Two Higgs doublet model in the light of muon g-2 anomaly

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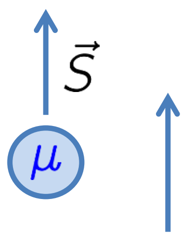
“Lepton-specific two higgs doublet model as a solution of muon g-2 anomaly”,
Tomohiro Abe, RS, Kei Yagyu, [arXiv:1504.xxxxx]

2015. 4. 21 @ Asian Linear Collider Workshop(ALCW2015)

Muon g-2 anomaly

Muon g-2



$$\vec{\mu} = g\frac{e}{2m_\mu}\vec{S} \qquad a_\mu = \frac{g-2}{2} = 11\ 659\ 208.0(5.4)(3.3)\times 10^{-10}$$

[BNL E821 experiment; hep-ex/0602035]

3 sigma Deviation from the standard model

$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (28.7 \pm 8.0)\times 10^{-10}$$ [Davier, Hoecker, Malaescu, Zhang (2010)]

$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (26.1 \pm 8.0)\times 10^{-10}$$ [Teubner, Hagiwara, Liao, Martin, Nomura (2011)]

New physics at electroweak scale?

There may be new particles with light mass and/or sizable coupling with lepton.

c.f.) Contribution of W, Z, h : $a_\mu^{\rm EW} \simeq 15\times 10^{-10}$

Muon g-2 and two Higgs doublet model

One of simple extension of the standard model.
We introduce two SU(2) doublet scalar field.

Higgs sector in two Higgs doublet model

$$\begin{pmatrix} H_1^{\pm} \\ H_1^0 \end{pmatrix}, \begin{pmatrix} H_2^{\pm} \\ H_2^0 \end{pmatrix}$$

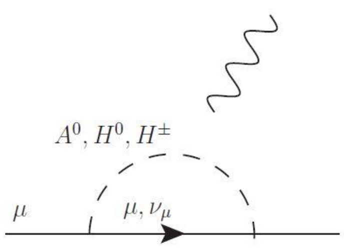
CP-even neutral Higgs	$h^0, \ H^0$
CP-odd neutral Higgs	A^0
Charged Higgs	$H^{\pm}$
NG-boson (eaten by W, Z)	$(W_L^{\pm}, Z_L)$

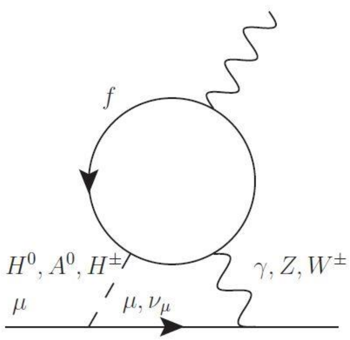
Muon g-2 in two Higgs doublet model

To explain muon g-2 anomaly:

- $m_A = \mathcal{O}(10)$ GeV
- Large $A^0\ell\ell$ coupling

[Chang, Chang, Chou, Keung (2000)]
[Dedes, Haber (2001)]
[Cheung, Chou, Kong (2001)]
[Krawczyk, (2001)]
[Wu, Zhou, (2001)]





(type-X)

Lepton-specific two Higgs doublet model

- Softly broken Z_2 prevents tree-level FCNC process.

Z_2even : $H_1,\ q_L,\ \ell_L,\ e_R^c$ Z_2odd : $H_2,\ u_R^c,\ d_R^c$

H_1 (H_2) only couples to SM leptons (quarks).

c.f.) other assignment of Z_2 charge is realized in type-I, II, Y THDM.

Yukawa interaction:

- Extra Higgs boson has large coupling with leptons with large tanbeta.

$$\langle H_2\rangle/\langle H_1\rangle = \tan\beta$$

$$\mathcal{L}_{\text{Yukawa}} = -y_u H_2 q_L u_R^c - y_d H_2 q_L d_R^c - y_\ell H_1 \ell_L e_R^c + h.c..$$

$$\supset \frac{im_u}{v}\frac{1}{\tan\beta}A^0\bar{u}\gamma^5 u - \frac{im_d}{v}\frac{1}{\tan\beta}A^0\bar{d}\gamma^5 d - \frac{im_\ell}{v}\tan\beta A^0\bar{\ell}\gamma^5\ell$$

Suppressed by tanbeta enhanced by tanbeta

Small couplings with quarks avoid various constraints. (B physics, LHC direct search)

Important constraints on type-X 2HDM

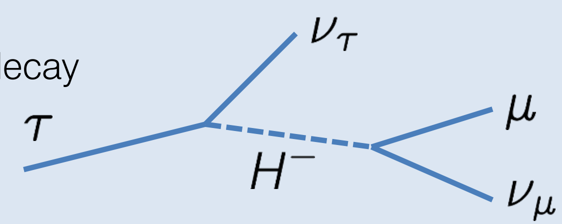
We need $m_A = \mathcal{O}(10)$ GeV, $\tan\beta = \mathcal{O}(10)$

See also [Broggino, Chun, Passera, Patel, Vempati (2014)]
[Wang, Han (2014)]

- LEP search ($e^+e^- \to \tau\tau A$ etc.)
- Electroweak precision ($Z \to \tau\tau$, T parameter)
- $B_s \to \mu^+\mu^-$
- $h \to AA \to 4\tau$

- Decay of tau lepton (lepton universality) **This constraint is forgotten so far.**

Charged Higgs destroys lepton universality of lepton decay
Lower bound on charged Higgs mass

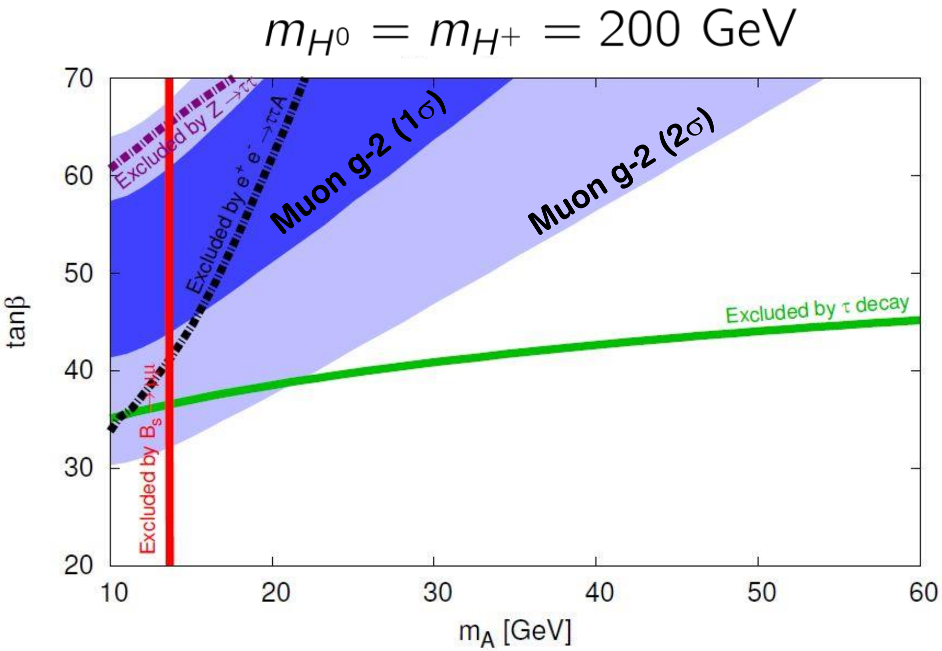


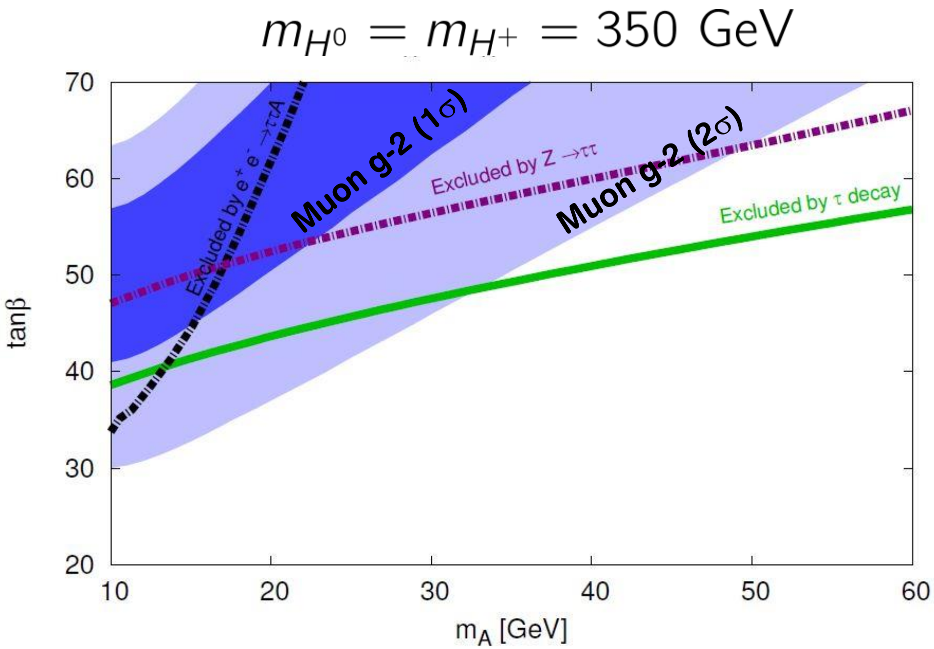
- Triviality bound

To obtain mass splitting, we need large Higgs couplings, $m_{H^\pm}^2 - m_A^2 = \frac{1}{2}(-\lambda_4 + \lambda_5)v^2$

For mA ~ O(10) GeV and there is no Landau pole up to 10 TeV,
upper bound on charged (& heavier CP-even) Higgs mass : $m_{H^+} \lesssim 350$ GeV

Muon g-2 versus constraints





In these figures, we take Higgs coupling which realizes $\mathrm{Br}(h \to AA)$ as 0.

- Smaller mH+ is severely constrainted by lepton universality test (decay of tau lepton)
- Larger mH+ is constrained by triviality bound (perturbativity of quartic coupling)

- 2sigma explanation is still possible in a small region.

Impacts on Higgs physics (very preliminary)

$$\mu \equiv \frac{\sigma \times \mathrm{Br}}{(\sigma \times \mathrm{Br})_{\mathrm{SM}}}$$

Tau channel : $h^0 \to \tau^+\tau^-$

- O(10-100)% enhancement

Favored by ATLAS, but there is a tension with CMS

$\mu = 1.43^{+0.43}_{-0.37}$ [ATLAS, 1501.04943]

$\mu = 0.78 \pm 0.27$ [CMS, 1401.5041]

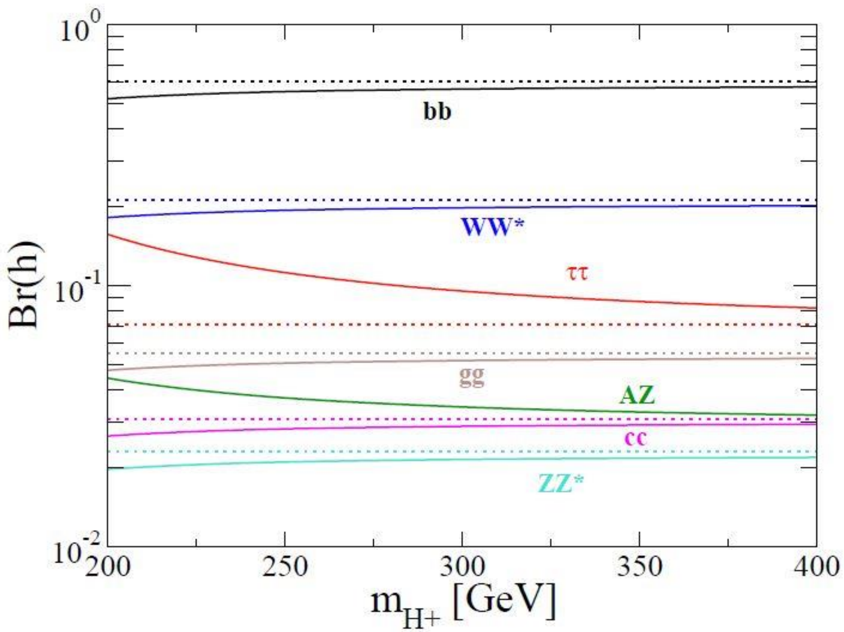
Exotic channel : $h^0 \to ZA$

- Branching fraction $\sim$ a few % for mA=20 GeV

A0 mainly decays into a pair of tau-lepton.
Thus, final state is $Z\tau\tau$

This channel could affect the measurement of

$$h \to ZZ^* \to 4\ell$$



$m_A = 20\ \mathrm{GeV},\ \ \tan\beta = 35$

Summary

- Lepton-specific Two Higgs doublet model as solution of muon g-2 anomaly.
- Lepton universality test (tau leptonic decay) gives a severe bound.
- Characteristic mass spectrum and parameter are obtained.
    - mA $\sim$ 10-30 GeV
    - mH, mH+ $\sim$ 200-350 GeV
    - Tanbeta $\sim$ 30-50
- Decay of SM-like Higgs boson deviates in a characteristic way.
    - O(10-100) % enhancement of tautau channel
    - Branching fraction of h to ZA is a few percent for mA=20 GeV.

A. Backup slides

Parameters of the Higgs sector

8 parameteres in Higgs potential :

$$V = m_{11}^2|H_1|^2 + m_{22}^2|H_2|^2 - (m_{12}^2 H_1^\dagger H_2 + h.c.) + \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \left(\frac{\lambda_5}{2}(H_1^\dagger H_2)^2 + h.c.\right).$$

$$\lambda_1,\ \lambda_2,\ \lambda_3,\ \lambda_4,\ \lambda_5,\ m_{11}^2,\ m_{22}^2,\ m_{12}^2$$

SM input

$$\tan\beta,\ m_Z,\ m_h,\ m_A,\ m_{H^\pm},\ m_H,\ \lambda_{hAA}$$

$\lambda_{hAA} = 0 \longrightarrow \mathrm{Br}(h \to AA \to 4\tau) = 0$

$m_H = m_{H^\pm} \longrightarrow \Delta T = 0$

Remaining 3 parameters : $m_A, m_{H^\pm}, \tan\beta$

In large tanbeta, $\frac{g_{hWW}}{g_{hWW,SM}} - 1 = \mathcal{O}(\tan^{-2}\beta)$

λ_1 is almost irrelevant with phenomenology for large tanbeta.

Parameters of the Higgs sector

$\tan\beta \gg 1$

$$V = m_{11}^2|H_1|^2 + m_{22}^2|H_2|^2 - (m_{12}^2 H_1^\dagger H_2 + h.c.) + \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \left(\frac{\lambda_5}{2}(H_1^\dagger H_2)^2 + h.c.\right).$$

$$\sin(\beta-\alpha) \simeq 1 - \frac{2}{\tan^2\beta}\left(1 + \frac{m_h^2}{m_{H^\pm}^2} - \frac{2m_A^2}{m_{H^\pm}^2}\right)$$

$$\cos(\beta-\alpha) \simeq \frac{2}{\tan\beta}\left(1 + \frac{m_h^2}{2m_{H^\pm}^2} - \frac{m_A^2}{m_{H^\pm}^2}\right)$$

$$m_h^2 \sim \lambda_2 v^2$$

$$m_A^2 \sim m_{11}^2 + \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5)v^2$$

$$m_{H^\pm}^2 \sim m_{11}^2 + \frac{1}{2}\lambda_3 v^2$$

$$m_H^2 \sim m_{11}^2 + \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)v^2$$

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

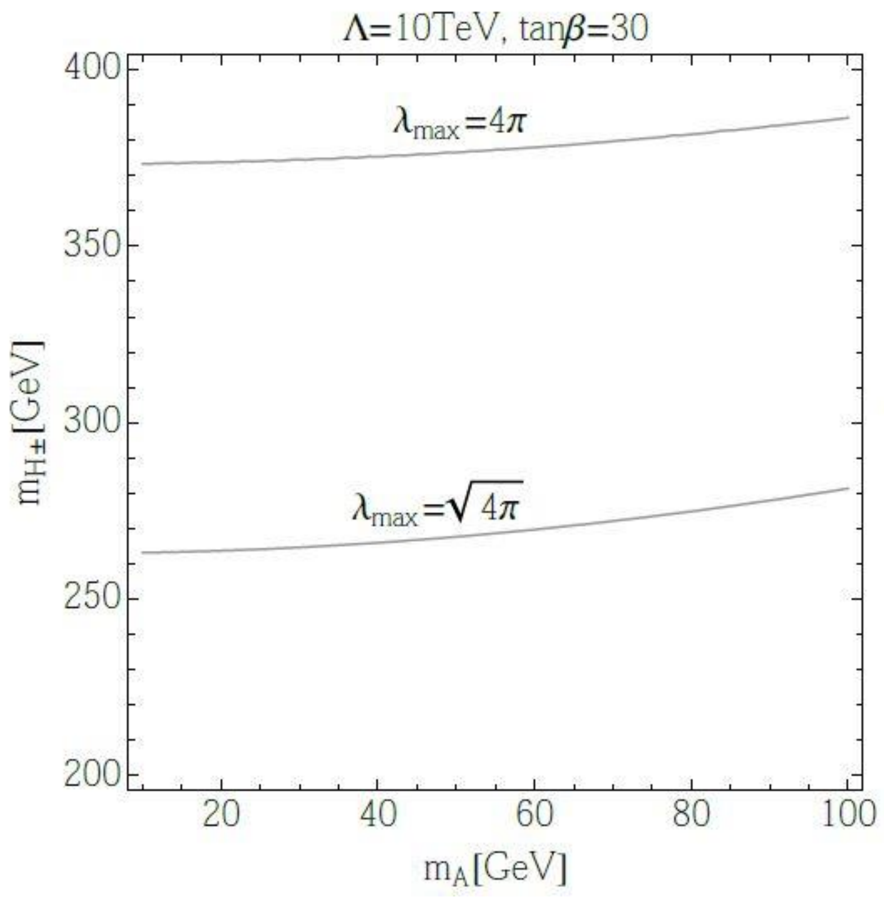
Triviarity bound

Muon g-2 requires $m_A \sim$ 10-30 GeV
$m_H, m_{H^\pm} \gtrsim 200$ GeV

Large mass splitting requires
Large Higgs coupling.

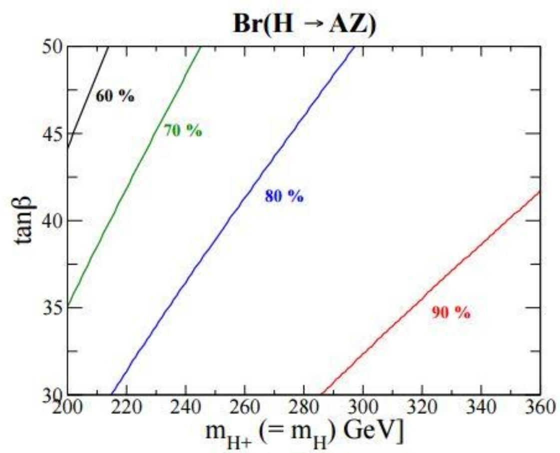
ex) $$m_{H^\pm}^2 - m_A^2 = \frac{1}{2}(-\lambda_4 + \lambda_5)v^2$$

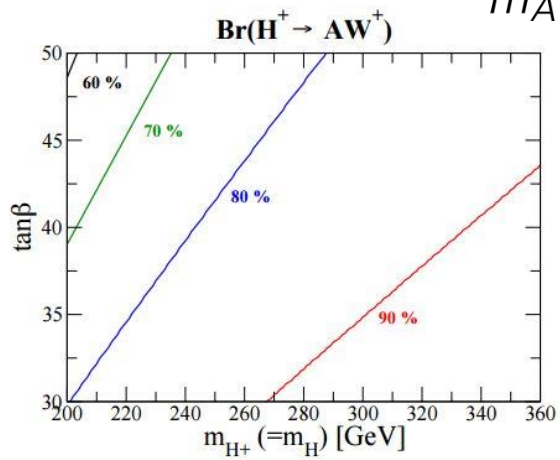
If we require $\Lambda \lesssim 10$ TeV,
$m_{H^+} \lesssim 350$ GeV



Decay and production of heavier Higgs bosons

$m_A = 20$ GeV





Heavy Higgs bosons mainly decay into pseudo-scalar and gauge boson. Large Higgs coupling. Longitudinal mode.

$m_{H^\pm}$ [GeV]	$\sigma_{H^+H^-}$	σ_{H^+H}	σ_{H^-H}	σ_{H^+A}	σ_{H^-A}	σ_{AH}	$\sigma_{4\tau}$	$\sigma_{3\tau}$	$\sigma_{4\tau W}$	$\sigma_{4\tau Z}$
200	18.6	22.0	11.3	116	67.0	101	29.3	50.1	143	70.7
250	8.0	9.7	4.7	53.5	29.5	45.1	7.2	12.8	72.5	37.4
300	3.9	4.8	2.3	28.2	14.9	23.2	2.3	4.3	39.4	20.6
350	2.1	2.6	1.1	16.2	8.2	13.0	0.9	1.7	22.9	12.0

Table 2: Cross sections of the electroweak production processes expressed in Eq. (65), and those of the multi-tau processes expressed in Eqs. (67)-(70) at $\sqrt{s} = 14$ TeV in the unit of fb. We take $m_A = 20$ GeV, $m_H = m_{H^\pm}$, $\sin(\beta - \alpha) = 1$ and $\tan\beta = 35$. The value of $\tan\beta$ is relevant to the cross sections shown in the last four columns.

[14]