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30 Oct. 2017

A Two-Higgs-Doublet Model for Muon g-2 and Dark Matter

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. Kim, arXiv:1605.06298
S. Dwivedi, T. Mondal, B. Mukhopadhyaya, 1707.07928
P. Bandyopadhyay, R. Mandal, 1709.08581

A mini-review: 1511.05225

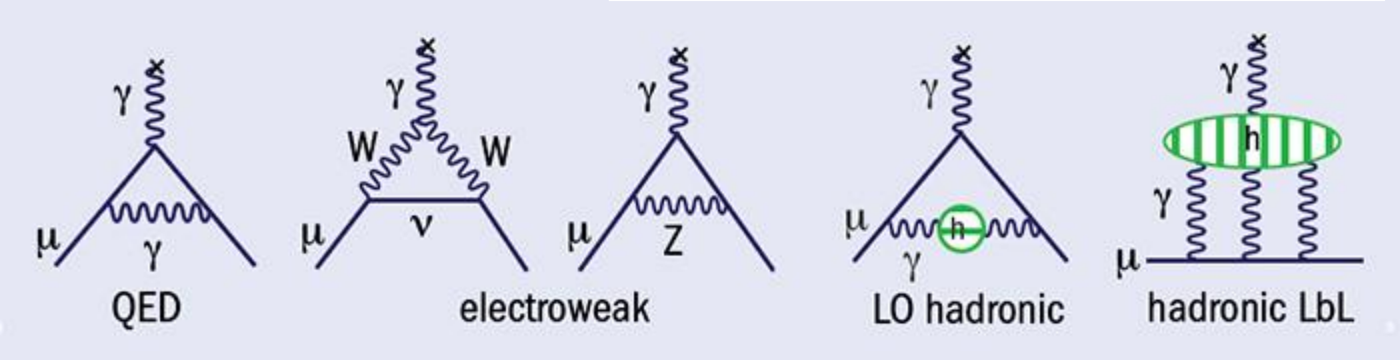
Muon g-2 anomaly

Magnetic moment:

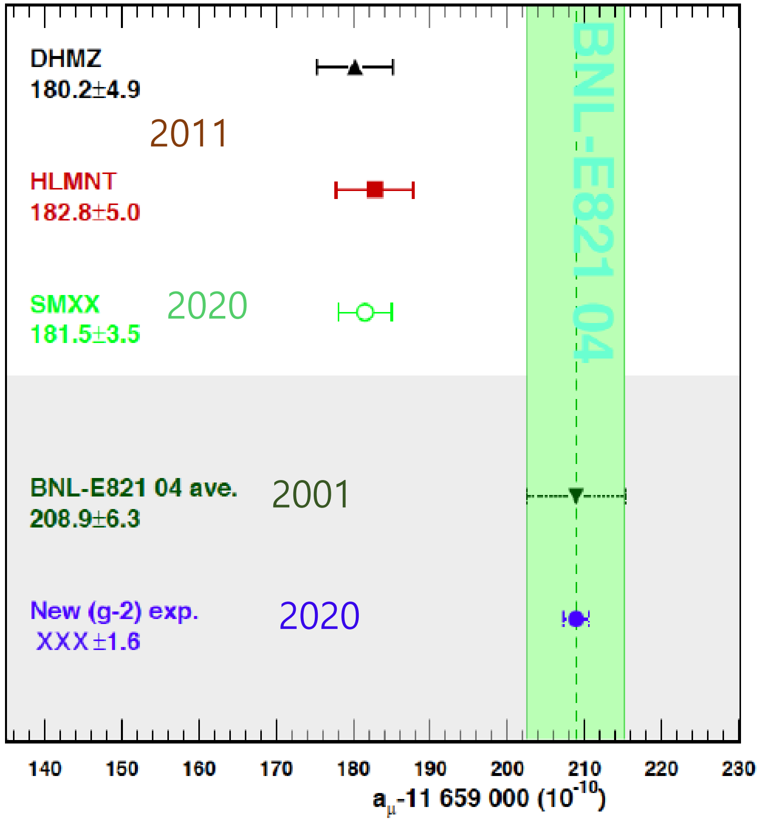
$$\overrightarrow{\mu_f} = g_f \frac{q}{2m} \vec{s}$$

$$g_f = 2(1 + a_f)$$

	VALUE ($\times 10^{-11}$) UNITS
QED	$116\,584\,718.95 \pm 0.08$
HVP	$6\,850.6 \pm 43$
HLbL	105 ± 26
EW	153.6 ± 1.0
Total SM	$116\,591\,828 \pm 49$



1701.02807



New physics contribution

- Improved theoretical and experimental inputs over the years established a concrete 3σ deviation from the SM prediction:

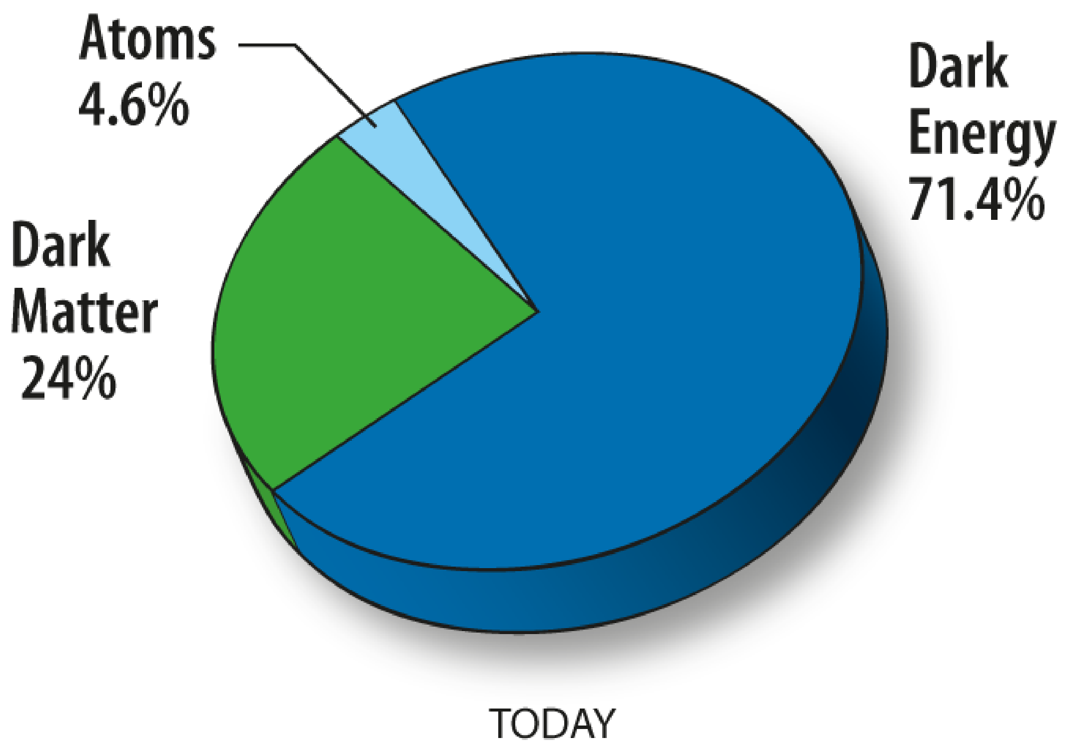
$$\boxed{\Delta a_\mu \equiv a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}} = +262\,(85) \times 10^{-11}}$$

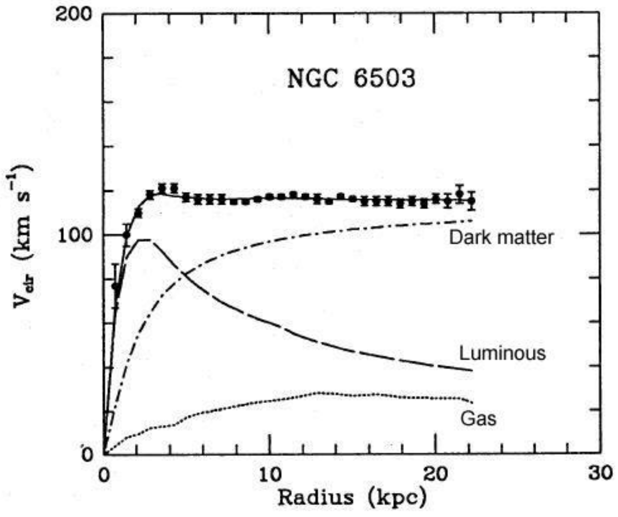
- The 2001 rush for new physics at TeV:

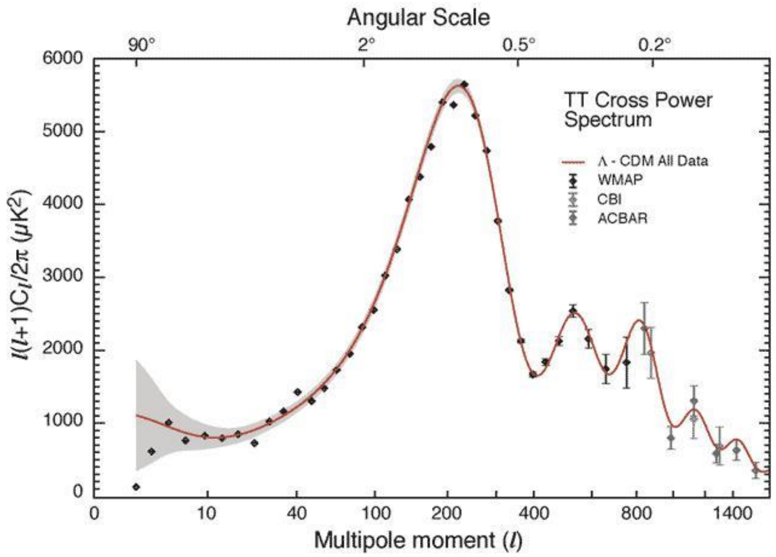
$$\Delta a_\mu \sim \frac{\alpha_{EW}}{4\pi}\frac{m_\mu^2}{\Lambda_{EW}^2}$$

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

Dark Matter


Atoms
4.6%
Dark Energy
71.4%
Dark Matter
24%
TODAY


NGC 6503
Dark matter
Luminous
Gas
Radius (kpc)
0
10
20
30
200
100
0


Angular Scale
90°
2°
0.5°
0.2°
TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR
6000
5000
4000
3000
2000
1000
0
0
10
40
100
200
400
800
1400
Multipole moment (l)

Scalar DM through Higgs Portal

- Introduce a stable singlet scalar in SM – the minimal (simplest-minded) model:

Silveira, Zee, 85
McDonalds 94
Bird, et.al., 06 and many

$$V = \mu_H^2|H|^2 + \lambda_H|H|^4 + \lambda_{HS}\,|H|^2|S|^2 + \mu_S^2|S|^2 + \lambda_S|S|^4$$

- Right relic density through freeze-out by controlling the parameters λ_{HS} & m_S.
- Strongly disfavored by direct detection experiments.
- Way out – more extension like in 2HDM…

A 2HDM for muon g-2 and DM

- The SM-like 125 GeV Higgs discovered.
- Extra Higgs spectrum constrained by

  EWPD, vacuum stability & perturbativity; arXiv:1409.3199

  New results on $\bar{B} \to X_s\gamma$ & $B_s \to \mu^+\mu^-$; Wang,Han,1412.4874

  Lepton universality tests. Abe,Sato,Yagyu, 1504.07059
- Viable Type-X 2HDM with large $tan\beta$ & light A. arXiv:1605.06298
- LHC test through **3/4 tau** & **2tau+2mu** signals. arXiv:1507.08067 arXiv:1707.07928
- Features of **scalar singlet DM.** arXiv: 1709.08581

Two-Higgs-Doublet-Model (2HDM)

- The most general Higgs potential – 10 parameters :

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

Z_2 symmetry

- 1+3 masses for physical Higgs bosons:

$$\Phi_{1,2} = (\phi_{1,2}^+, \frac{1}{\sqrt{2}}[v_{1,2} + \rho_{1,2} + i\,\eta_{1,2}]) \to h(125), H, A, H^\pm$$

- 1+2 parameters: $v,\ t_\beta = \dfrac{v_2}{v_1}, \alpha$

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

Models with natural flavor conservation

- To avoid dangerous flavor-changing processes:

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

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

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

4 types of 2HDMs

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

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

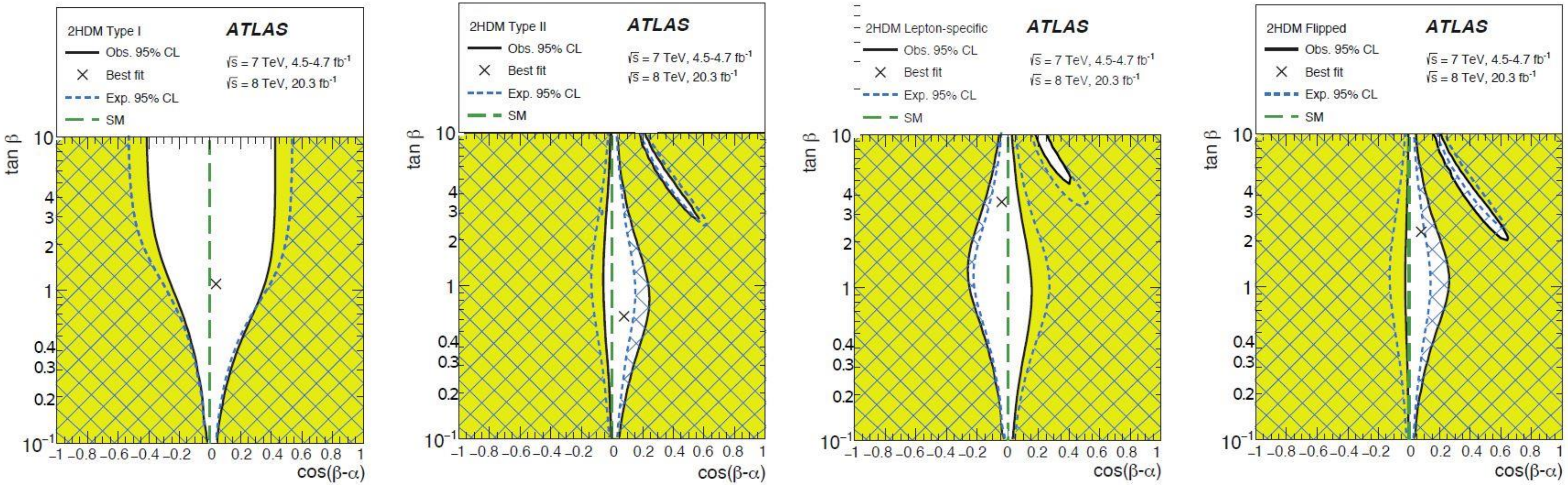
125 GeV

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

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

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

ATLAS 1509.00672



Aligned/decoupled 2HDMs

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

$\approx$

± 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

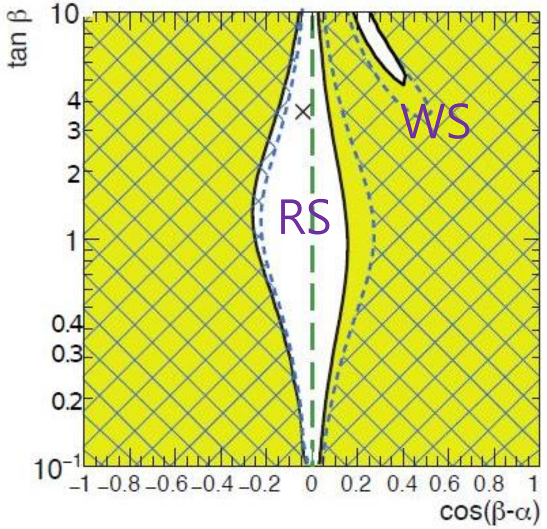
$$+\left[\sqrt{2}V_{ud}H^+\bar{u}\left(\frac{m_u}{v}y_u^A P_L + \frac{m_d}{v}y_A^d P_R\right)d + \sqrt{2}\frac{m_l}{v}y_l^A H^+\bar{\nu}P_R l + h.c.\right]$$

Right & Wrong Sign limit of Yukawas

- Tau Yukawa coupling to h(125) can be negative in 2HDM (II,X):

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

Ferreira, et.al, 1403.4736
1410.1926



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

Muon g-2 at 1-loop

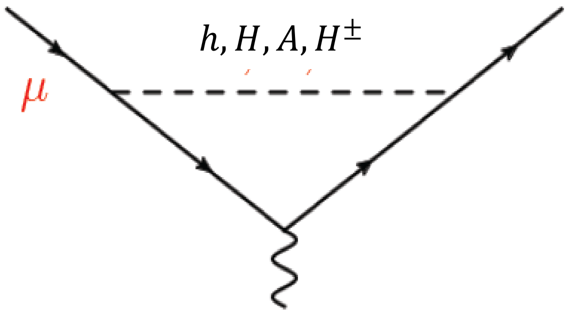
- For a light H and large $y_\mu^H \approx t_\beta$ (II, X):

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

roughly scales with m_μ^4!

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

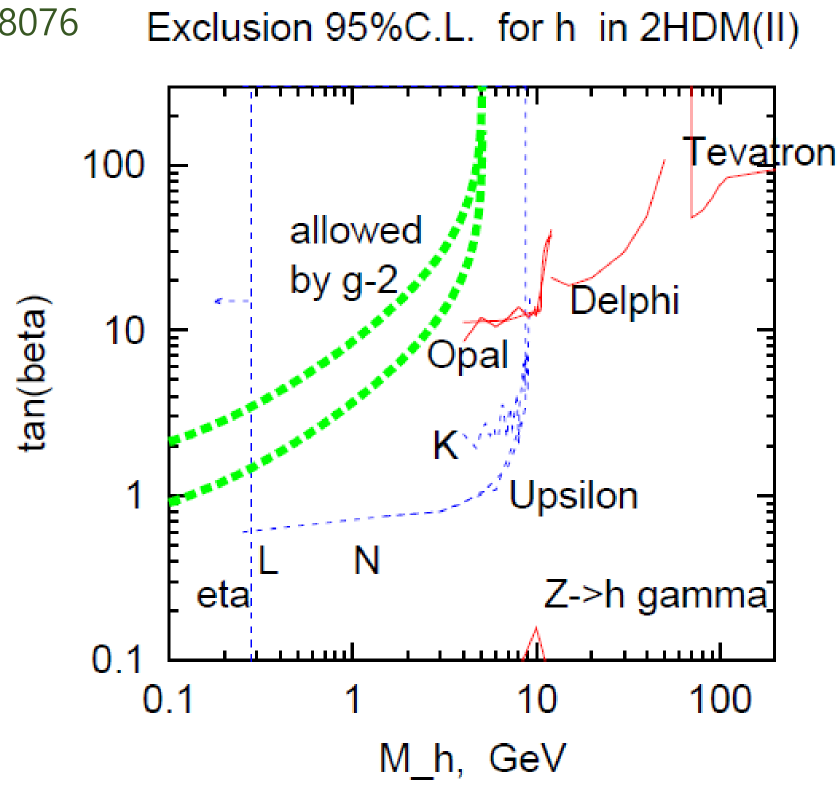
$$\begin{aligned} f_{h,H}(r) &\sim -\ln r - 7/6 + O(r) > 0 \\ f_A(r) &\sim +\ln r + 11/6 + O(r) < 0 \\ f_{H^\pm}(r) &\sim -1/6 + O(r) < 0 \end{aligned}$$



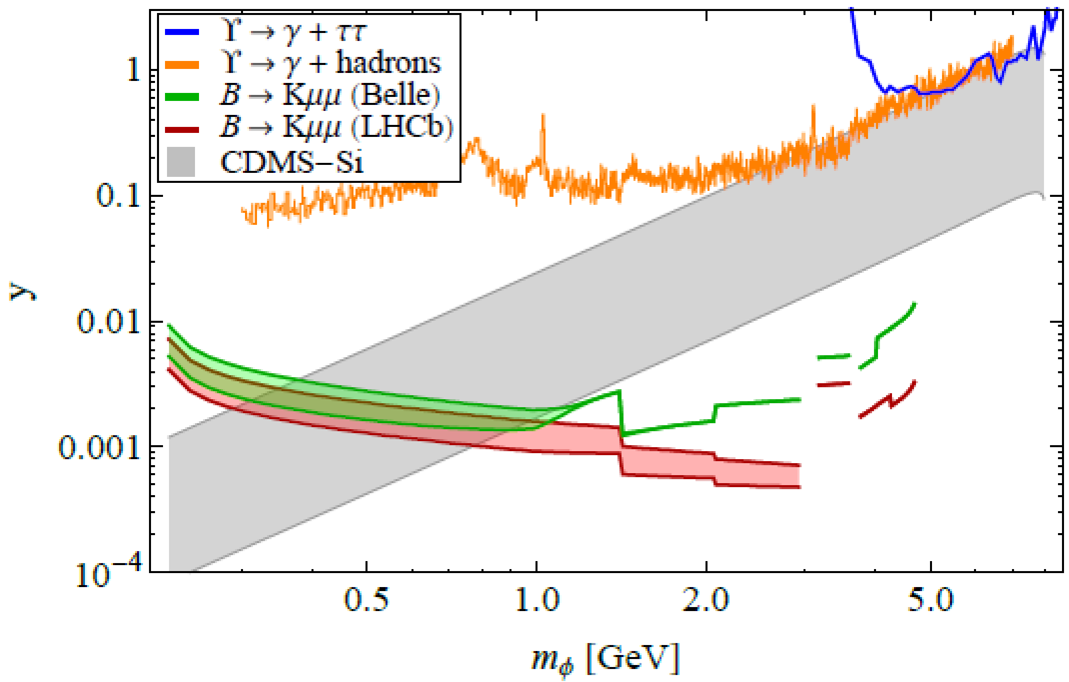
One-loop solution excluded

- Muon g-2 requires H below 5 GeV – 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 at 2-loop

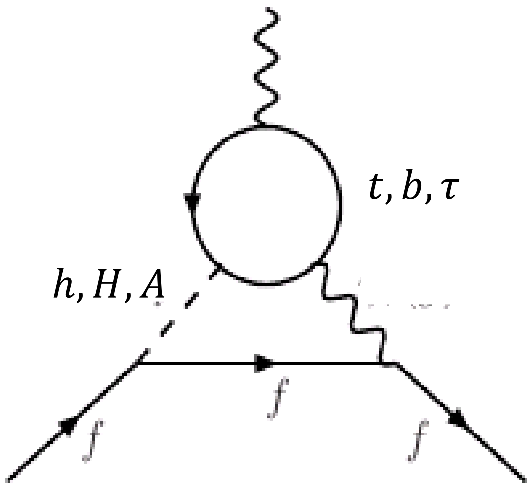
- For a light A and large $y^A_{\mu,f} \approx t_\beta$ (II, X):

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

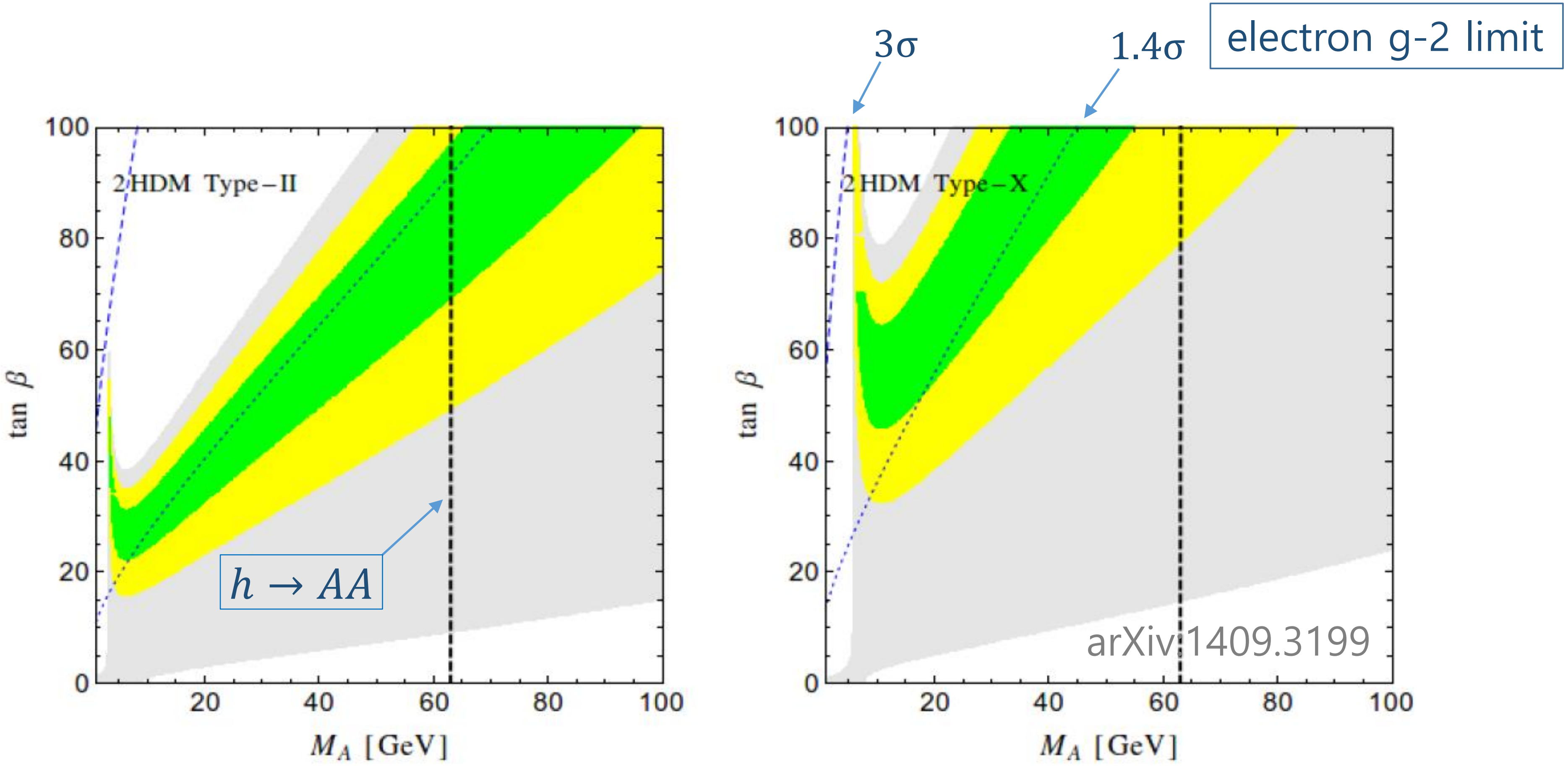
m_f^2/m_μ^2

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

	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 EWPD

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

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

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

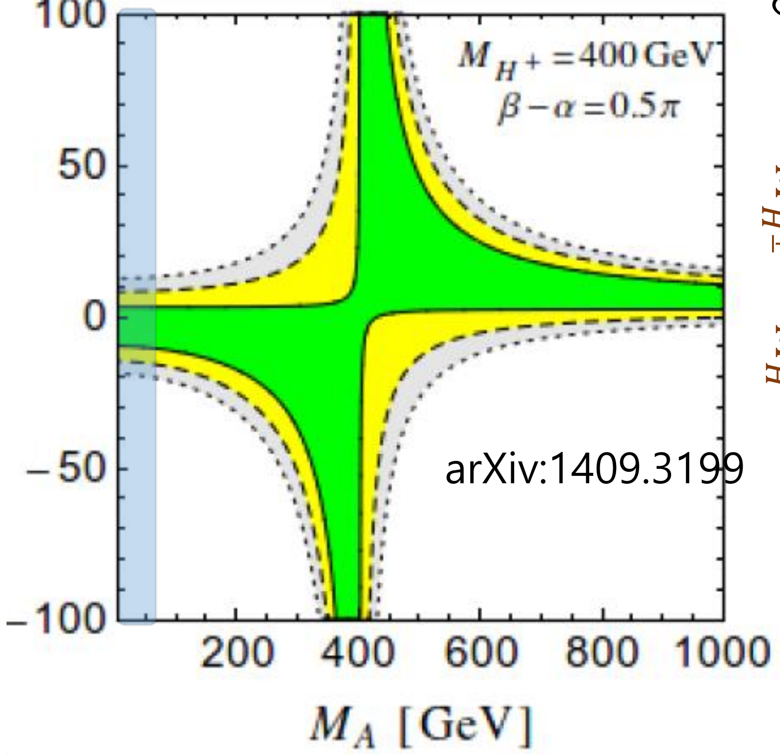
$$\Delta r^{\rm 2HDM} = \Delta\alpha^{\rm 2HDM} - \frac{\cos^2\theta_W}{\sin^2\theta_W}\Delta\rho^{\rm 2HDM} + \dots,$$

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

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

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

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



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

Generalized custodial symmetry
Gerard-Herquet, 0703051

Vacuum stability

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

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

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

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

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

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

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

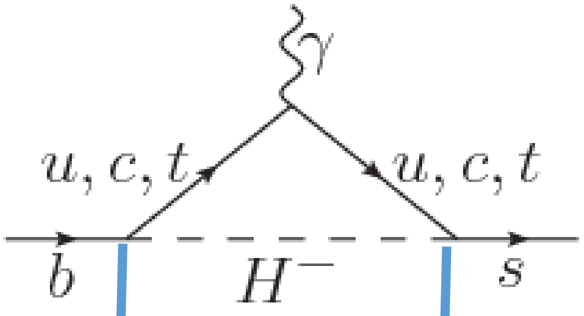
$$\lambda_4 v^2 \approx -2M_{H^\pm}^2 + M_H^2 + M_A^2$$

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

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

Constraints from B decays

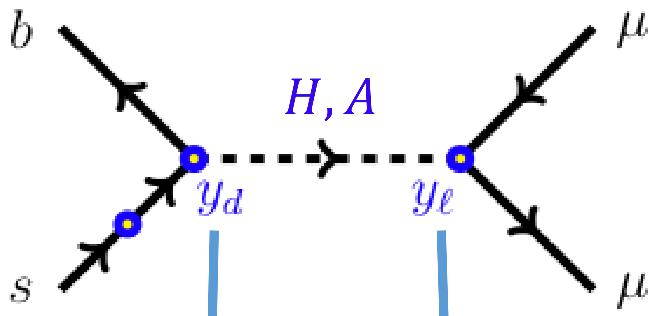
- $\bar{B} \to X_s \gamma$



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

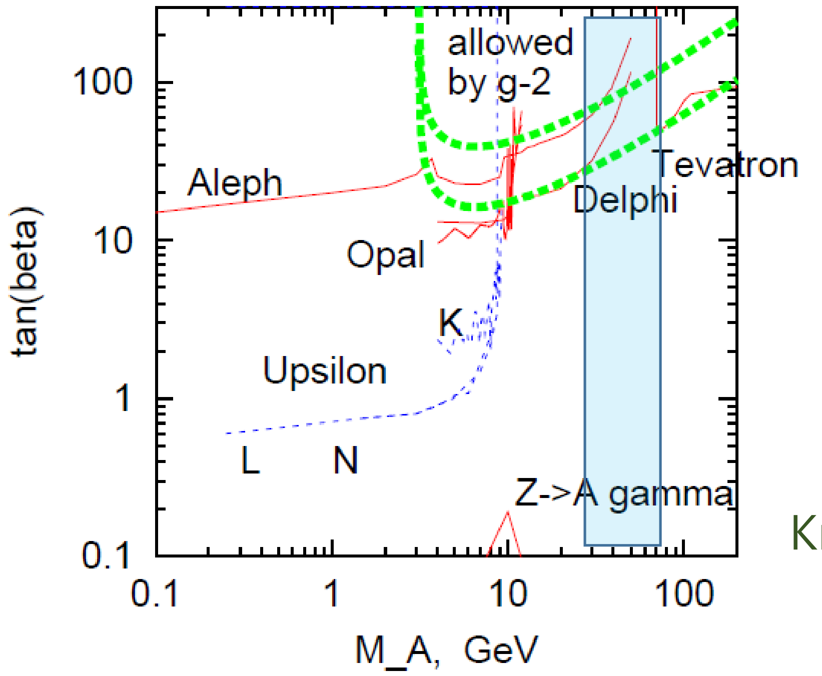
$\propto \frac{t_\beta^2}{m_{H,A}^2}$ (II)

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

Type II is excluded

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

Exclusion 95%C.L. for A in 2HDM(II)



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

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

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

Krawczyk, 0208076

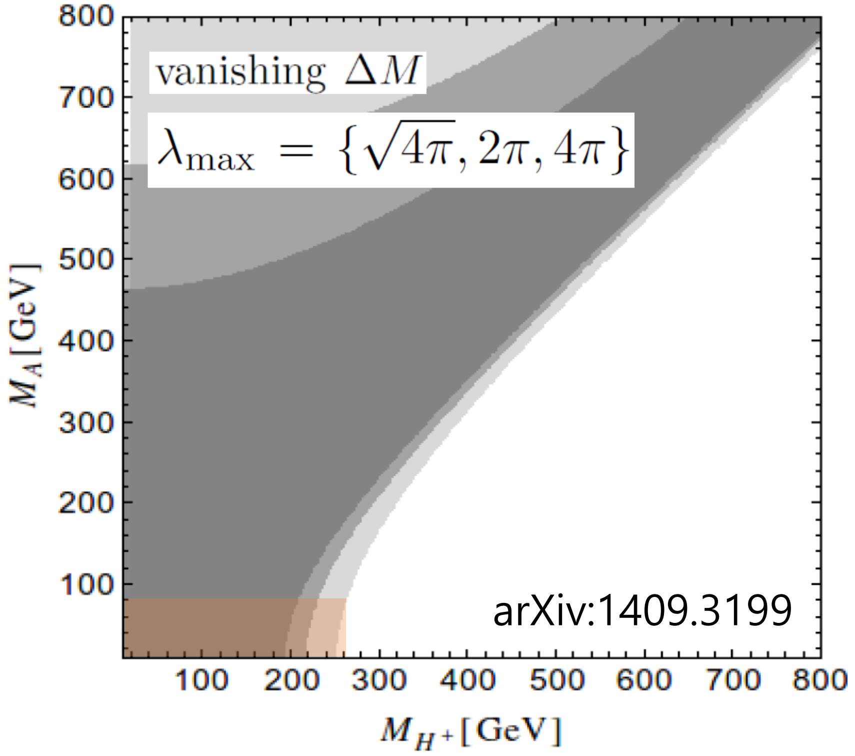
Type X is still viable

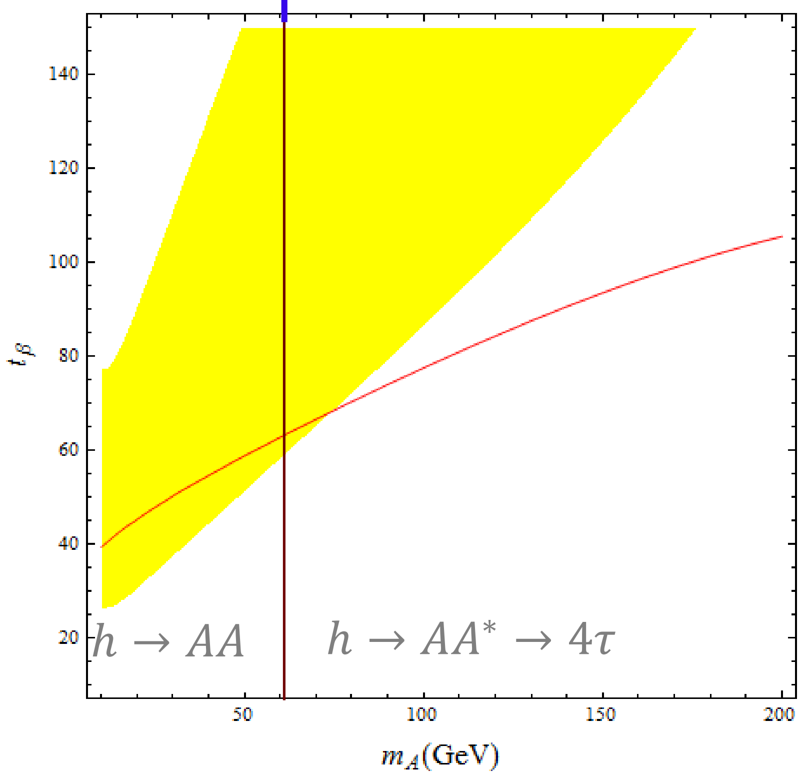
- $\bar{B} \to X_s\gamma$ puts no bound on $m_{H^\pm}$ for $t_\beta > 2$.
- $B_s \to \mu^+\mu^-$ not affected if $m_A \gtrsim 15\,GeV$.
- Type X at large t_β, being hadrophobic, is elusive at LHC.
- Being leptophilic, strong limits from precision leptonic observables like lepton universality in $Z \to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

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

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

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





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

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

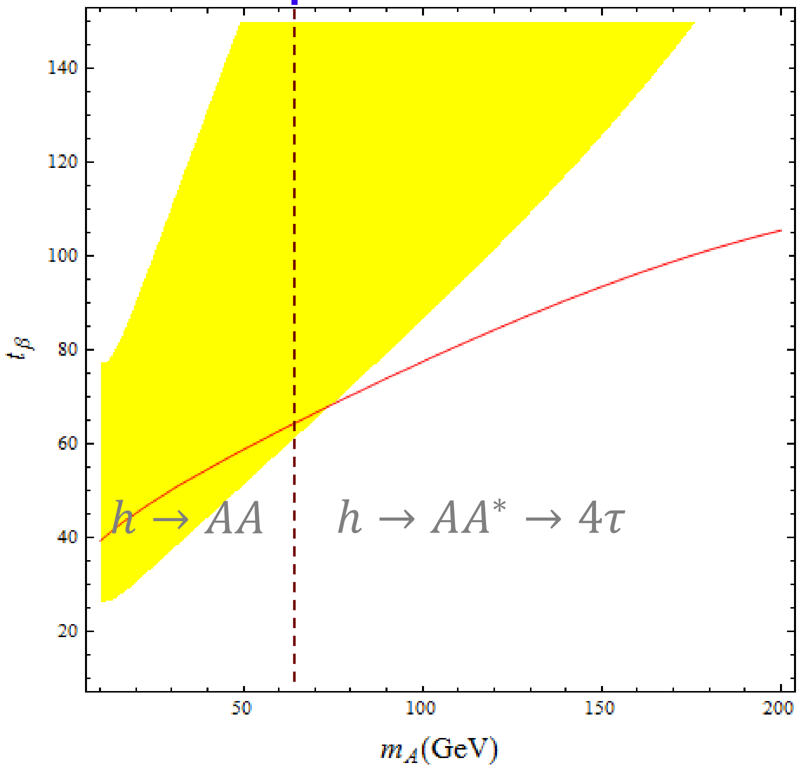
$$\lambda_{hAA} v \approx -(1 + s_{\beta-\alpha} y_\tau) M_H^2 + 2M_A^2 + s_{\beta-\alpha} y_\tau M_h^2 \rightarrow \mathbf{0}$$

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

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

Wang, Han, arXiv:1412.4874

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



Lepton universality in Z decays

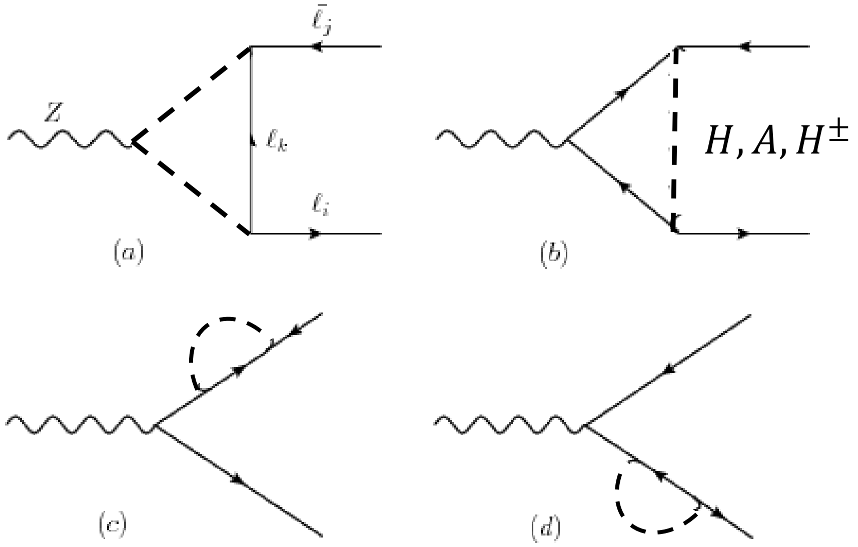
- Precision EW measurements on Z poles determine

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

LEP EWWG, 0509008

with correlation +0.63

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



L2HDM corrections

- Large corrections to $Z \to \tau\tau$ 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:

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

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

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

Hollik, Kuehn, 1991

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

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

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

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

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

Lepton Universality & τ decay

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

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

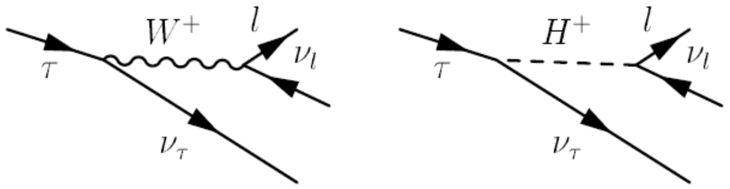
$$\left(\frac{g_\tau}{g_\mu}\right)_K = 0.9858 \pm 0.0071$$

- Correlation matrix:

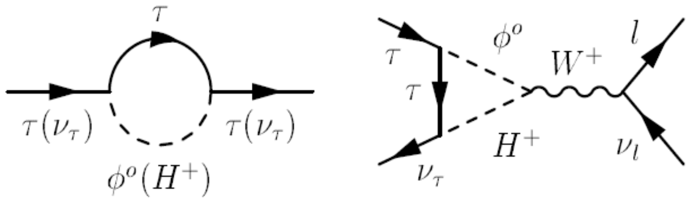
$$\begin{pmatrix} 1 & +0.53 & -0.49 & +0.24 & +0.12 \\ +0.53 & 1 & +0.48 & +0.26 & +0.10 \\ -0.49 & +0.48 & 1 & +0.02 & -0.02 \\ +0.24 & +0.26 & +0.02 & 1 & +0.05 \\ +0.12 & +0.10 & -0.02 & +0.05 & 1 \end{pmatrix}$$

L2HDM corrections

- Tree-level contribution from $H^{\pm}$:



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



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

Krawczyk, Temes, 0410248

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

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

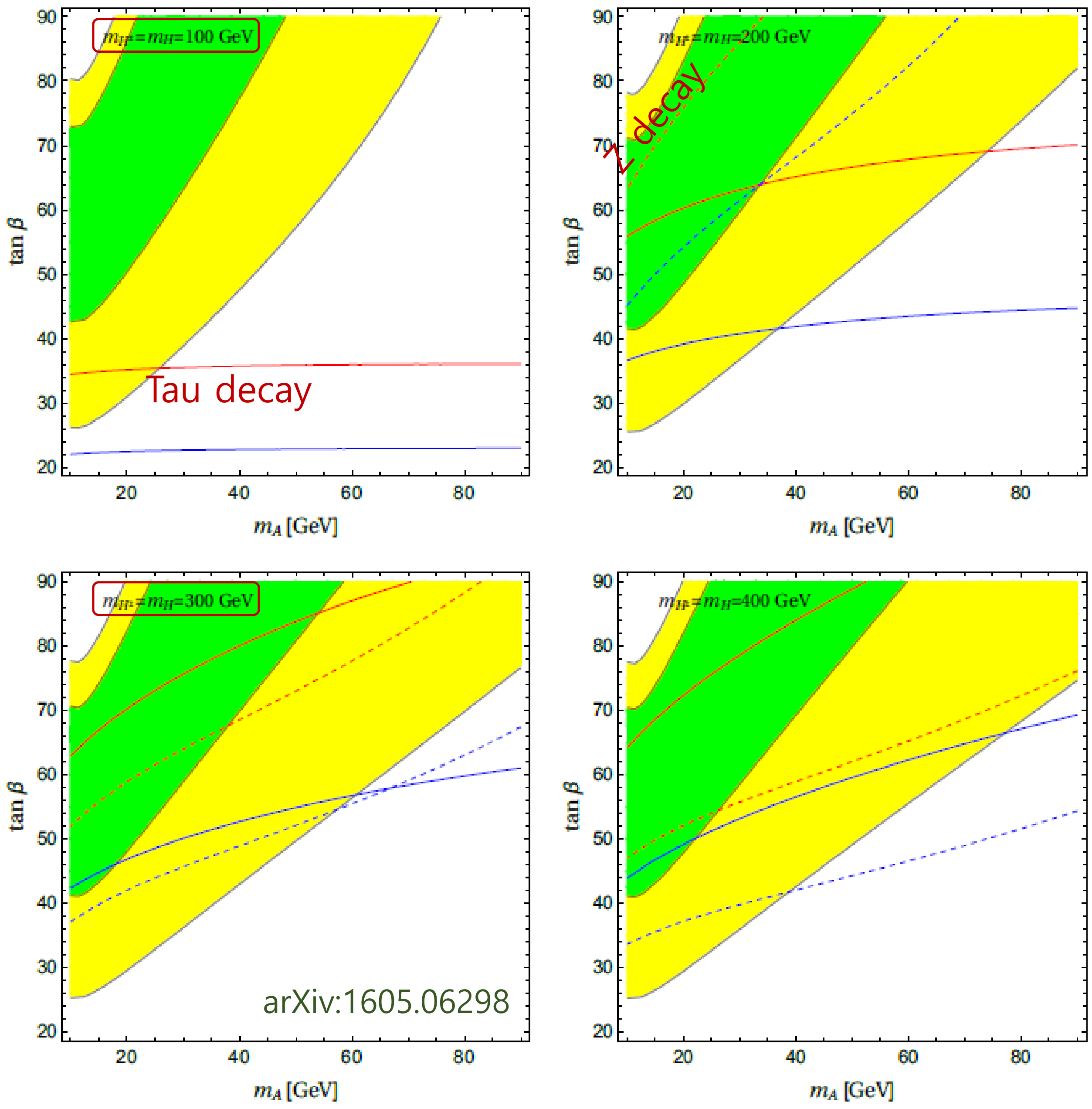
$$\left(\frac{g_\tau}{g_\mu}\right)_\pi = 1 + \delta_{\rm loop}, \quad \left(\frac{g_\tau}{g_\mu}\right)_K = 1 + \delta_{\rm loop}.$$

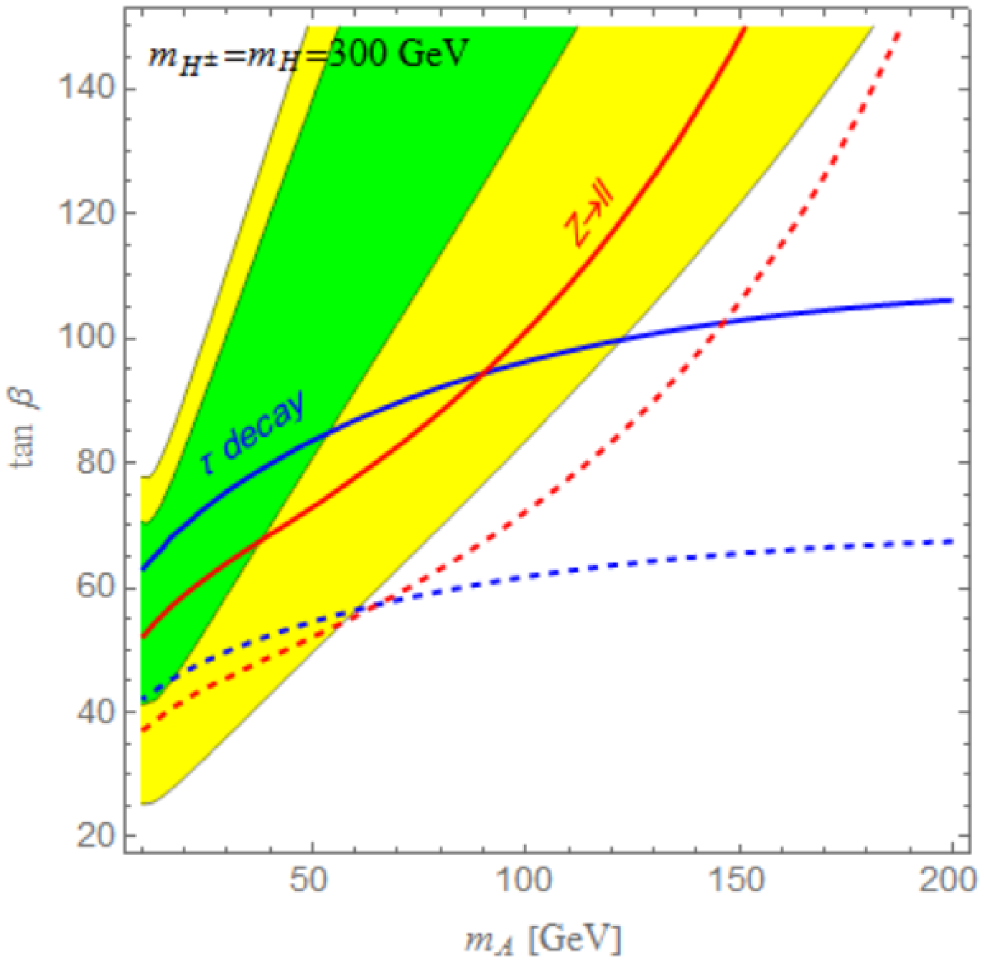
Results

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

Poor χ^2_{min}~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
50
100
150
200
$\tan\beta$
m_A [GeV]
τ decay
$Z\to ll$

LHC tests

- Discover a light pseudo-scalar with large tanbeta:

$$B(A \to \tau\tau) \simeq 100\%$$

- Electroweak production of $H^{\pm}A$ & HA

- Exotic Higgs decay: $h \to AA$

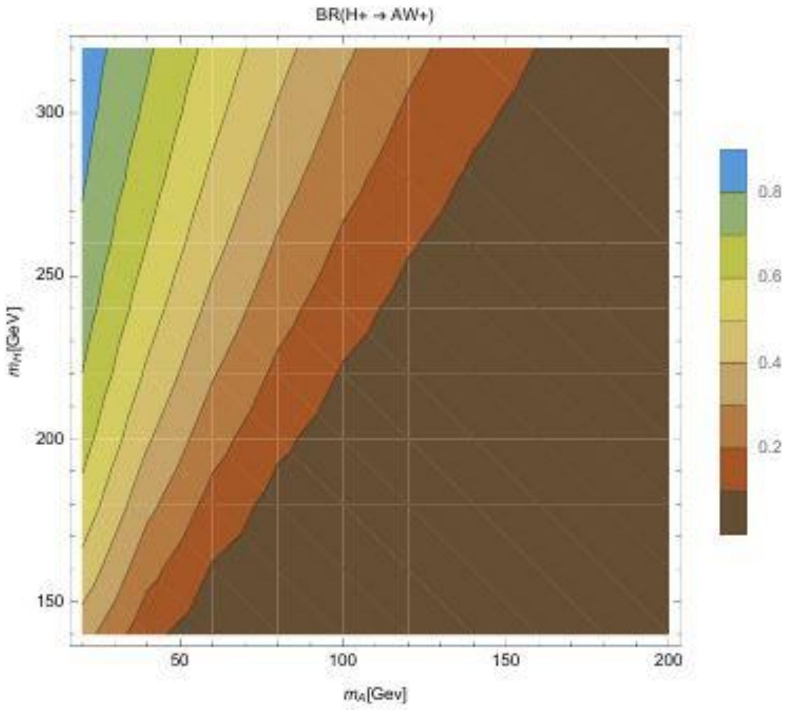
Tau-rich signatures at LHC

- EW production of extra Higges decaying mainly to taus

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

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

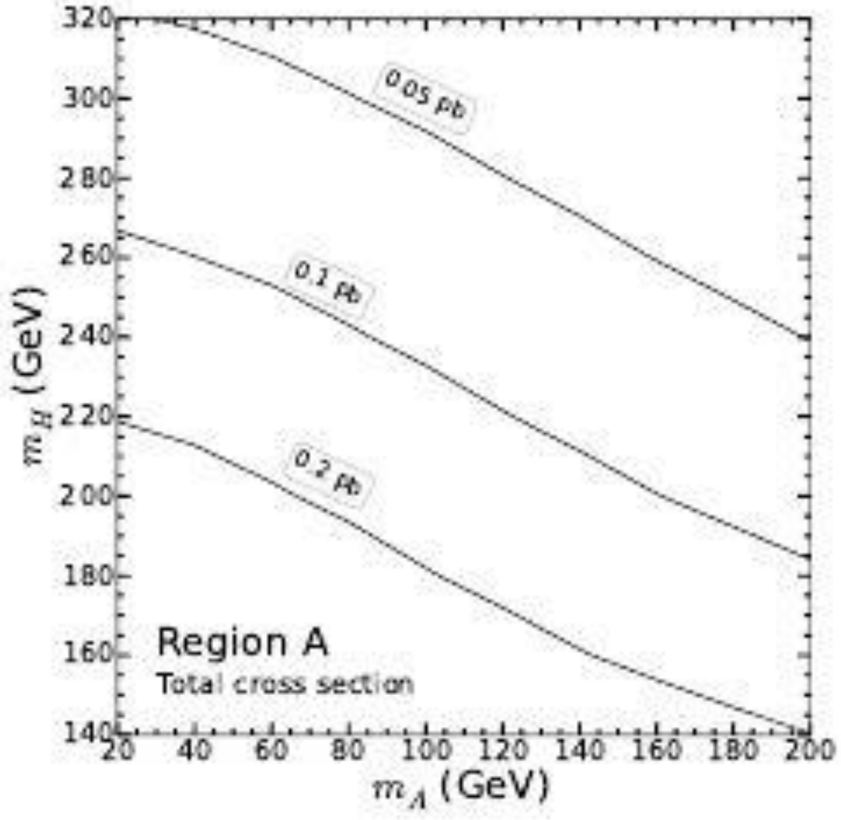
Region A: $m_{H^{\pm}} = m_H + 15$ GeV

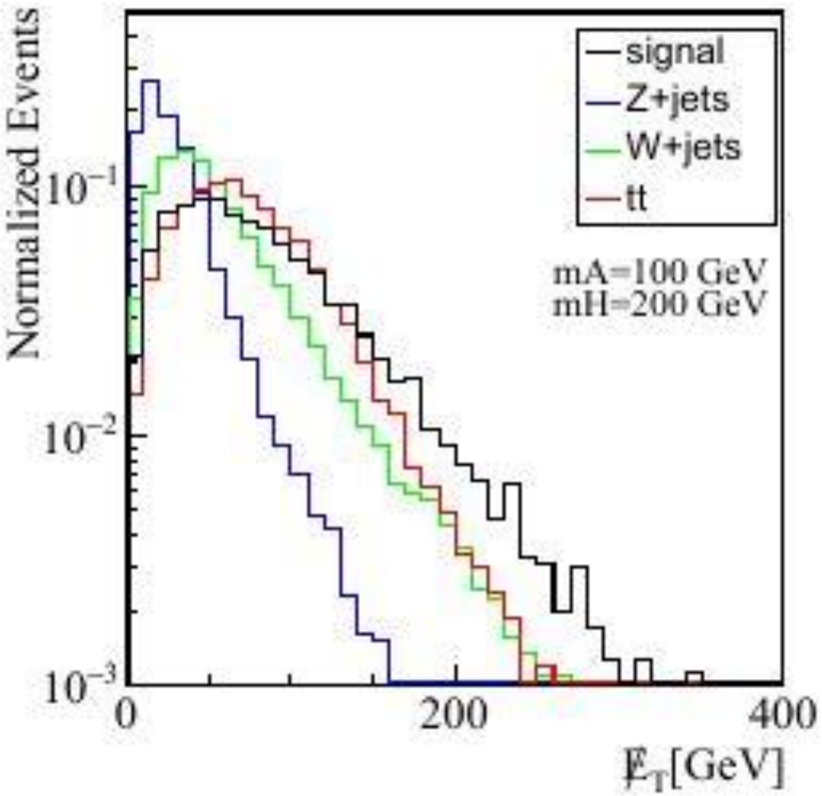


$$H^{\pm} \to A\,W^{\pm} \quad vs. \quad \nu\,\tau^{\pm}$$
$$H \to A\,Z \quad vs. \quad \tau^{+}\tau^{-}$$

LHC14 perspective

- Production X-section & missing signature:





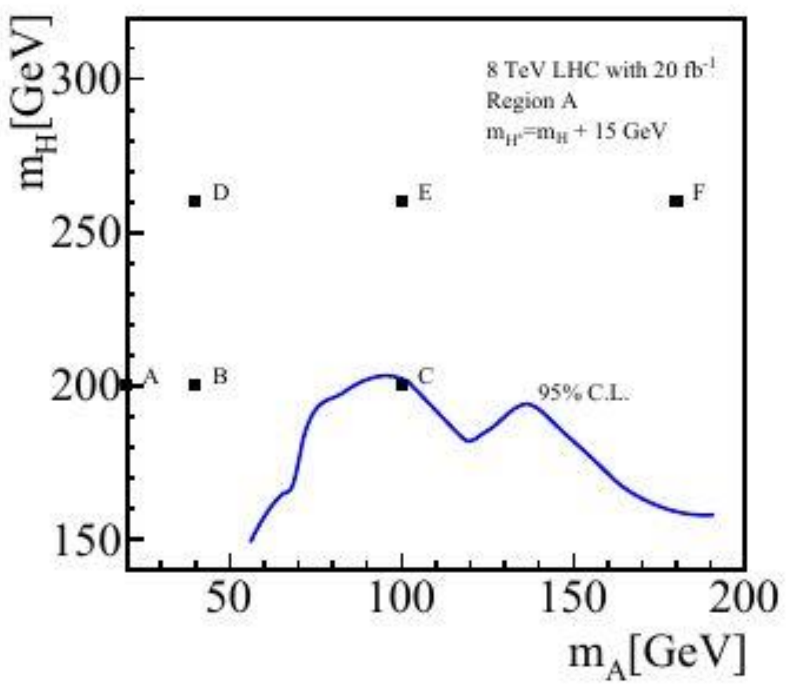
Event selection cuts

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

selection cuts	point C	$t\bar{t}$	W+jets	Z+jets	WW	WZ	ZZ	total BG	S/B	$S/\sqrt{B}_{25\mathrm{fb}^{-1}}$
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

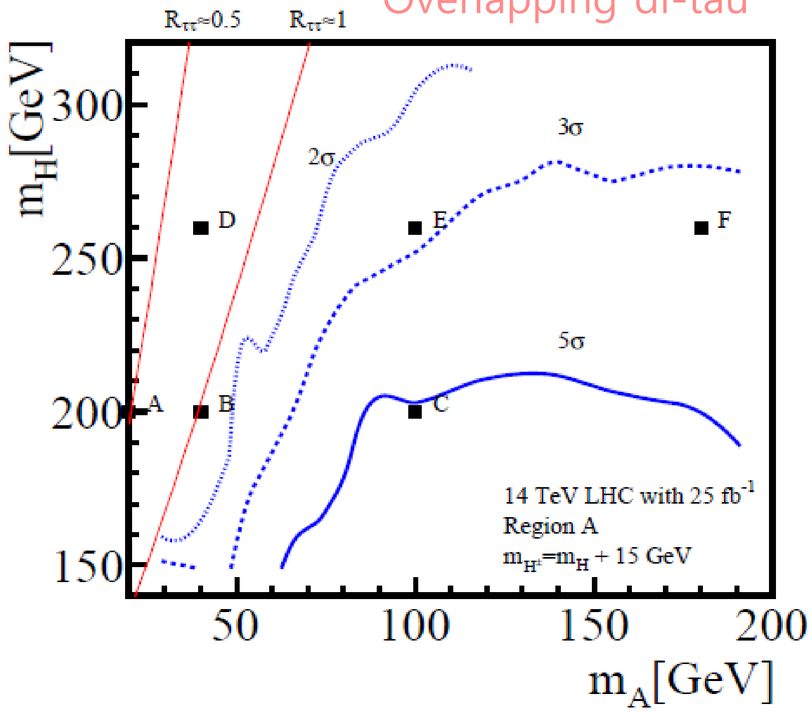
Current limits & future perspective

- LHC8 constraints mostly from chargino-neuralino searches.
- Challenges to probe light A producing soft taus, and heavy $H^{\pm}/H$ producing boosted $A(\tau\tau)$.



Overlapping di-tau

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

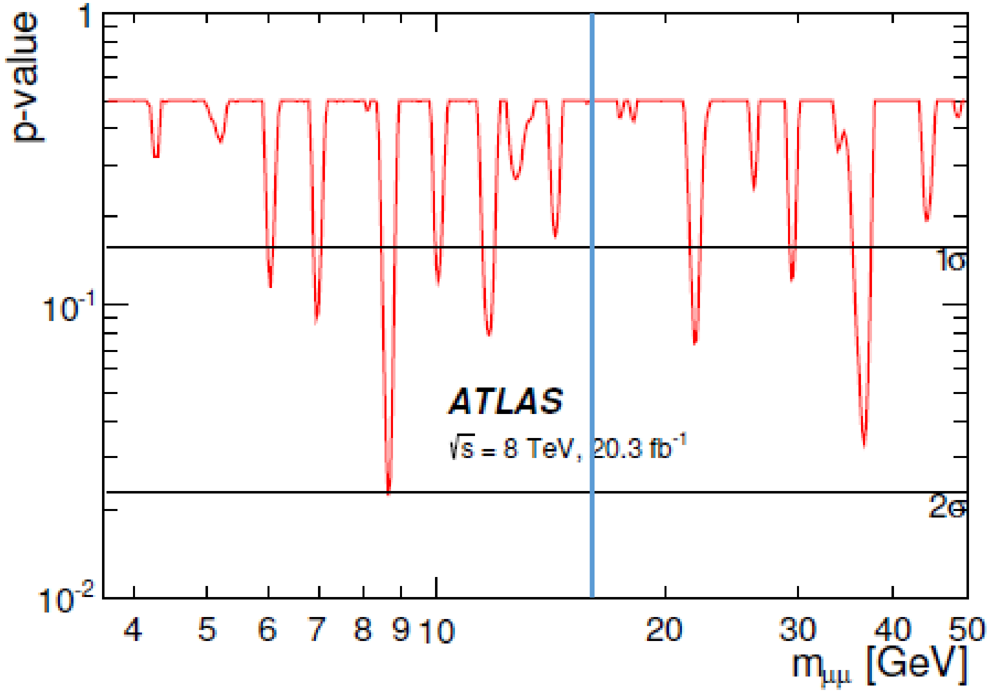


Benchmark study of significance at 25/fb

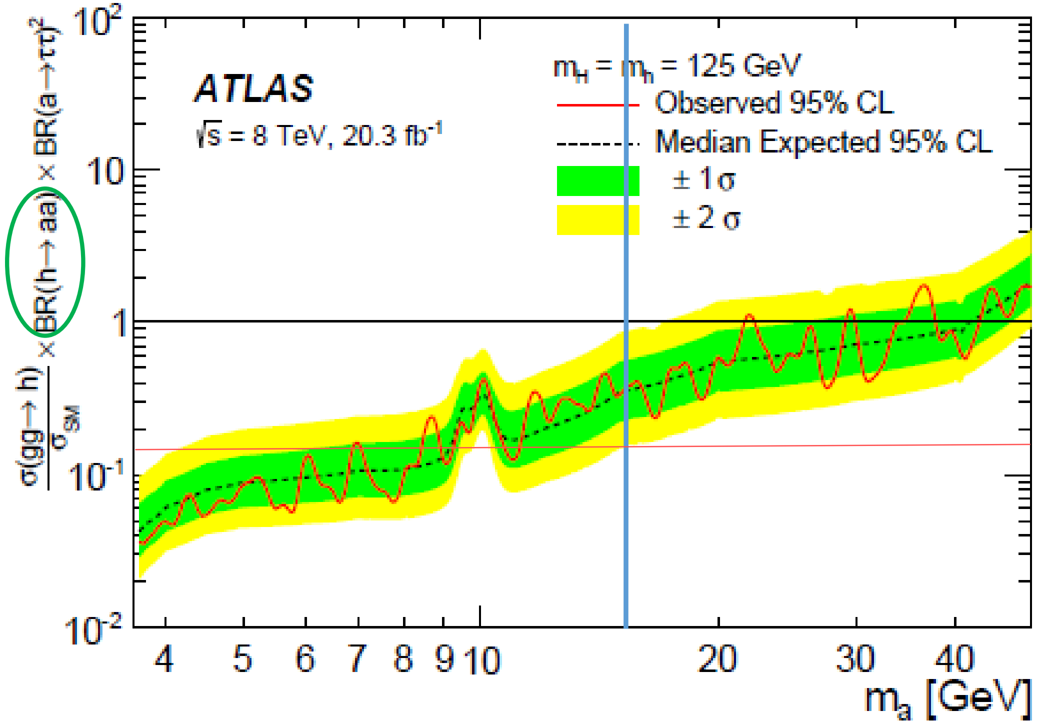
	point A	point B	point C	point D	point E	point F
m_A [GeV]	20	40	100	40	100	180
m_H [GeV]	200	200	200	260	260	260
total σ_{gen} [fb]	270.980	241.830	153.580	100.430	71.271	44.163
$n_\ell \geq 3$	6.606	16.681	21.713	7.110	11.962	8.822
$n_\tau \geq 3$	0.894	2.602	4.386	0.888	2.346	1.971
$\not{E}_T > 100$ 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

Needs HL-LHC to probe the favored region

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



BR($h \to AA$)



ATLAS, 1505.01609

LHC search for $h \to AA \to \mu\mu\tau\tau$

EJC, S. Dwivedi, T. Mondal, B. Mukhopadhyaya, arXiv:1707.07928

$$B(h \to AA) = 15\%$$
$$\sigma(h \to AA) \approx 7.5\, pb; \quad \sigma(h \to AA \to \mu\mu\tau\tau) \approx 52\, fb$$

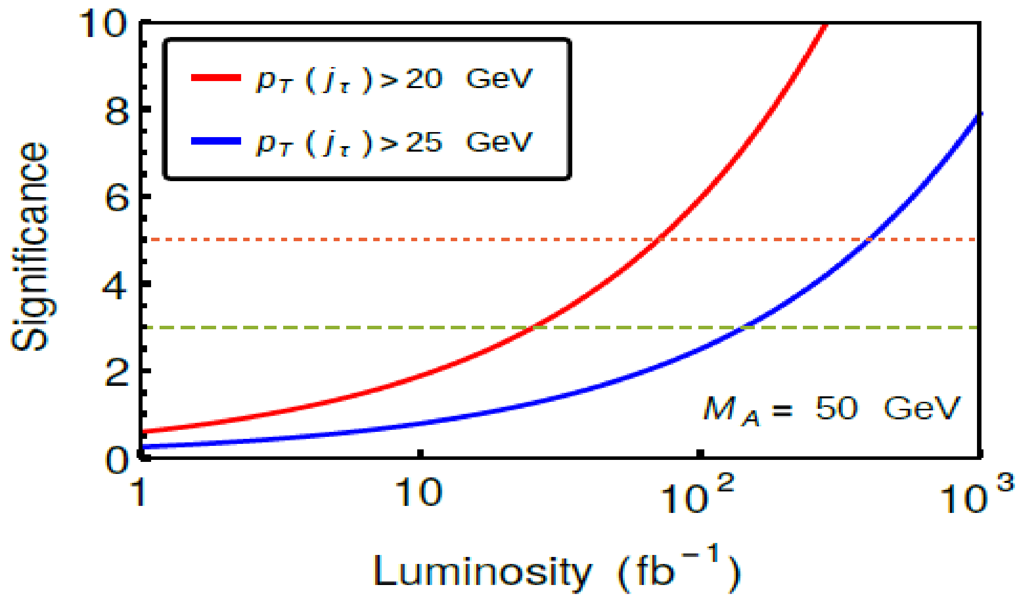
Parameters	M_A (GeV)	$\tan\beta$	$\cos(\beta-\alpha)$	λ_{hAA}/v
BP1	50	60	0.03	0.02
BP2	60	60	0.03	0.03

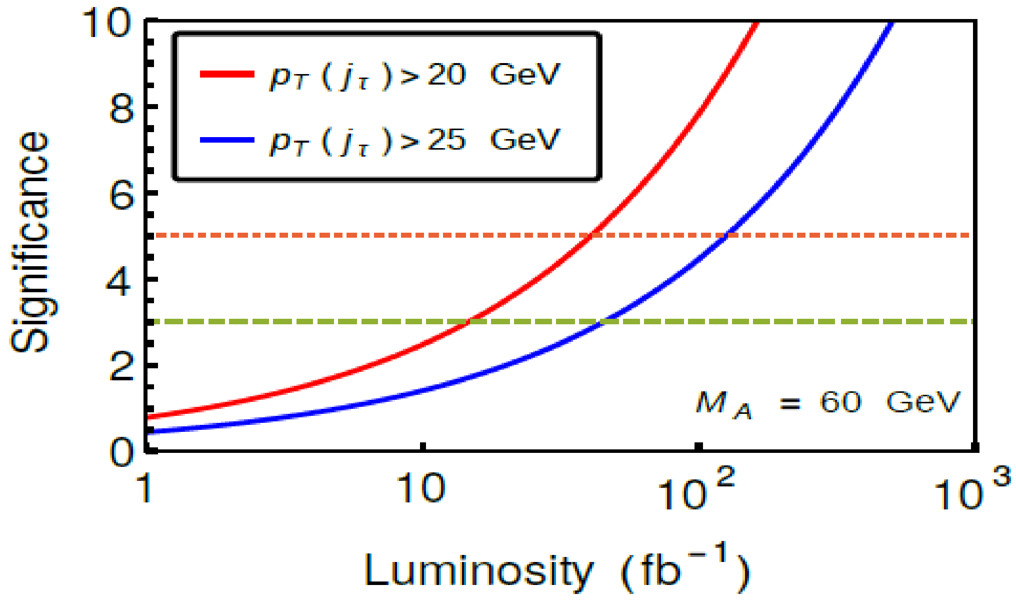
Event selection with $m_A = 50\ (60)\ GeV$

with 3/ab

Cuts	Signal	$pp \to \mu^+\mu^-$ $+jets$	$pp \to VV$ $+jets$	$pp \to t\bar{t}$ $+jets$
$p_T(j_\tau) > 20$ GeV				
Preselection	858 (1480)	41041 (41041)	107890 (107890)	14486 (14486)
$\lvert M_{\mu\mu} - M_A \rvert < 7.5$ GeV	836 (1430)	909 (779)	1189 (1325)	1637 (1697)
$M_{j_\tau j_\tau} > M_A - 20$ & $M_{j_\tau j_\tau} < M_A + 10$ GeV	760 (1336)	130 (390)	307 (654)	330 (419)
$M_{2\mu 2j_\tau} > M_h - 20$ & $M_{2\mu 2j_\tau} < M_h + 10$ GeV	698 (1283)	< 130 (< 390)$*$	81 (109)	65 (51)
$p_T(j_\tau) > 25$ GeV				
Preselection	277 (493)	28833 (28833)	75209 (75209)	11629 (11629)
$\lvert M_{\mu\mu} - M_A \rvert < 7.5$ GeV	269 (475)	649 (390)	794 (924)	1324 (1396)
$\lvert M(j_\tau j_\tau) - M_A \rvert < 15$ GeV	228 (420)	< 649 (130)	112 (416)	182 (196)
$\lvert M_{2\mu 2 j_\tau} - M_h \rvert < 15$ GeV	211 (410)	< 649 (< 130)$*$	20 (15)	27 (27)

LHC prospective





BP1 (BP2) with 3/ab

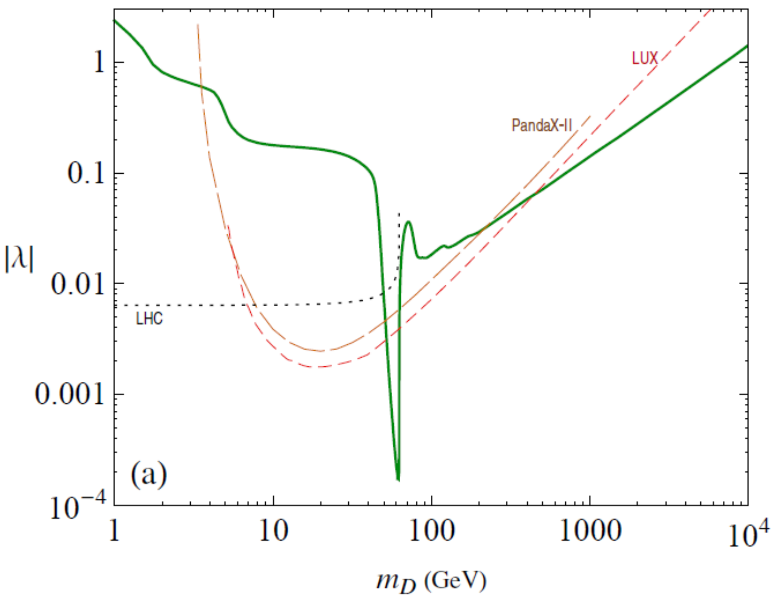
SM + Scalar DM

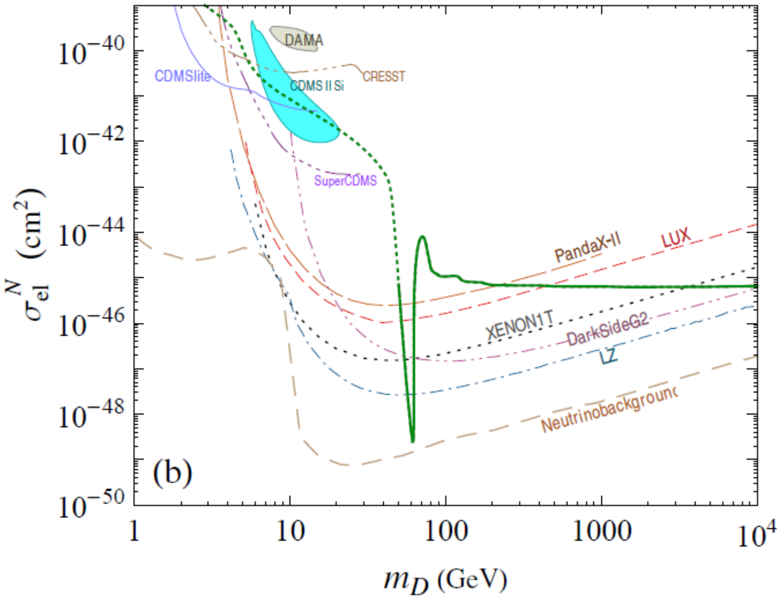
$$V = \mu_H^2|H|^2 + \lambda_H|H|^4 + \lambda_{HS}\,|H|^2|S|^2 + \mu_S^2|S|^2 + \lambda_S|S|^4$$

$$\sigma_{\rm ann} = \sigma(DD \to h^* \to X_{\rm SM}) + \sigma(DD \to hh)$$

$$\sigma(DD \to h^* \to X_{\rm SM}) = \frac{4\lambda^2 v^2}{(m_h^2 - s)^2 + \Gamma_h^2 m_h^2}\,\frac{\sum_i \Gamma(\tilde{h} \to X_{i,\rm SM})}{\sqrt{s - 4m_D^2}}$$

$$\sigma_{\rm el}^N = \frac{\lambda^2 g_{NNh}^2 m_N^2 v^2}{\pi\,(m_D + m_N)^2 m_h^4}$$





L2HDM+Scalar DM

$$V = \frac{1}{2}m_0^2 S^2 + \frac{\lambda_S}{4}S^4 + \frac{1}{2}S^2\left[\kappa_1|\Phi_1|^2 + \kappa_2|\Phi_2|^2\right]$$

$\boxed{\Phi_1 \sim A, H, H^{\pm}}$

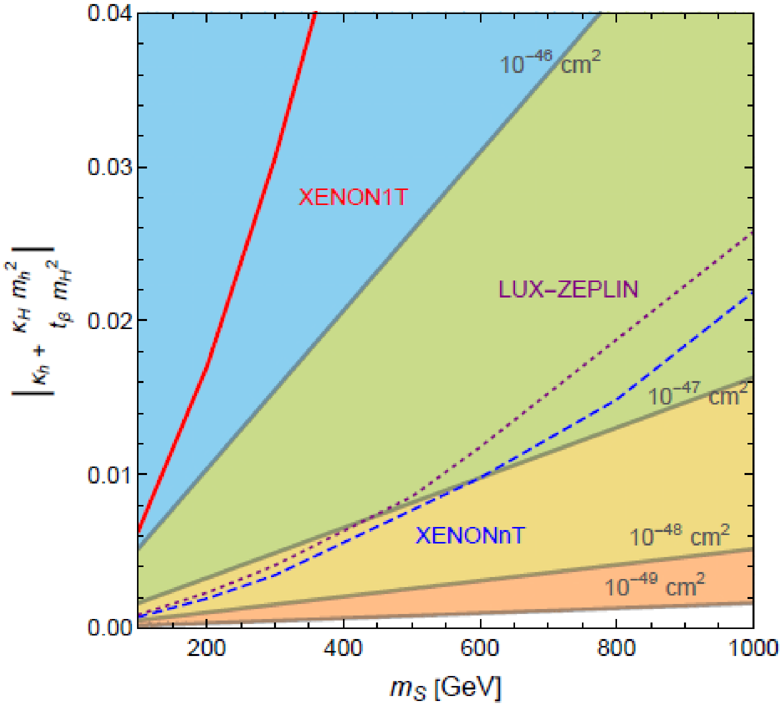
$\boxed{\Phi_2 \sim h}$

$$\begin{aligned} V &= \frac{1}{2}S^2\Big[2v(\kappa_h h + \kappa_H H) \\ &\quad + \kappa_{hh}h^2 + 2\kappa_{hH}hH + \kappa_{HH}H^2 + \kappa_{AA}(A^2 + 2H^+H^-)\Big] \end{aligned}$$

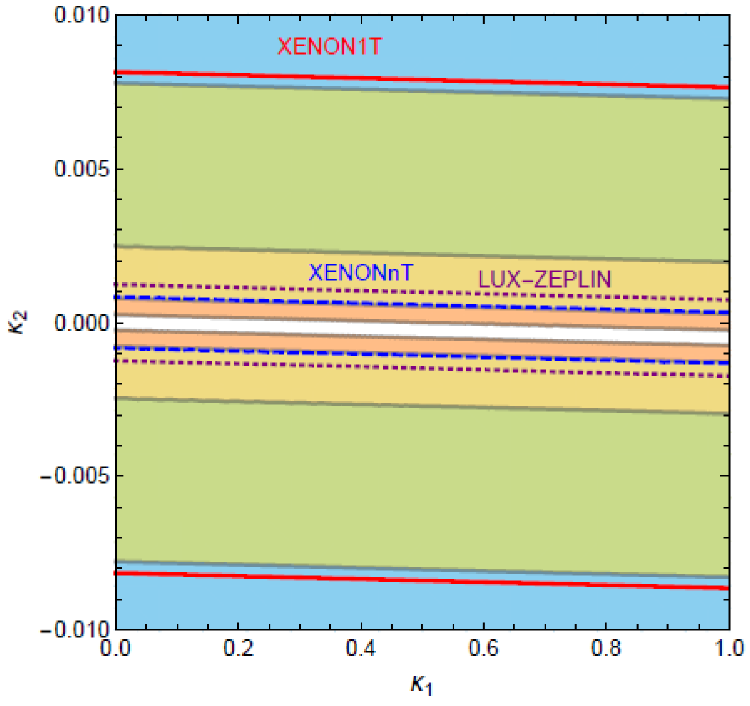
$$\begin{aligned} \text{where}\quad \kappa_h &= -\kappa_1 s_\alpha c_\beta + \kappa_2 c_\alpha s_\beta \approx \kappa_1 c_\beta^2 + \kappa_2 s_\beta^2, \\ \kappa_H &= +\kappa_1 c_\alpha c_\beta + \kappa_2 s_\alpha s_\beta \approx (\kappa_1 - \kappa_2)c_\beta s_\beta. \\ \kappa_{hh} &= \kappa_1 s_\alpha^2 + \kappa_2 c_\alpha^2 \approx \kappa_1 c_\beta^2 + \kappa_2 s_\beta^2, \\ \kappa_{hH} &= -(\kappa_1 - \kappa_2)c_\alpha s_\alpha \approx (\kappa_1 - \kappa_2)c_\beta s_\beta, \\ \kappa_{HH} &= \kappa_1 c_\alpha^2 + \kappa_2 s_\alpha^2 \approx \kappa_1 s_\beta^2 + \kappa_2 c_\beta^2, \\ \kappa_{AA} &= \kappa_1 s_\beta^2 + \kappa_2 c_\beta^2 \end{aligned}$$

DM-Nucleon scattering

$\tan\beta = 50, m_A = 50GeV, m_{H,H^\pm} = 250GeV,$



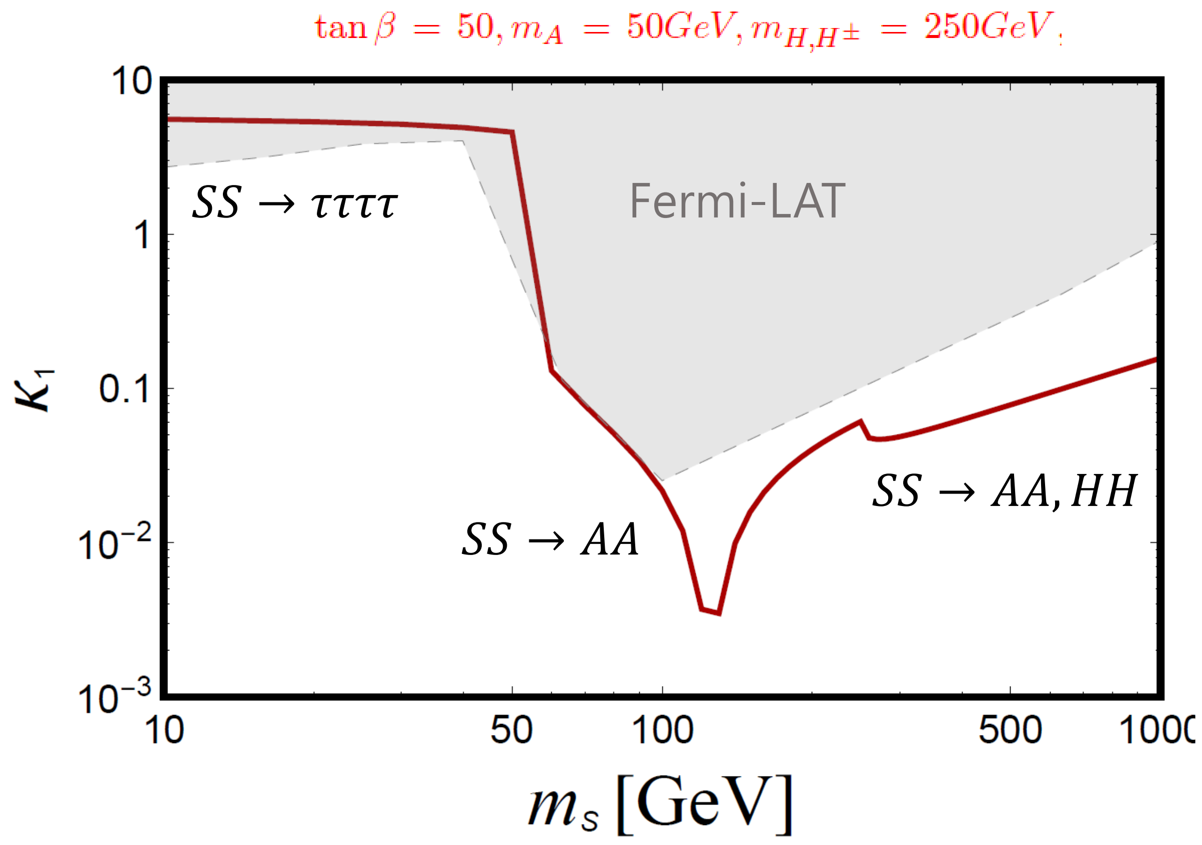
(a)



(b)

P. Bandyopadhyay, EJC, R. Mandal, to appear

DM annihilation



SS
$\to$

P. Bandyopadhyay, EJC, R. Mandal, to appear

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 $h \to AA^{(*)} \to 4\tau\ (2\mu 2\tau)$; $H^{0,\pm}\, A \to AA \to 4\tau\ (2\mu 2\tau)$.
- Higgs-portal Scalar DM can be realized successfully.