Workshop on Multi Higgs Models, 6-9 September 2016, Lisbon

Leptonic precision test of leptophilic 2HDM

Eung Jin Chun

Based on collaborations 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. Kim, arXiv:1605.06298

KIAS KOREA INSTITUTE FOR ADVANCED STUDY

Outline

- Type X (lepton-specific) 2HDM with a light CP-odd boson A and large t_β as an explanation of muon g-2.

Cf) A mini-review: 1511.05225

- Strong constraints from lepton universality tests in $l \to l'\nu\nu$ & $Z \to ll$.

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

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

Type X (lepton-specific) 2HDM

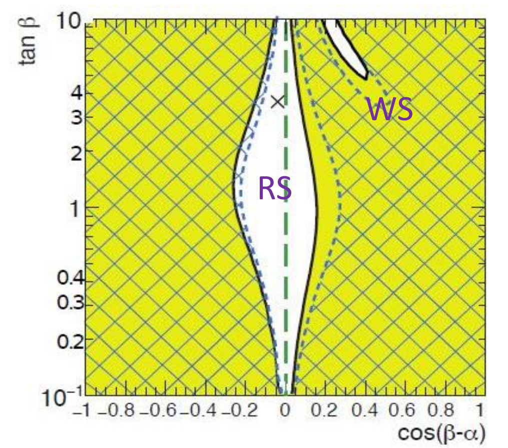
$$-\mathcal{L}_Y = y^u_{ij}\widetilde{\Phi}_2 q_i u^c_j + y^d_{ij}\Phi_2 q_i d^c_j + y^e_{ij}\Phi_1 l_i e^c_j + h.c.$$

$$\rightarrow \sum_{f=u,d,l} \frac{m_f}{v}\left(y^h_f h \bar{f} f + y^H_f H \bar{f} f - i y^A_f A \bar{f}\gamma_5 f\right)$$

125 GeV

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

ATLAS 1509.00672



	y^A_u	y^A_d	y^A_l	y^H_u	y^H_d	y^H_l	y^h_u	y^h_d	y^h_l
Type X	$\cot\beta$	$-\cot\beta$	$\tan\beta$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$

≈ (Decoupled/aligned limit)

Decoupled/aligned limit

$\cos(\beta-\alpha) \rightarrow 0$

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

RS
WS

Ferreira, et.al, 1403.4736; 1410.1926

Leptophilic 2HDM (L2HDM)

- Type X 2HDM at large $\tan\beta$: extra Higgs boson couplings to leptons (quarks) $\propto \tan\beta (1/\tan\beta)$.
- Being leptophilic (hadrophobic), significant (negligible) contribution to leptonic (hadronic) processes:

  Elusive at the LHC;

  $\bar{B} \to X_s \gamma$ puts no bound on $m_{H^\pm}$ for $t_\beta > 2$;

  $B_s \to \mu^+\mu^-$ not affected if $m_A \gtrsim 15\ GeV$.
- The Barr-Zee 2-loop can be enhanced enough for light A to explain the muon g-2 anomaly:

  Strong limits from lepton universality in $Z \to ll,\ l \to l'\nu\nu'$.

Cao, et.al., 0909.5148
Broggio, et.al. 1409.3199
Wang-Han, 1412.4874
Abe, et.al, 1504.07059

Muon g-2 from two-loop

- A concrete 3σ deviation: $\Delta a_\mu \equiv a_\mu^{\rm EXP} - a_\mu^{\rm SM} = +262\,(85) \times 10^{-11}$

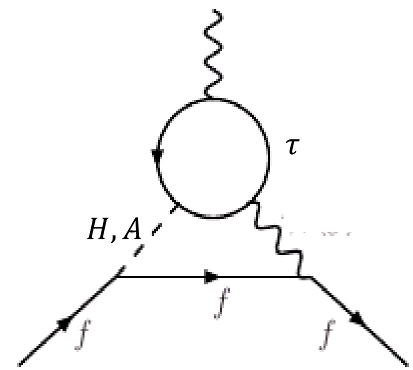
- Barr-Zee two-loop with a light A & large $\tan\beta$:

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

$y_\mu^i\, y_f^i \rightarrow \tan^2\beta$, $r_f^i \rightarrow m_\tau^2$

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

$g_A(r) > 0$

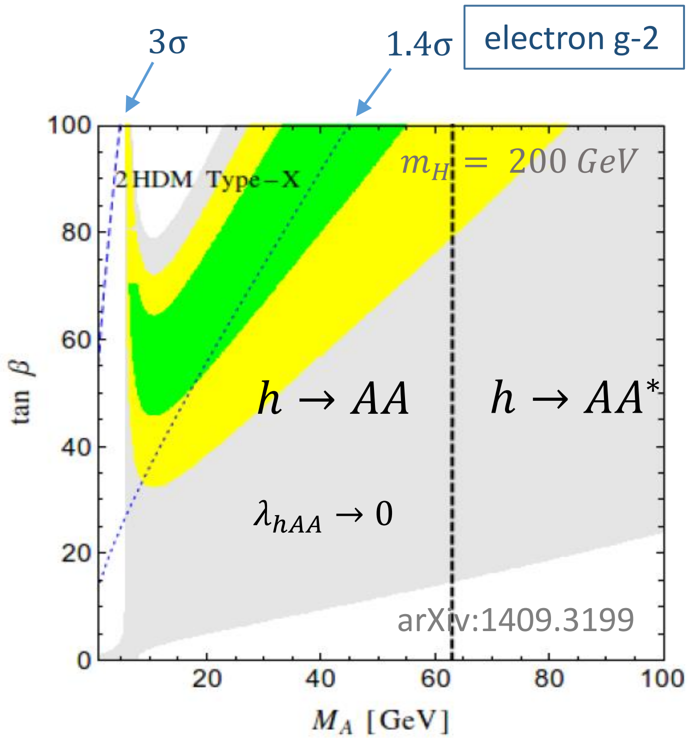


Cf) For complete two-loop contributions:

Ilisie, 1502.04199

Cherchiglia, et.al. 1607.06292

Limiting L2HDM for muon g-2



- For $m_A < m_h/2$, the decay $h \to AA$ needs to be suppressed by $\lambda_{hAA} \to 0$.

$$\lambda_{hAA} v \approx (1 + s_{\beta-\alpha} y_\tau) m_H^2 - 2m_A^2 - s_{\beta-\alpha} y_\tau m_h^2$$

RS: $y_\tau \approx +1 \Rightarrow \frac{\lambda_{hAA}}{v} \gtrsim y_\tau$

WS: $y_\tau \approx -1 \Rightarrow \lambda_{hAA} \to 0$

Constraints from EWPD

- The "ρ" parameter bound on the split mass spectrum:

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

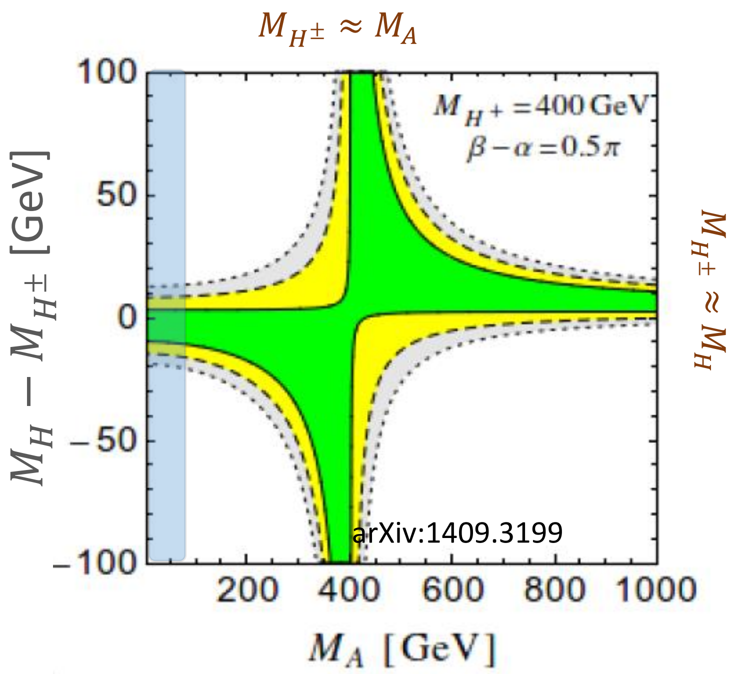
$$\sin^2\theta_{\rm eff}^{\rm lept} = k_l\left(M_Z^2\right)\sin^2\theta_W$$

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

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

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

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



Generalized custodial symmetry
Gerard-Herquet, 0703051

Vacuum stability & perturbativity

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

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

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

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

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

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

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

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

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

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

$M_A \ll M_H \approx M_{H^\pm} \lesssim 250\ GeV$ (RS)

$\lesssim \sqrt{4\pi} v$ (WS)

Lepton universality in Z decays

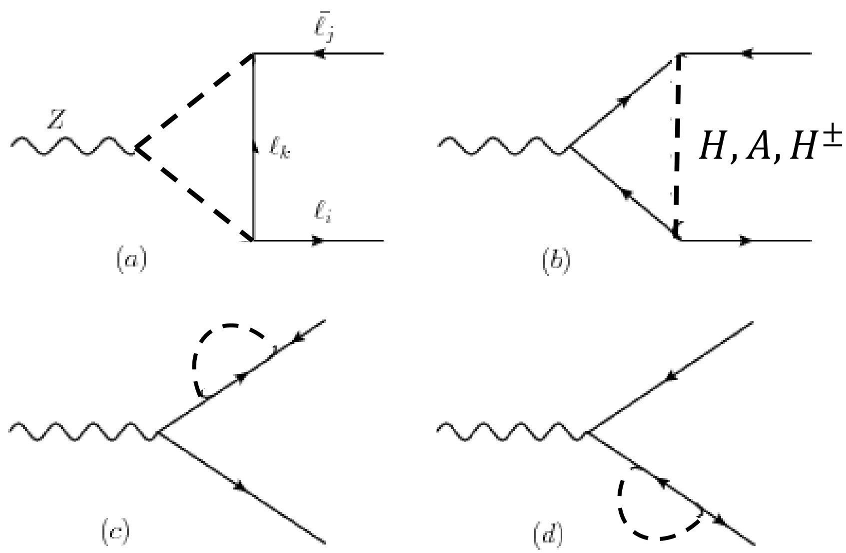
LEP EWWG, 0509008

- Precision EW measurements on Z poles determine

$$\frac{\Gamma_{Z\to\mu^+\mu^-}}{\Gamma_{Z\to e^+e^-}} = 1.0009 \pm 0.0028\,,$$
$$\frac{\Gamma_{Z\to\tau^+\tau^-}}{\Gamma_{Z\to e^+e^-}} = 1.0019 \pm 0.0032\,,$$

with correlation +0.63

- One-loop corrections mediated by extra Higgs bosons can be sizable for large $\tan\beta$.



L2HDM corrections

- Large corrections to $Z \rightarrow \tau\tau$ at large $\tan\beta$:

$$-\mathcal{L} = \frac{g}{c_W} Z^\mu \{ \bar{f}\gamma_\mu (g_L P_L + g_R P_R) f + i(-\frac{1}{2} + s_W^2) H^+ \overleftrightarrow{\partial_\mu} H^- + A \overleftrightarrow{\partial_\mu} H \}$$

- Deviation from lepton universality:

$$\delta_{ll} = (\Gamma_{Z\to l^+l^-}/\Gamma_{Z\to e^+e^-}) - 1$$

$$\delta_{\mu\mu} \simeq 0\,,$$

$$\delta_{\tau\tau} = \frac{2g_L^e \mathrm{Re}(\delta g_L^{\mathrm{2HDM}}) + 2g_R^e \mathrm{Re}(\delta g_R^{\mathrm{2HDM}})}{{g_L^e}^2 + {g_R^e}^2}\,,$$

Hollik, Kuehn, 1991

$$\delta g_L^{\rm 2HDM} = \frac{1}{16\pi^2}\frac{m_f^2}{v^2}t_\beta^2\Big\{ -\frac{1}{2}B_Z(r_A) - \frac{1}{2}B_Z(r_H) - 2C_Z(r_A, r_H)$$
$$+s_W^2\left[B_Z(r_A) + B_Z(r_H) + \tilde{C}_Z(r_A) + \tilde{C}_Z(r_H)\right]\Big\},$$
$$\delta g_R^{\rm 2HDM} = \frac{1}{16\pi^2}\frac{m_f^2}{v^2}t_\beta^2\Big\{2C_Z(r_A, r_H) - 2C_Z(r_{H^\pm}, r_{H^\pm}) + \tilde{C}_Z(r_{H^\pm}) - \frac{1}{2}\tilde{C}_Z(r_A) - \frac{1}{2}\tilde{C}_Z(r_H)$$
$$+s_W^2\left[B_Z(r_A) + B_Z(r_H) + 2B_Z(r_{H^\pm}) + \tilde{C}_Z(r_A) + \tilde{C}_Z(r_H) + 4C_Z(r_{H^\pm}, r_{H^\pm})\right]\Big\}$$

$$r_\phi = \boxed{m_\phi^2/m_Z^2} \text{ with } \phi = A, H, H^\pm$$

$$B_Z(r) = -\frac{\Delta_\epsilon}{2} - \frac{1}{4} + \frac{1}{2}\log(r)\,,$$
$$C_Z(r_1, r_2) = \frac{\Delta_\epsilon}{4} - \frac{1}{2}\int_0^1 dx \int_0^x dy\, \log[r_2(1-x) + (r_1 - 1)y + xy]\,,$$
$$\tilde{C}_Z(r) = \frac{\Delta_\epsilon}{2} + \frac{1}{2} - r[1 + \log(r)] + r^2\left[\log(r)\log(1 + r^{-1}) - \mathrm{dilog}(-r^{-1})\right]$$
$$-\frac{i\pi}{2}\left[1 - 2r + 2r^2\log(1 + r^{-1})\right].$$

Large correction for larger hierarchy: $m_A \ll m_H \approx m_{H^\pm}$ and $m_\phi \gg m_Z$

Lepton Universality test by HFAG

HFAG, 1412.7515

- From pure leptonic processes:

$$\frac{\tau \to e\nu\nu}{\mu \to e\nu\nu}, \frac{\tau \to \mu\nu\nu}{\mu \to e\nu\nu}, \frac{\tau \to \mu\nu\nu}{\tau \to e\nu\nu}$$

$$\left(\frac{g_\tau}{g_\mu}\right) = 1.0011 \pm 0.0015$$

$$\left(\frac{g_\tau}{g_e}\right) = 1.0029 \pm 0.0015$$

$$\left(\frac{g_\mu}{g_e}\right) = 1.0018 \pm 0.0014$$

Note) Only two ratios are independent:
The redundant direction should be projected out.

- From semi-hadronic processes:

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

$$\left(\frac{g_\tau}{g_\mu}\right)_\pi = 0.9963 \pm 0.0027$$

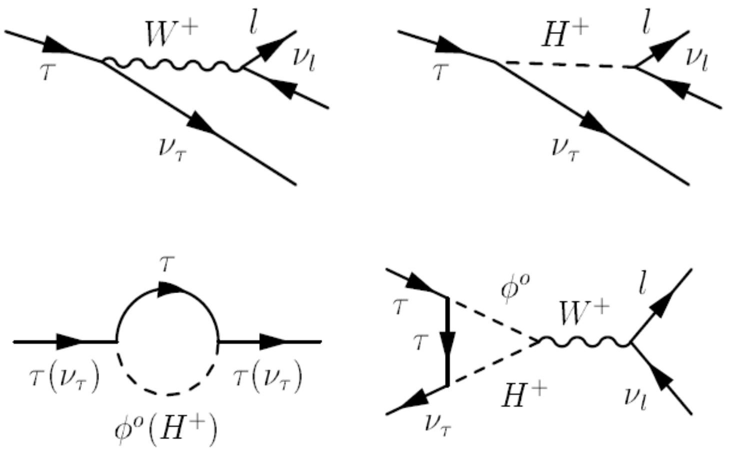
$$\left(\frac{g_\tau}{g_\mu}\right)_K = 0.9858 \pm 0.0071$$

- Correlation matrix:

$$\begin{pmatrix} 1 & +0.53 & -0.49 & +0.24 & +0.12 \\ +0.53 & 1 & +0.48 & +0.26 & +0.10 \\ -0.49 & +0.48 & 1 & +0.02 & -0.02 \\ +0.24 & +0.26 & +0.02 & 1 & +0.05 \\ +0.12 & +0.10 & -0.02 & +0.05 & 1 \end{pmatrix}$$

L2HDM corrections

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



Krawczyk, Temes, 0410248

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

$$\delta_{loop} = \frac{m_\tau^2 t_\beta^2}{16\pi^2 v^2}\left(1 + \frac{1}{4}\left[H\left(\frac{m_A}{m_{H^\pm}}\right) + s_{\beta-\alpha}^2\, H\left(\frac{m_H}{m_{H^\pm}}\right) + c_{\beta-\alpha}^2 H\left(\frac{m_h}{m_{H^\pm}}\right)\right]\right)$$

$\Rightarrow$

$$\left(\frac{g_\tau}{g_\mu}\right) = 1 + \delta_{\rm loop}, \quad \left(\frac{g_\tau}{g_e}\right) = 1 + \delta_{\rm tree} + \delta_{\rm loop}, \quad \left(\frac{g_\mu}{g_e}\right) = 1 + \delta_{\rm tree},$$

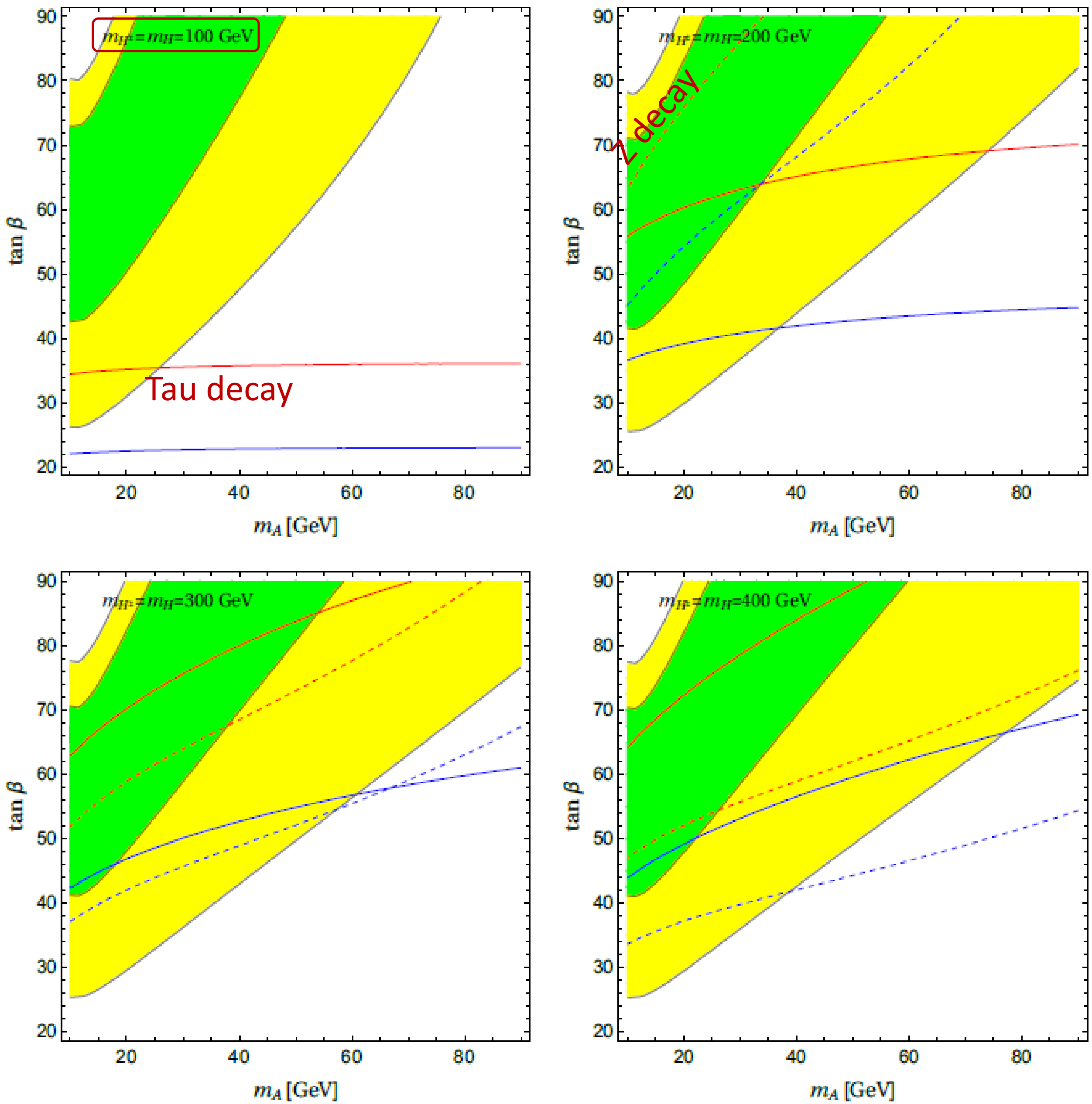
$$\left(\frac{g_\tau}{g_\mu}\right)_\pi = 1 + \delta_{\rm loop}, \quad \left(\frac{g_\tau}{g_\mu}\right)_K = 1 + \delta_{\rm loop}.$$

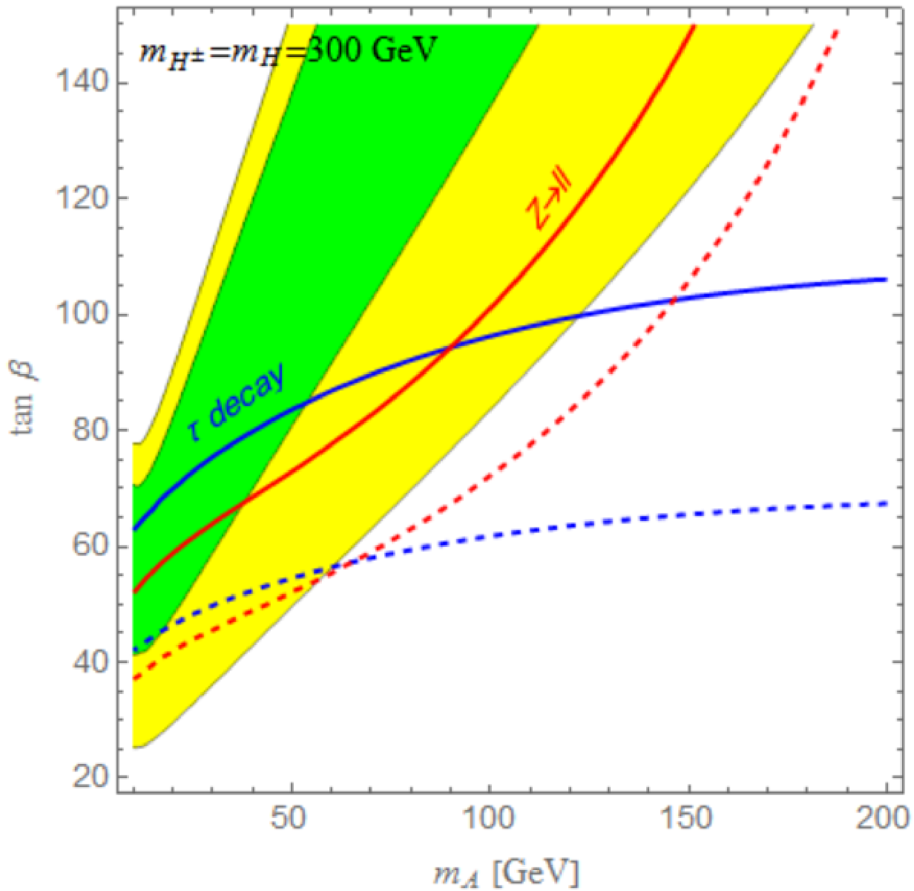
Results

1 and 2σ regions for constraints from the muon g-2, Z and tau decays.

Poor $\chi^2_{min}\sim 12$ for tau decay; SM about 2σ away

Allowed region larger than in the previous studies: 1504.07059, 1507.08067.



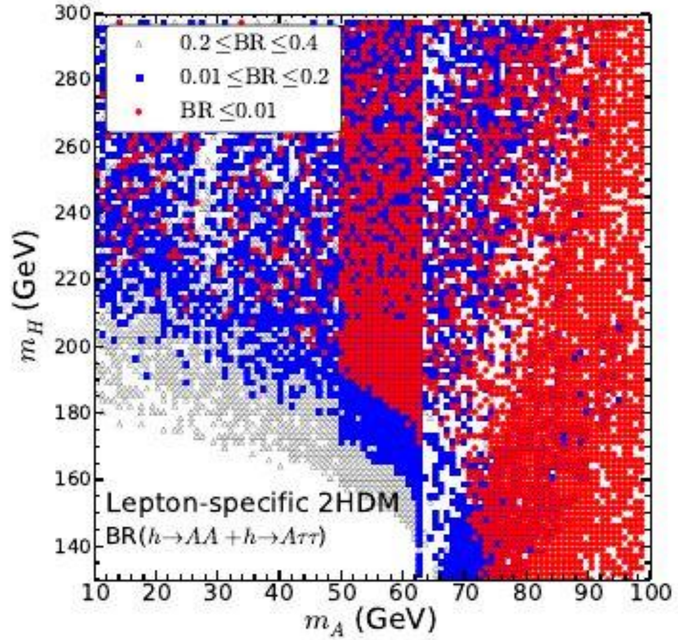


$m_{H^\pm}=m_H=300$ GeV
140
120
100
80
60
40
20
$\tan\beta$
τ decay
Z→ll
50
100
150
200
m_A [GeV]

Tau-rich signatures at LHC

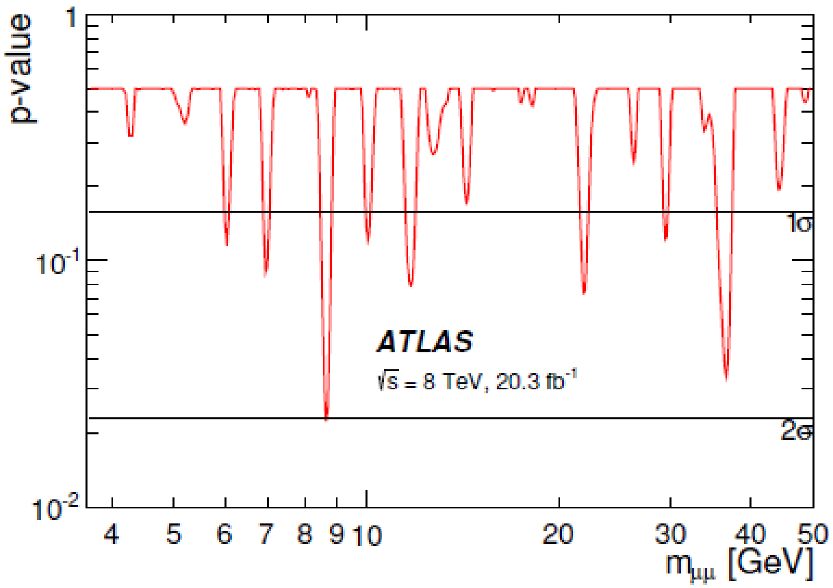
- h(125) → AA → 4 tau

arXiv:1507.08067

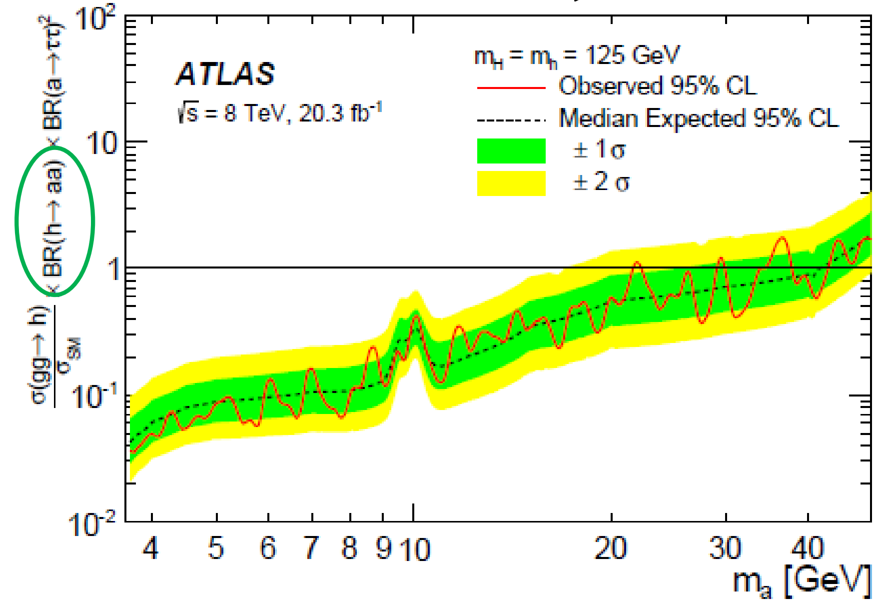


Search for $h \to A\,A \to \mu\mu\,\tau\tau$

ATLAS, 1505.01609



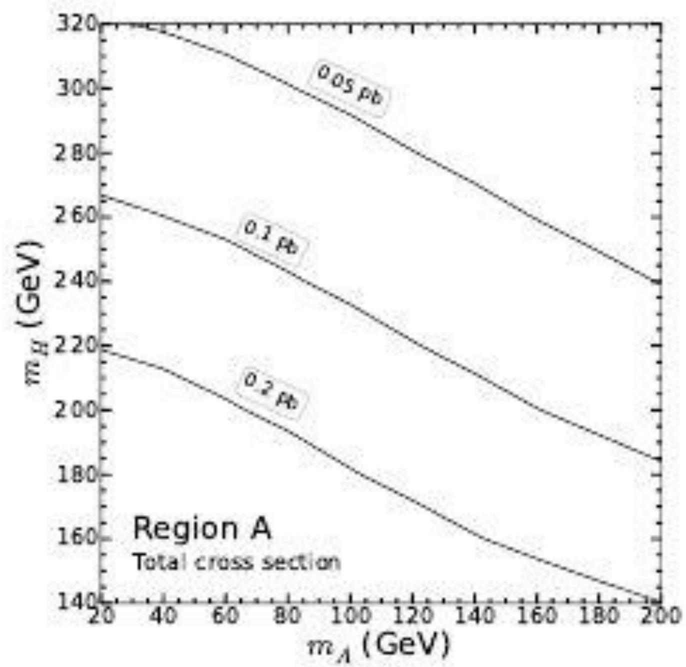
BR($h \to AA$)



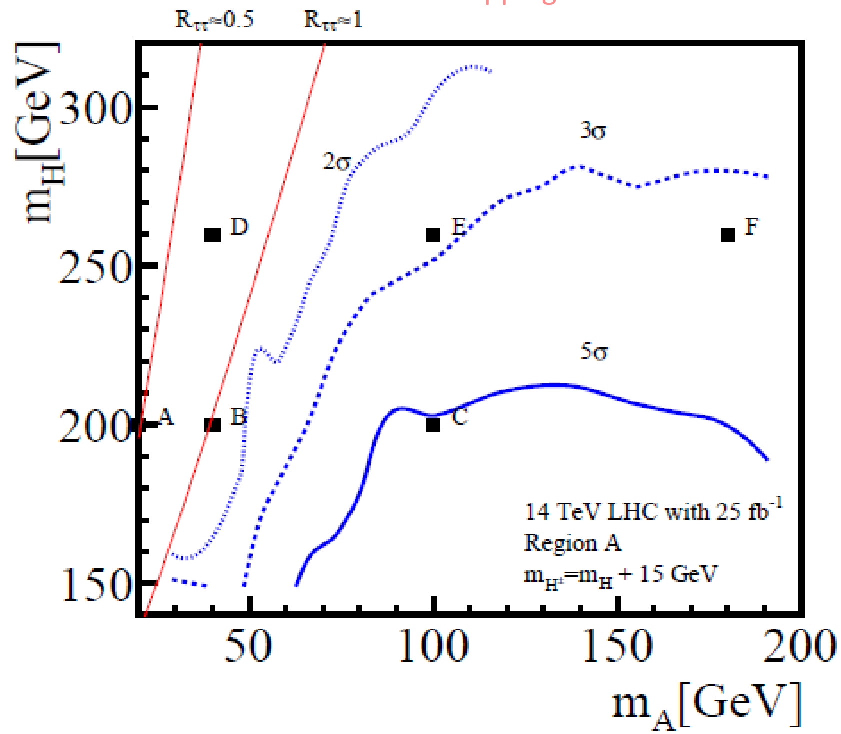
$pp \to AH(H^{\pm}) \to AA \to 4\tau$

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

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



Overlapping di-tau



Benchmark study

	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 $\sigma_{\rm gen}$ [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
$S/\sqrt{B}_{25{\rm fb}^{-1}}$	0.6	1.9	5.2	0.7	2.9	3.8

Needs HL-LHC to probe the favored region

Conclusion

- L2HDM with large $\tan\beta$ and light A is a viable option for the muon g-2.
- Lepton universality tests in Z and tau decays strongly limit the parameter space $(m_A, \tan\beta)$.
- No region is allowed at 1σ, but large region opens up at 2σ, particularly, for $m_H = m_{H^\pm} = 200 - 400\ GeV$.
- It can be tested through tau-rich signatures: $h \to AA^{(*)} \to 4\tau\ (2\mu 2\tau)$; $H^{0,\pm} A \to AA \to 4\tau\ (2\mu 2\tau)$