Workshop on "Flavour changing and conserving processes" 2015 (FCCP2015)

10-12 September 2015 *Villa Orlandi, Anacapri, Capri Island, Italy*
Europe/Rome timezone

KOREA INSTITUTE FOR ADVANCED STUDY

The $(g\text{-}2)_\mu$ 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?"

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

a lot of studies in SUSY, much less in 2HDMs (of Type I & II)...

0102145, 146, 147, ... vs. Dedes, Haber, 0102297
Cheung, Chou, Kong, 0103183

Cao, et.al, 0909.5148 (in Type X)

- Revisit the question with new experimental inputs:

arXiv:1409.3199

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

- Predicted tau-rich signatures need to be searched for. arXiv:1507.08067

2HDMs

- Two Higgs Doublets:

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

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

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

- Gauge coupling: $\mathcal{L}_g = g_V m_V \big(s_{\beta-\alpha} h + c_{\beta-\alpha} H\big) VV + \cdots$
- Yukawa coupling of two Higgses → FCNC if Mass $\not\approx$ Yukawa

$$\mathcal{L}_{Yuk} = y^{u,2}_{ij} \Phi_2 q_i u^c_j + y^{d,1,2}_{ij} \Phi_p q_i d^c_j + y^{e,1,2}_{ij} \Phi_q l_i e^c_j + h.c.$$

$$M^f_{ij} = y^{f,1}_{ij} \frac{v_1}{\sqrt{2}} + y^{f,2}_{ij} \frac{v_2}{\sqrt{2}} \quad \to \quad y^d_{ij}\, h d_i d^c_j + \cdots$$

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
$y^1_{ij} \sim y^2_{ij}$

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

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

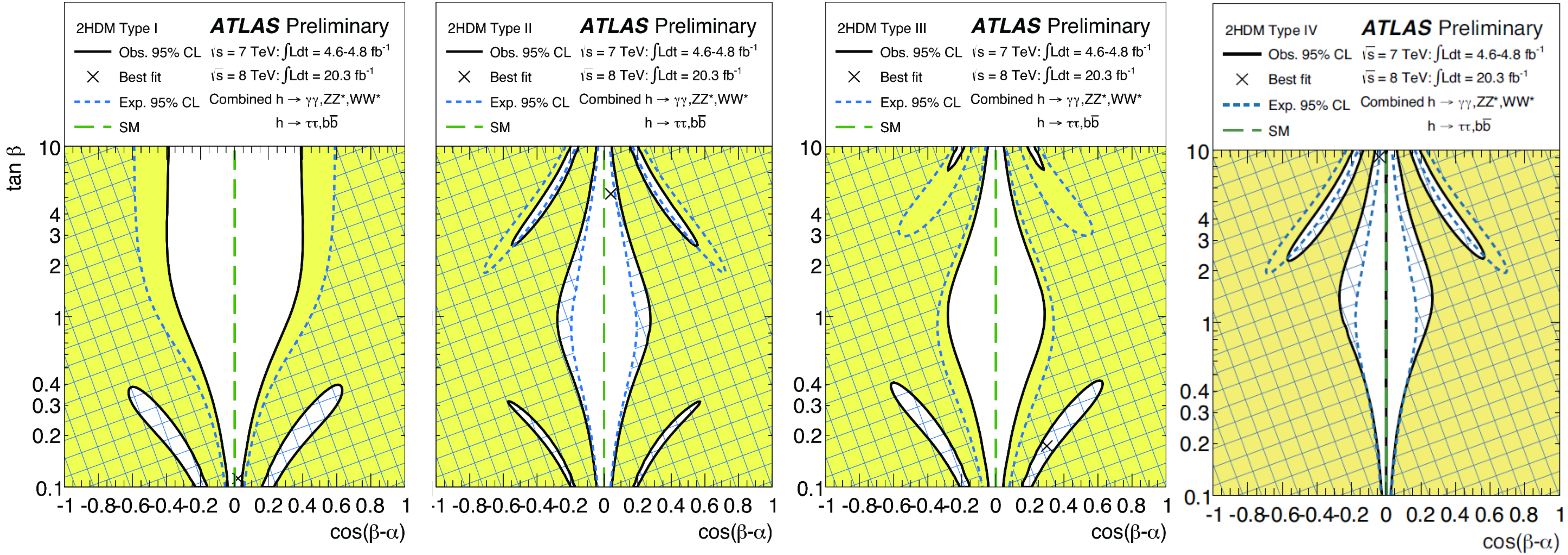
$$\mathcal{L}_{\rm Yukawa}^{\rm 2HDM} = -\sum_{f=u,d,\ell} \frac{m_f}{v}\left(\xi_h^f \overline{f} f h + \xi_H^f \overline{f} f H - i\xi_A^f \overline{f}\gamma_5 f A\right)$$

125 GeV

$$-\left\{\frac{\sqrt{2}V_{ud}}{v}\overline{u}\left(m_u\xi_A^u \mathrm{P}_L + m_d\xi_A^d \mathrm{P}_R\right) d H^+ + \frac{\sqrt{2}m_\ell \xi_A^\ell}{v}\overline{\nu_L}\ell_R H^+ + \mathrm{H.c.}\right\}$$

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

ATLAS-CONF-2014-010



Aligned/decoupled 2HDMs

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

LHC Higgs data

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

$y_f^h \sim 1$

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

$\approx$

$$y_{b,\tau}^h = -\frac{s_\alpha}{c_\beta} = s_{\beta-\alpha} - t_\beta c_{\beta-\alpha} \to \pm 1\,!$$

$$\mathcal{L}_{\text{Yukawa}}^{\text{2HDM}} = -\sum_{f=u,d,\ell} \frac{m_f}{v}\left(\xi_h^f \overline{f} f h + \xi_H^f \overline{f} f H - i\xi_A^f \overline{f}\gamma_5 f A\right)$$

125 GeV

$$-\left\{\frac{\sqrt{2}V_{ud}}{v}\overline{u}\left(m_u\xi_A^u \text{P}_L + m_d\xi_A^d \text{P}_R\right) d H^+ + \frac{\sqrt{2}m_\ell \xi_A^\ell}{v}\overline{\nu_L}\ell_R H^+ + \text{H.c.}\right\}$$

SM (right-sign) limit
vs. Wrong-sign limit

Ferreira, et.al, 1403.4736

Muon g-2 with an extra Higgs at 1-loop

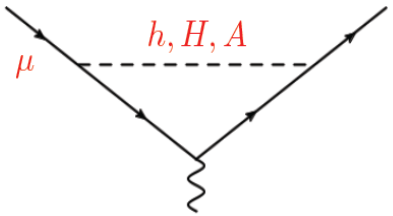
- A light H and large $y_\mu^H \approx t_\beta$ (II, X):

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

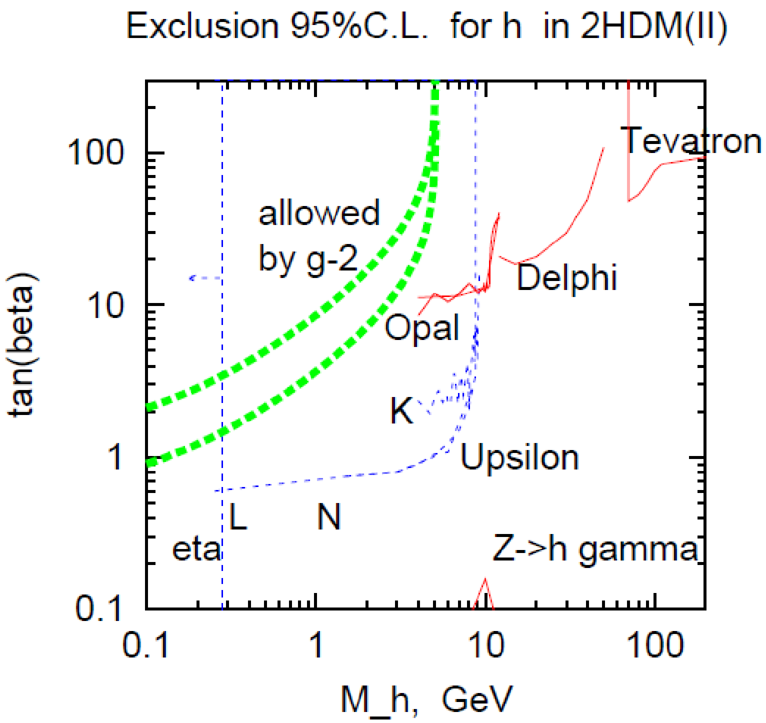
roughly scales with m_μ^4!

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

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



- Requires H below 5GeV → Excluded!



Krawczyk, 0208076

Muon g-2 with an extra Higgs at 2-loop

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

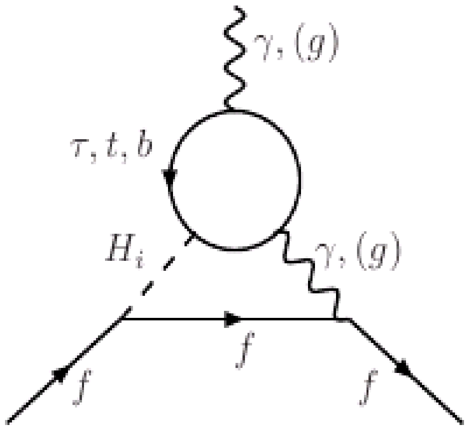
$$\delta a_\mu^{\rm 2HDM}(2{\rm loop}-{\rm BZ}) = \frac{G_F\, m_\mu^2}{4\pi^2\sqrt{2}} \frac{\alpha_{\rm em}}{\pi} \sum_{f;\, i=h,H,A} N_f^c\, Q_f^2\, y_\mu^i\, y_f^i\, r_f^i\, g_i(r_f^i)$$

r_f^i → m_f^2/m_μ^2

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

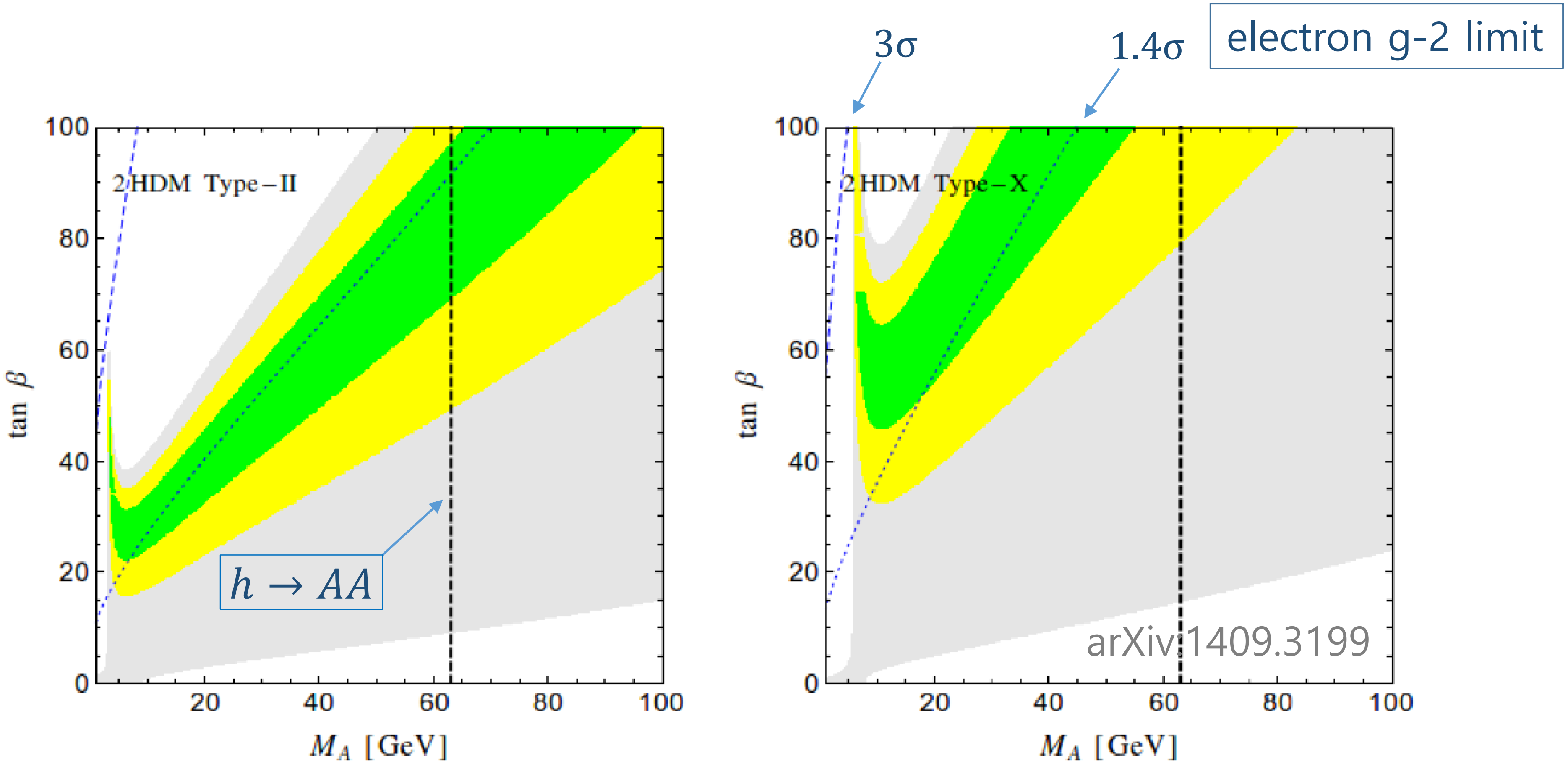
$g_A(r) > 0$

	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



- A light A and large t_β → B, tau decays (LU) & LHC searches.

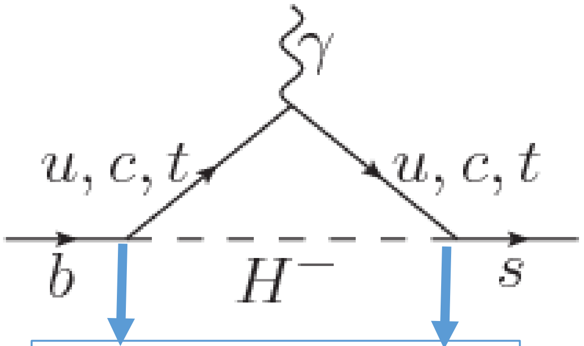
Muon g-2 in Type II & X



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

Constraints from B decays

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



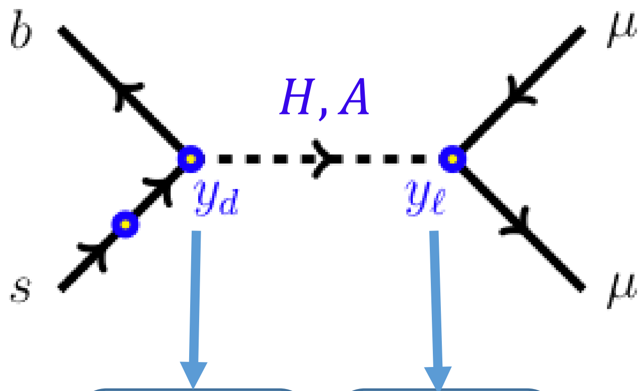
$\propto t_\beta^2/m_{H^\pm}^2$ (II)

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

$\frac{m_t}{t_\beta} P_L - \frac{m_b}{t_\beta} P_R \quad (X, I)$

$\frac{m_t}{t_\beta} P_L + m_b t_\beta P_R \; (II, Y)$

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



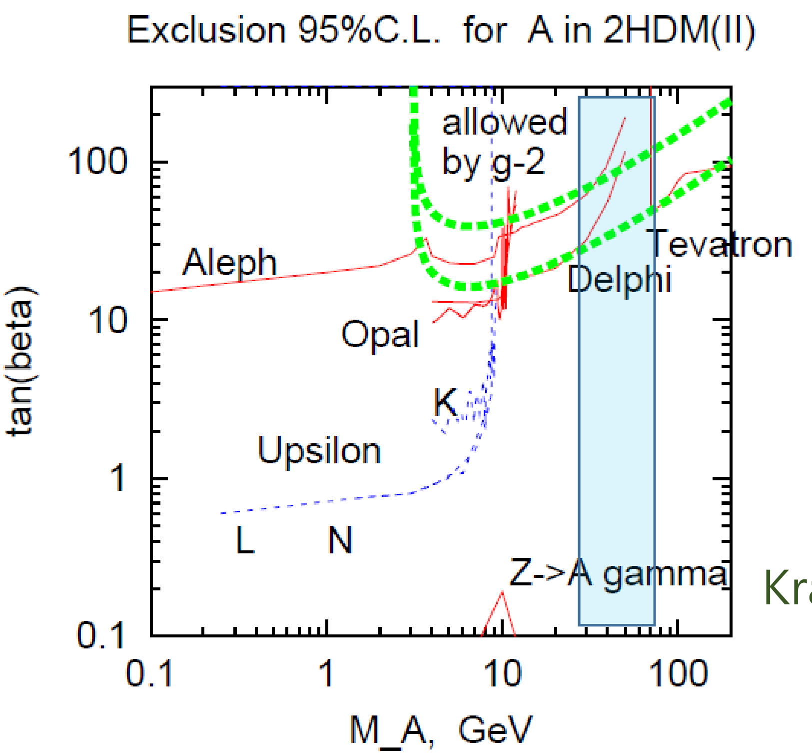
$\propto t_\beta^2/m_A^2$ (II)

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

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

In 2HDM-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

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

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

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

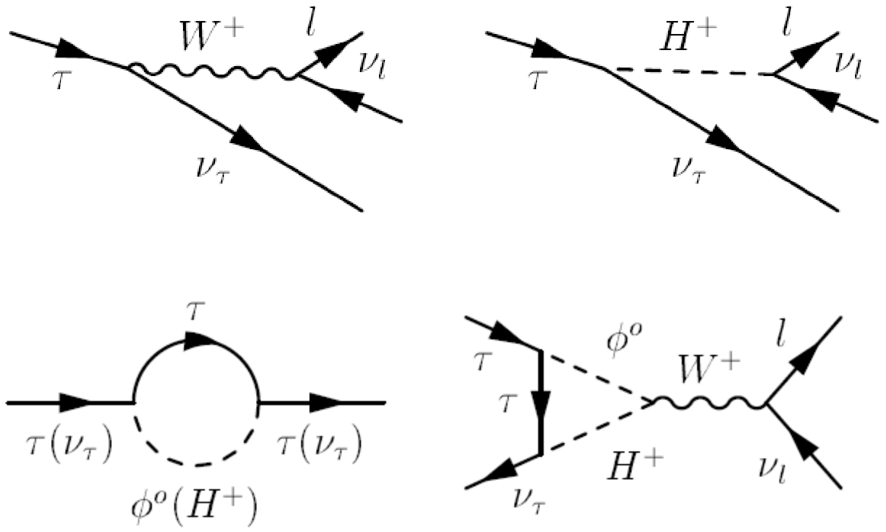
In 2HDM-X,

- $\bar{B} \to X_s \gamma$ 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 on $t_\beta / m_{H^\pm}$ from Lepton Universality tests:

Abe, et.al., 1504.07059

Cao, et.al, 0909.5148

Krawczyk, Temes, 0410248



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

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

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

Lepton Universality tests

HFAG, 1412.7515

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

Note) Only two ratios are independent

$$\left(\frac{g_l}{g_{l'}}\right) \equiv 1 + \delta_{l/l'} \quad \delta_{\tau/\mu} = 0.0011 \pm 0.0015, \;\; \delta_{\tau/e} = 0.0029 \pm 0.0015, \;\; \delta_{\mu/e} = 0.0018 \pm 0.0014$$

- From semi-hadronic processes: $\frac{(\tau\to\nu\pi/K)}{(\pi/K\to\mu\nu)} \to \left(\frac{g_\tau}{g_\mu}\right)_{\pi,K} \equiv 1 + \delta^{\pi,K}_{\tau/\mu}$

$$\delta^{\pi}_{\tau/\mu} = -0.0142 \pm 0.0071, \;\; \delta^{K}_{\tau/\mu} = -0.0037 \pm 0.0027$$

Thanks to A. Lusiani

- The redundant direction to be projected out: $(\delta_{\tau/\mu} - \delta_{\tau/e} + \delta_{\mu/e})/\sqrt{3}$

-- consistent with zero best-fit value and zero eigenvalue of the covariance matrix

- Two independent orthogonal directions:

$$\delta_1 \equiv (\delta_{\tau/\mu} + \delta_{\tau/e})/\sqrt{2} \qquad \delta_2 \equiv (-\delta_{\tau/\mu} + \delta_{\tau/e} + 2\delta_{\mu/e})/\sqrt{6}$$

LU constraining the muon g-2 region

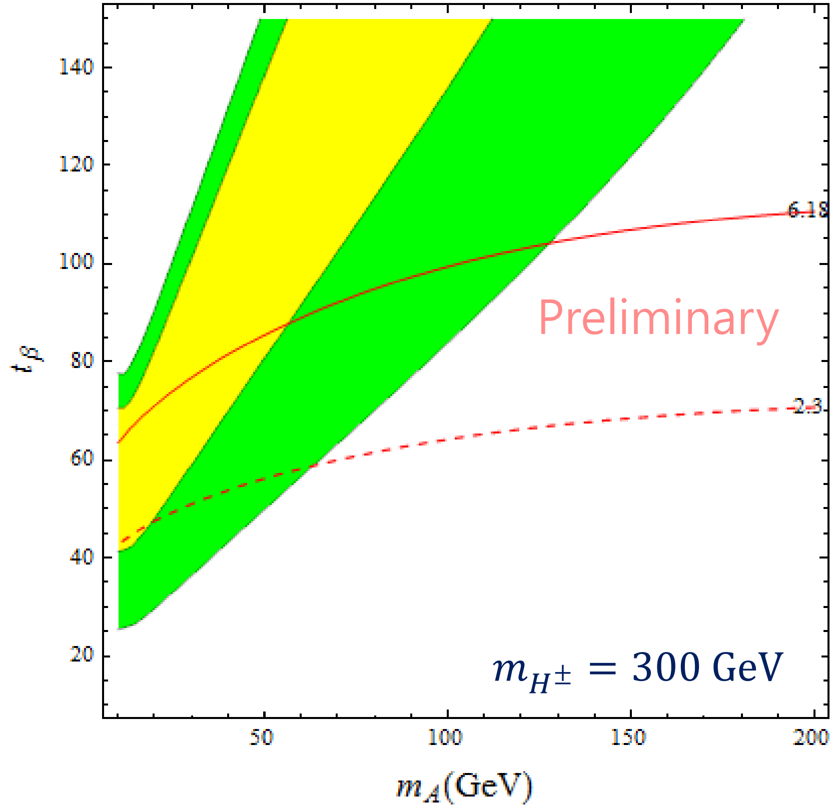
- In 2HDM-X;

  $\delta_1 = \frac{1}{\sqrt{2}}\delta_{tree} + \sqrt{2}\delta_{loop}$,

  $\delta_2 = \delta_{tree}$, $\delta^{\pi}_{\tau/\mu} = \delta^{K}_{\tau/\mu} = \delta_{loop}$

- Construct the 4x4 covariance matrix to constrain $(\mathrm{m_A}, \mathrm{t}_\beta)$ for given $m_H = m_{H^\pm}$

- Viable only at 2σ, but still a large region allowed



Constraints from EWPD

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

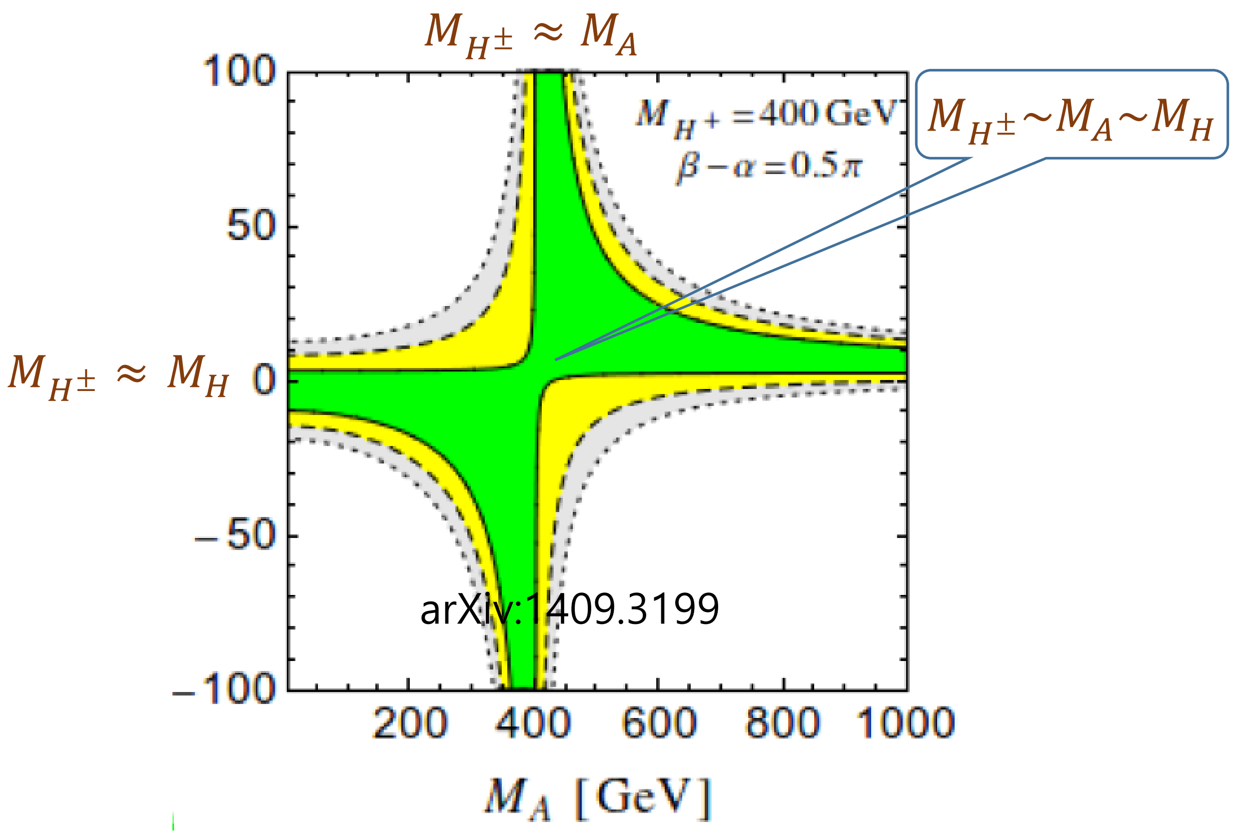
$$\sin^2\theta_{\rm eff}^{\rm lept} = k_l\left(M_Z^2\right)\sin^2\theta_W$$

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

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

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

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



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

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

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

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

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

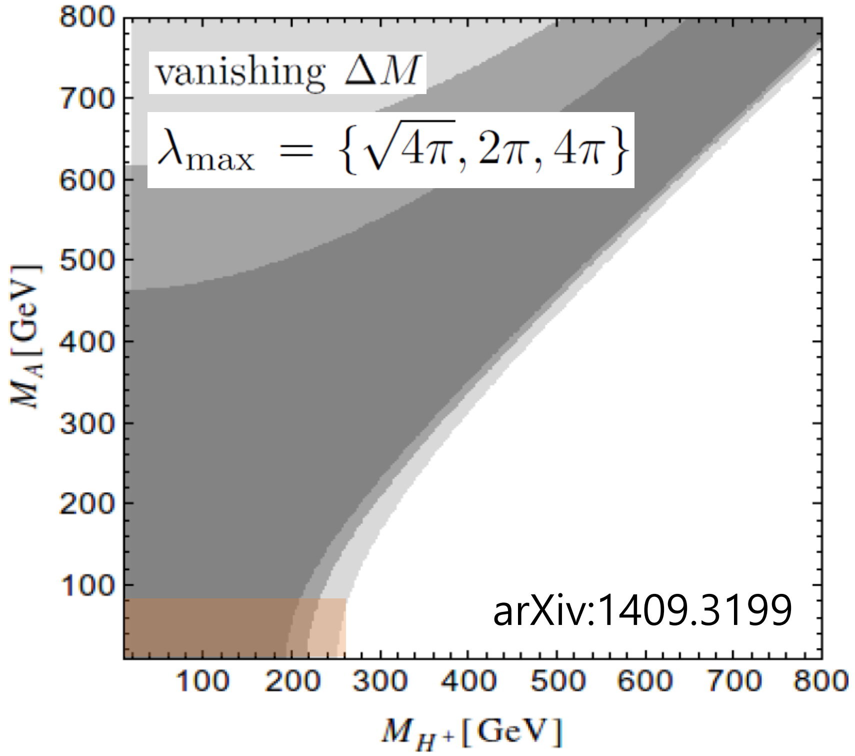
$$\lambda_5 - \lambda_3 - \lambda_4 < \sqrt{\lambda_1\lambda_2}$$

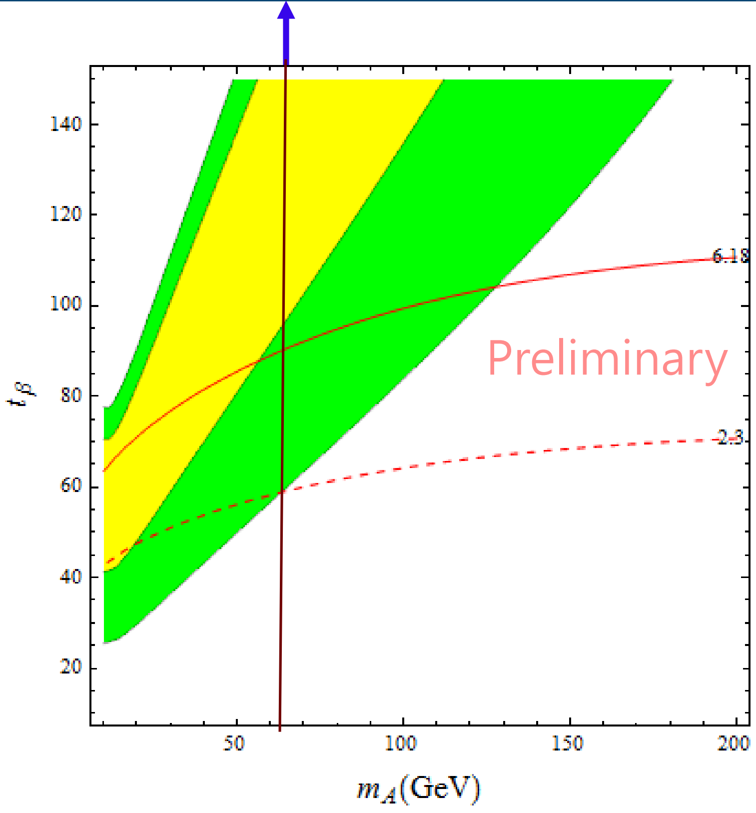
$$\rightarrow (1 + s_{\beta-\alpha}y_l^h)M_H^2 - 2M_A^2 - s_{\beta-\alpha}y_l^h M_h^2 < \sqrt{\lambda_1} v M_h$$

± 1 ($s_{\beta-\alpha}y_l^h$)

Type X in the SM (right-sign) limit $(y_l^h s_{\beta-\alpha} \approx +1)$

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





$63\ GeV \lesssim M_A \ll M_H \approx M_{H^\pm} \lesssim 250 GeV$, or $2\ M_A^2 + M_h^2 \sim 2M_H^2$

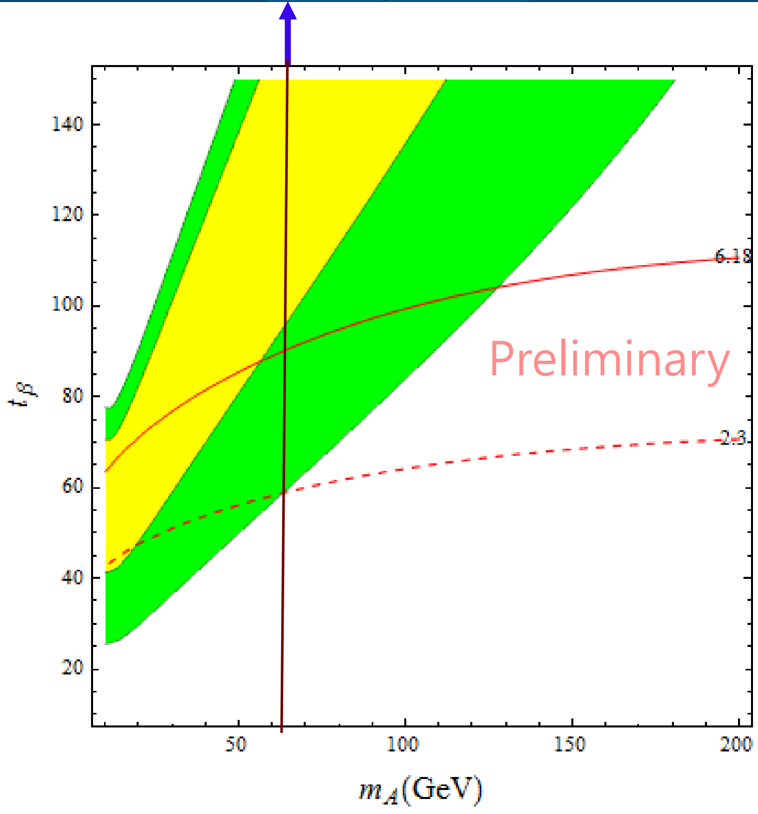
Type X in the wrong-sign limit $(y_l^h s_{\beta-\alpha} \approx -1)$

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

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

Wang, Han, arXiv:1412.4874

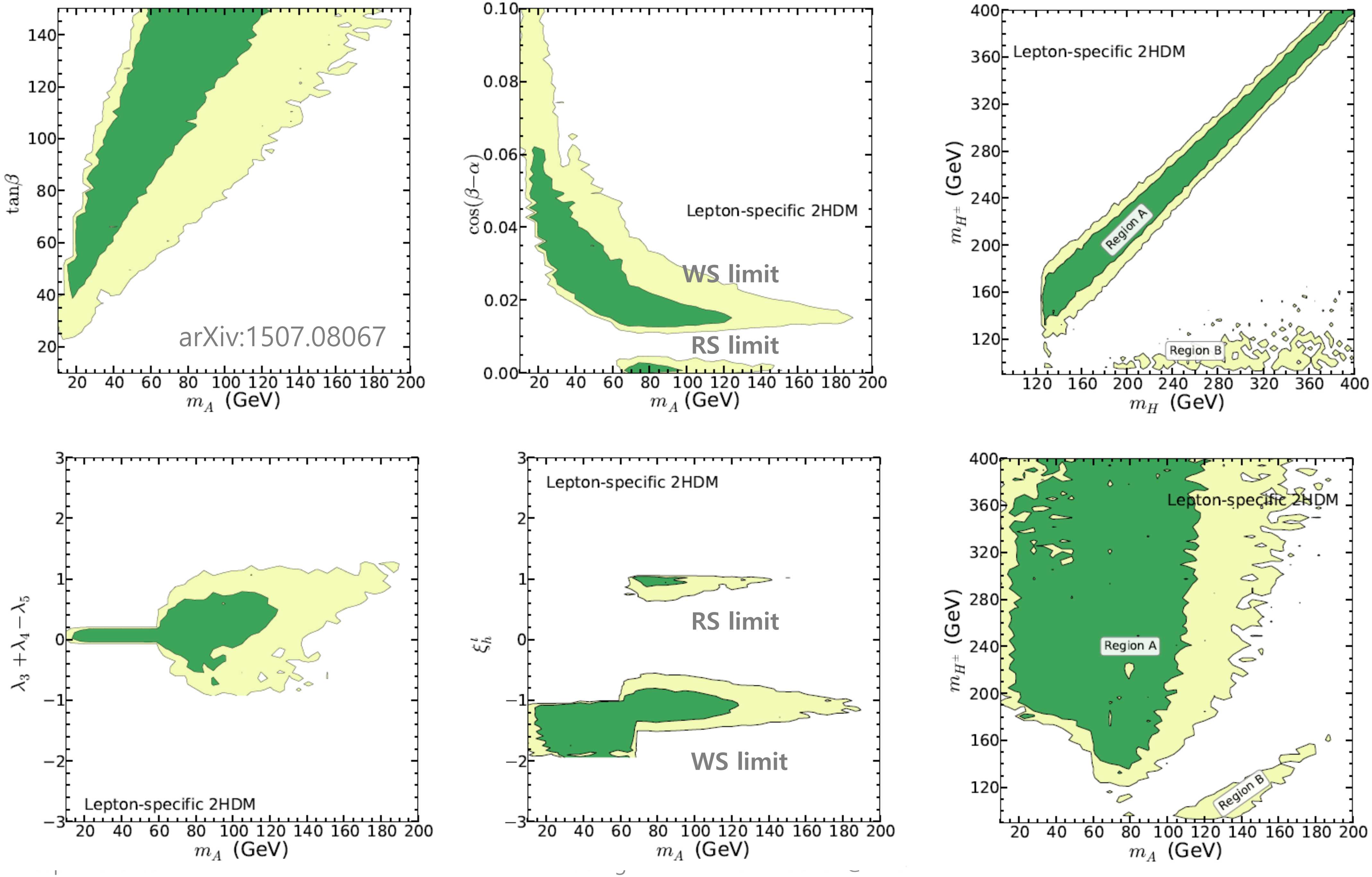
$$10\ GeV \lesssim m_A \ll m_H \approx m_{H^\pm} \lesssim \sqrt{4\pi} v$$



Scanning analysis

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

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	$0.0 < \lambda_1 < 4\pi$


tanβ
m_A (GeV)
arXiv:1507.08067
cos(β−α)
Lepton-specific 2HDM
WS limit
RS limit
m_A (GeV)
m_{H±} (GeV)
Lepton-specific 2HDM
Region A
Region B
m_H (GeV)
λ3 + λ4 − λ5
Lepton-specific 2HDM
m_A (GeV)
ξ_h^ℓ
Lepton-specific 2HDM
RS limit
WS limit
m_A (GeV)
m_{H±} (GeV)
Lepton-specific 2HDM
Region A
Region B
m_A (GeV)

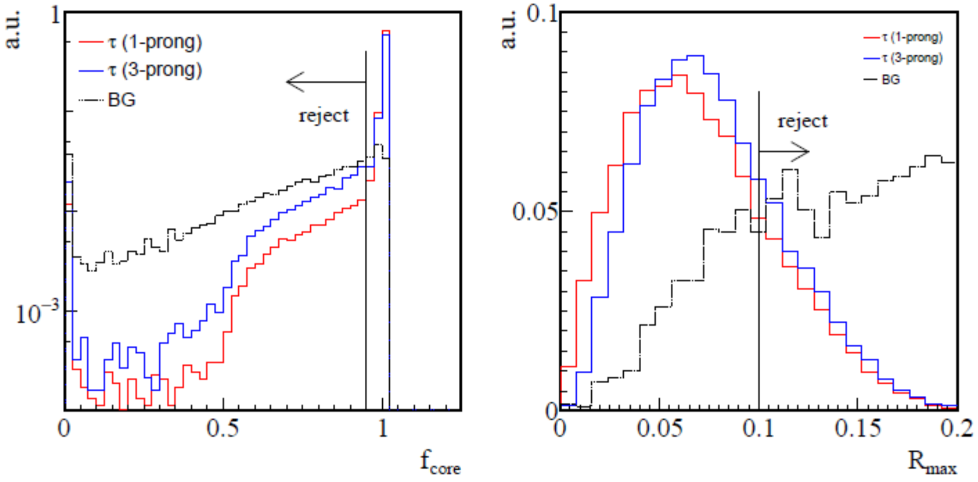
Tau-rich signatures at LHC

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

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

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

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



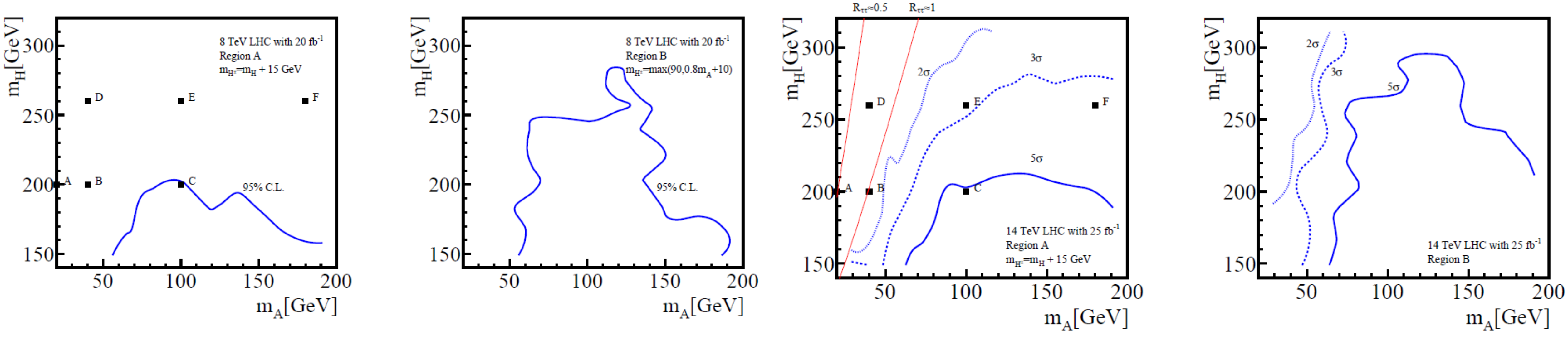
	point A	point B	point C	point D	point E	point F
m_A [GeV]	20	40	100	40	100	180
m_H [GeV]	200	200	200	260	260	260
total $\sigma_{\rm gen}$ [fb]	270.980	241.830	153.580	100.430	71.271	44.163
$n_\ell \geq 3$	6.606	16.681	21.713	7.110	11.962	8.822
$n_\tau \geq 3$	0.894	2.602	4.386	0.888	2.346	1.971
$\not{E}_T > 100$ 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
$S/\sqrt{B}_{25\mathrm{fb}^{-1}}$	0.6	1.9	5.2	0.7	2.9	3.8

Current limits & future perspective

- LHC8 constraints mostly from chargino-neuralino searches.
- LHC14 with 25/fb, 60% of tau-tagging efficiency.
- Requires a boosted di-tau tagging ($A \to \tau\tau$) to probe $m_A < 50\,GeV$.

Boosted di-tau separation

arXiv:1507.08067



Conclusion

- 2HDM-X is still a viable option for muon g-2.
- The LU tests are not compatible at 1σ, but still allow a large region at 2σ.
- 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 test.
- Dedicated searches for tau-rich signals are required to probe light A.

Back-up

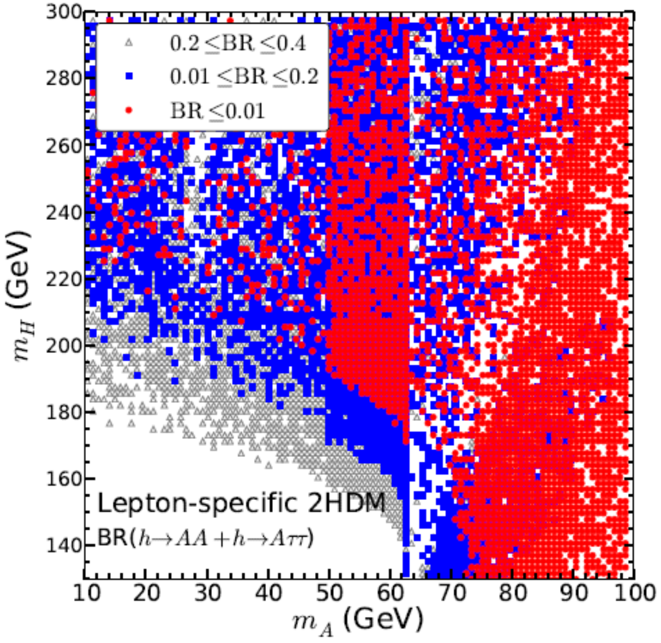


FIG. 4: Plots of the SM-like Higgs exotic decay Br($h \to AA$) (for $m_A \lesssim m_h/2$) and Br($h \to A\tau^+\tau^-$) (for $m_h/2 \lesssim m_A \lesssim m_h$.). All the scatter points satisfy the constraints described in the text in 2σ.

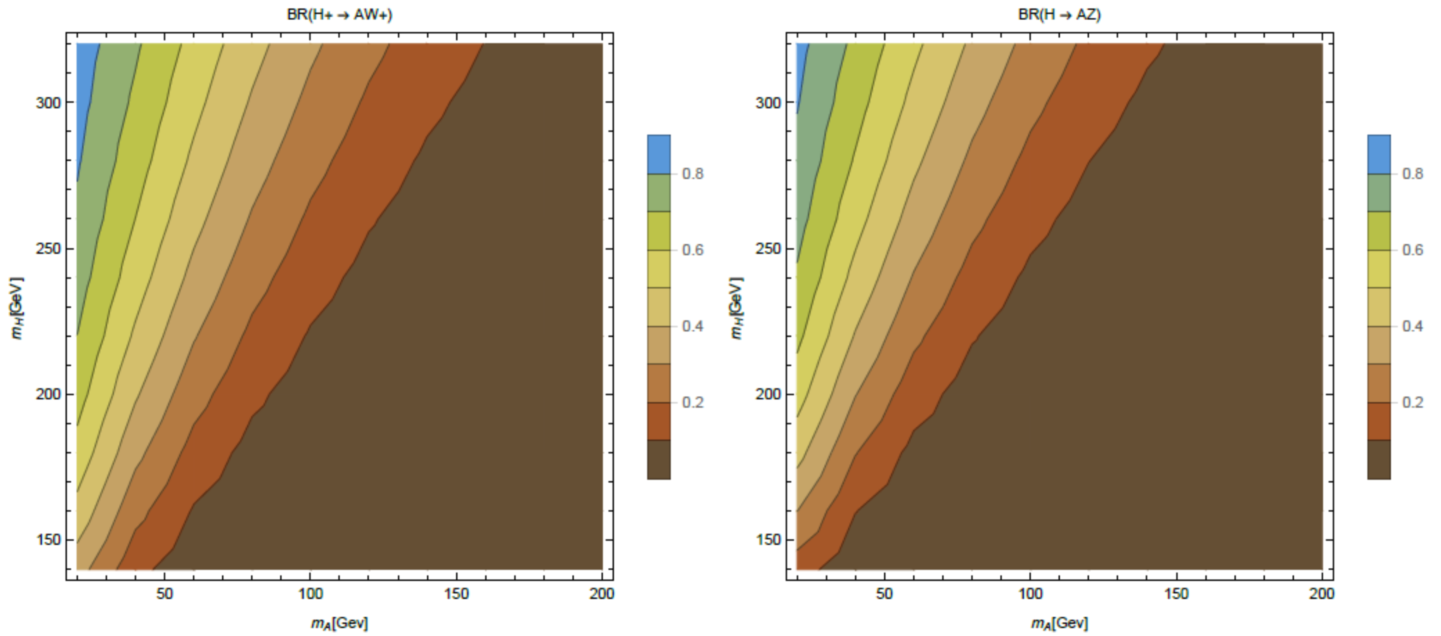


FIG. 5: Contour plot of branching ratio $\mathrm{Br}(H^+ \to AW^+)$ and $\mathrm{Br}(H \to AZ)$. $\mathrm{Br}(H^+ \to AW^+) + \mathrm{Br}(H^+ \to \tau^+ \nu) \simeq 1$ in Region A. The relation $\tan\beta = 1.25 m_A + 25$ is used.

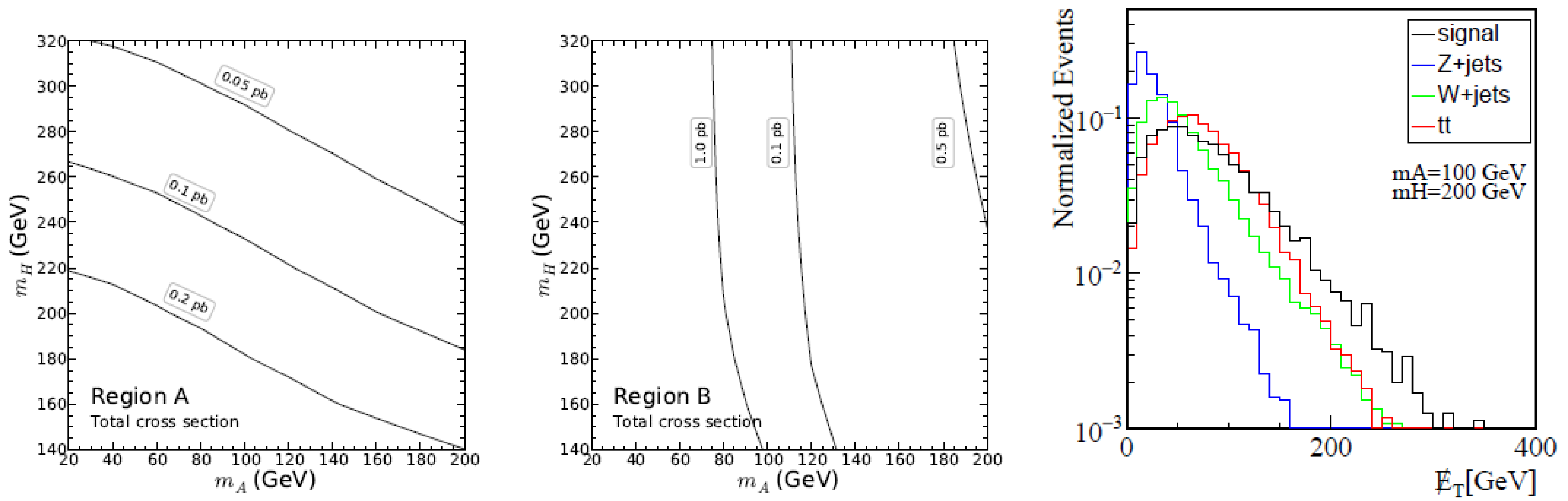


FIG. 7: Total signal cross section dependence in m_A vs. m_H plane in Region A (left) and Region B (center). Right panel: Missing transverse momentum distributions for the signal benchmark point C ($m_A = 100$ GeV and $m_H = 200$ GeV in Region A) and various BG processes.

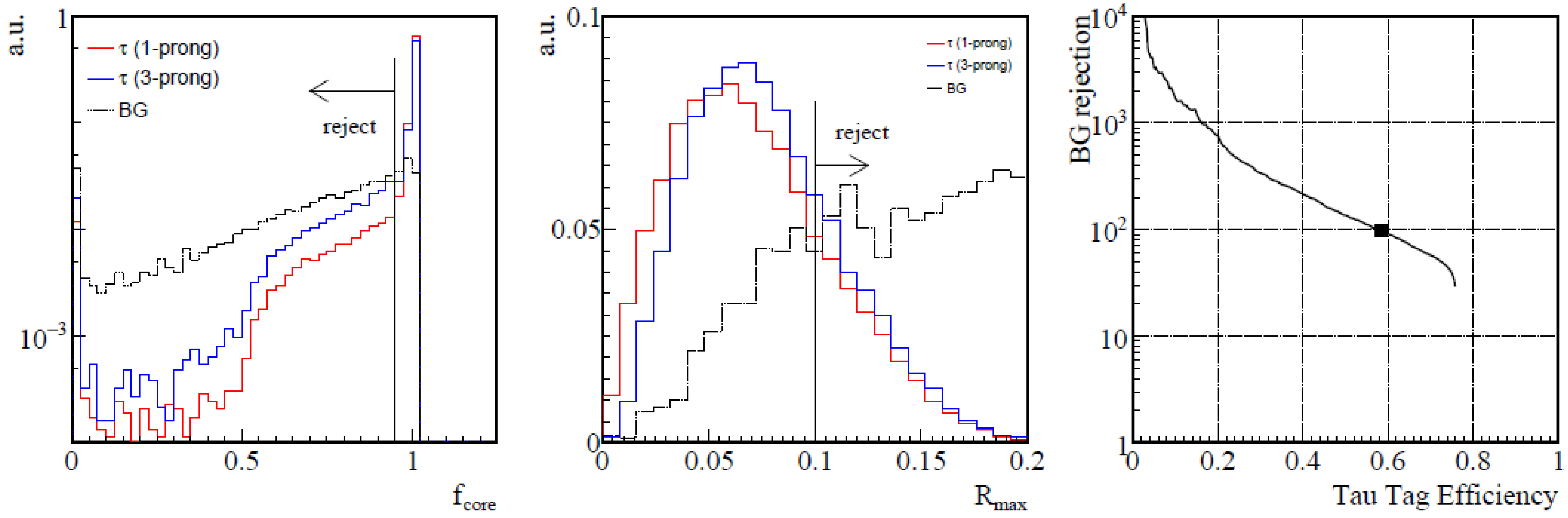


FIG. 8: ROC curve for our τ-tagging algorithm. Our working point is denoted with a filled square, where 59% efficiency with 1% mis-identification efficiency for QCD jets is obtained.

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

TABLE III: The number of events after applying successive cut for 14 TeV LHC. Benchmark point C ($m_A = 100$ GeV, $m_H = 200$ GeV) is shown for the signal. The significance quoted is based on integrated luminosity of 25 fb^{-1}.