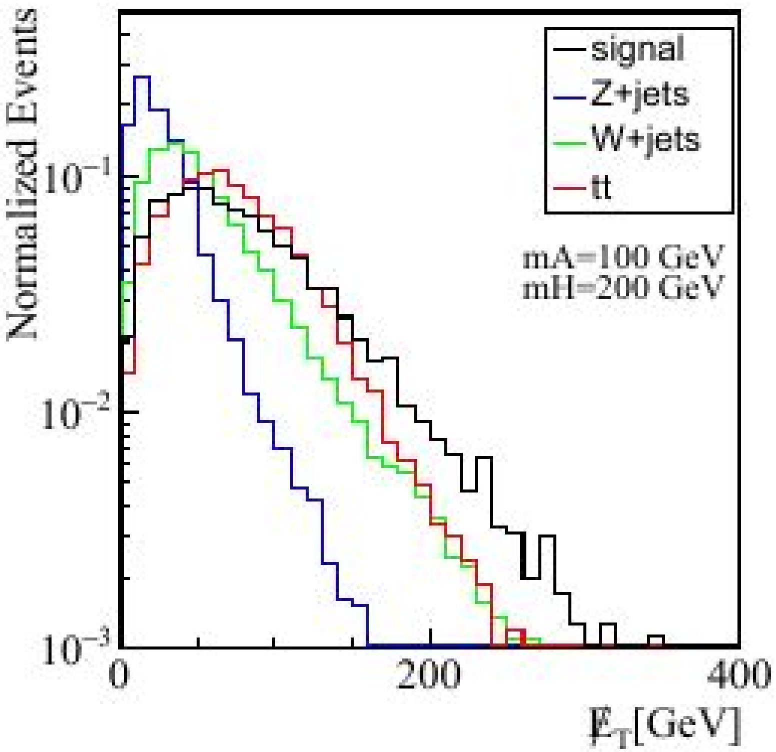



Excluded by $Z \to \tau\tau$

# LHC tau-rich signatures

- Production X-section & missing signature:

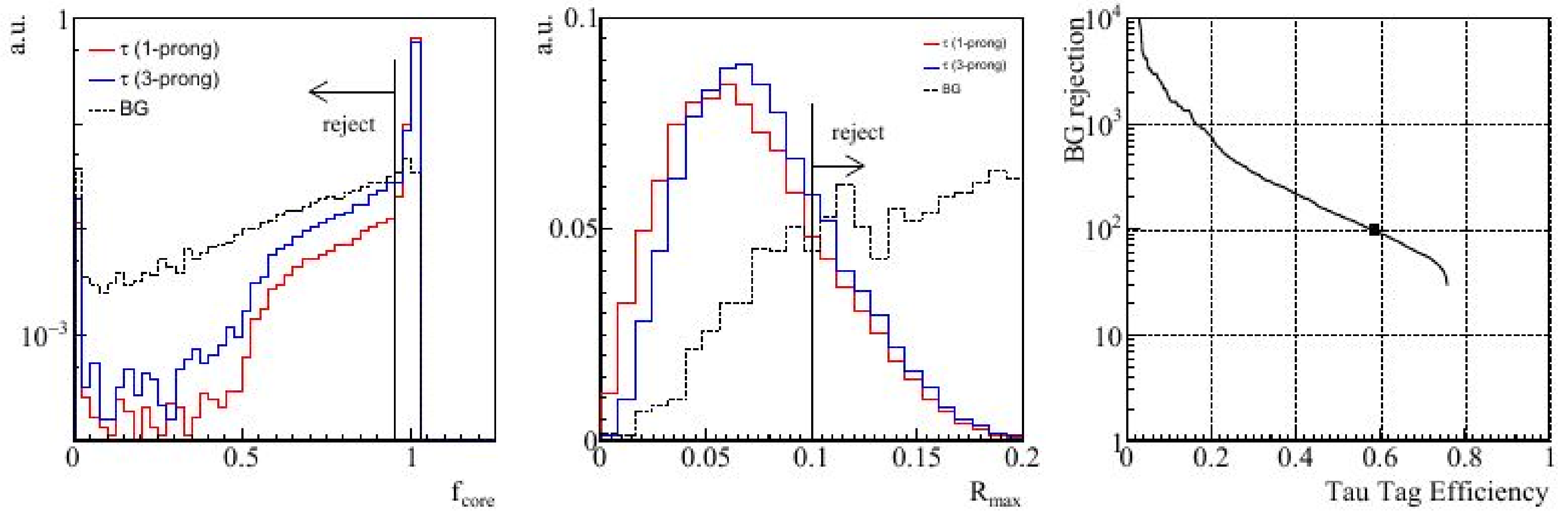


# Tau identification and reconstruction

- 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 $\sigma_{\text{gen}}$ [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 |

# LHC8 limits

- mostly from chargino-neuralino searches.