Muon g-2 anomaly and constraints on two Higgs doublet model

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“Lepton-specific two higgs doublet model as a solution of muon g-2 anomaly”,
Tomohiro Abe, RS, Kei Yagyu, [arXiv:1504.07059], to be appeared in JHEP

2015. 7. 8 @ 京都大学

1. **Introduction (Muon g-2 anomaly)**

2. **Review on two Higgs doublet model**

   type-I, II, X, Y THDM are introduced.
   Only type-X THDM is viable to explain muon g-2.

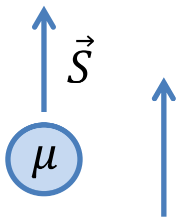
3. **Constraints on type-X (lepton-specific) THDM**

   Precision measurement of tau decay is the most important.

4. **Impact on Higgs physics**

   $\mathrm{Br}(h \to \tau\tau)$ deviates from the SM value.

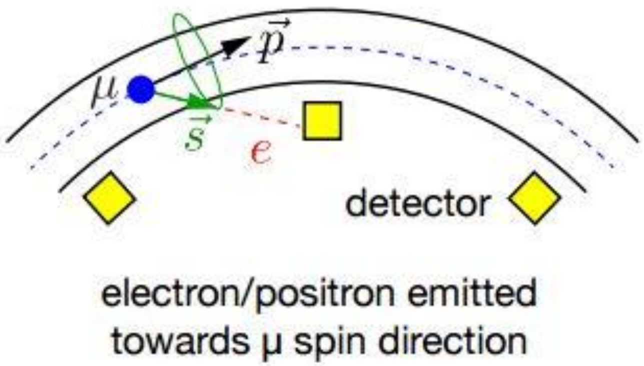
Muon anomalous magnetic moment (g-2)

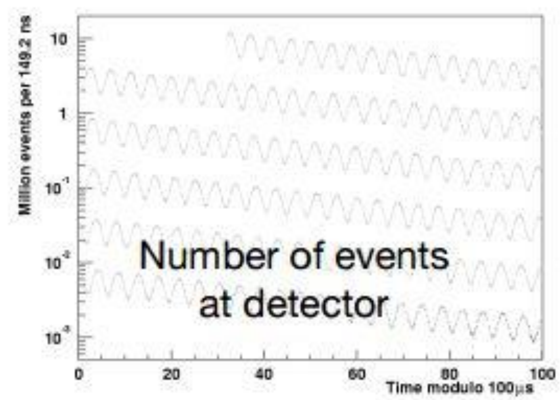


$$\vec{\mu} = g\frac{e}{2m_\mu}\vec{S}$$

g-factor is measured by spin precession:

$$\frac{d}{dt}\vec{S} = \vec{\omega}\times\vec{S}, \qquad \vec{\omega} = -\frac{e}{m}\left(\frac{g-2}{2}\vec{B} - \left(\frac{g-2}{2} - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right)$$





[a slide by M. Endo, Flavors of New physics (2015)]

$g-2$ is measured at the level of ppm :

$$a_\mu = \frac{g-2}{2} = (11\,659\,208.0 \pm 6.3)\times 10^{-10}$$

[BNL E821 experiment; hep-ex/0602035]

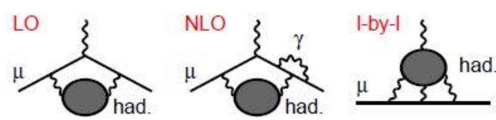
Theoretical calculation for muon g-2

SM value :

QED contribution	11 658 471.808 (0.015) $\times 10^{-10}$	Kinoshita & Nio, Aoyama et al
EW contribution	15.4 (0.2) $\times 10^{-10}$	Czarnecki et al
Hadronic contribution		
LO hadronic	**694.9 (4.3)** $\times 10^{-10}$	HLMNT11
NLO hadronic	-9.8 (0.1) $\times 10^{-10}$	HLMNT11
light-by-light	10.5 (2.6) $\times 10^{-10}$	Prades, de Rafael & Vainshtein
Theory TOTAL	**11 659 182.8 (4.9)** $\times 10^{-10}$	
Experiment	**11 659 208.9 (6.3)** $\times 10^{-10}$	world avg
Exp − Theory	**26.1 (8.0)** $\times 10^{-10}$	**3.3 σ discrepancy**

(Numbers taken from HLMNT11, arXiv:1105.3149)

n.b.: hadronic contributions:



[a slide by D. Nomura, SUSY11]

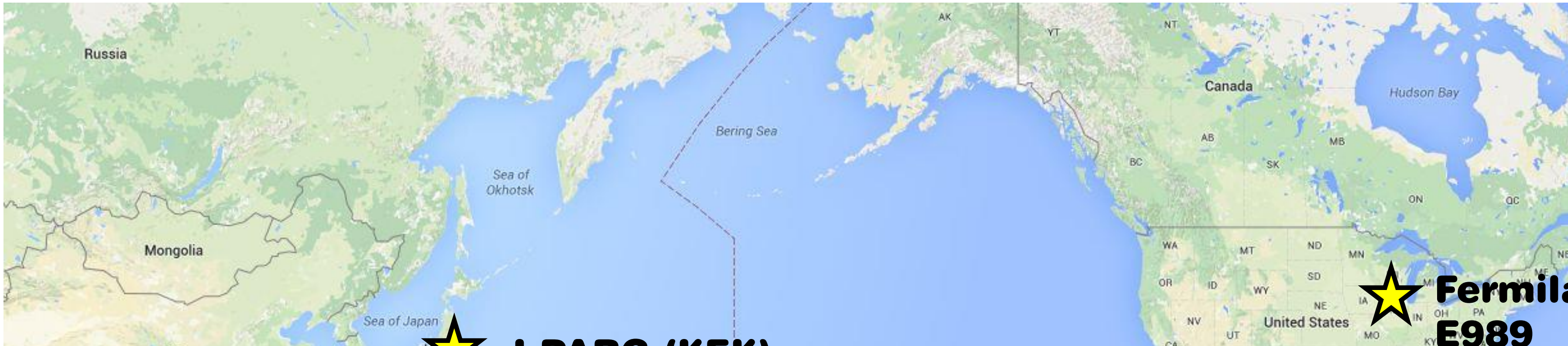
The dominant error comes from LO hadronic diagram.
It is calculated by using dispersion relation and $\sigma(e^+e^- \to \mathrm{hadrons})$.

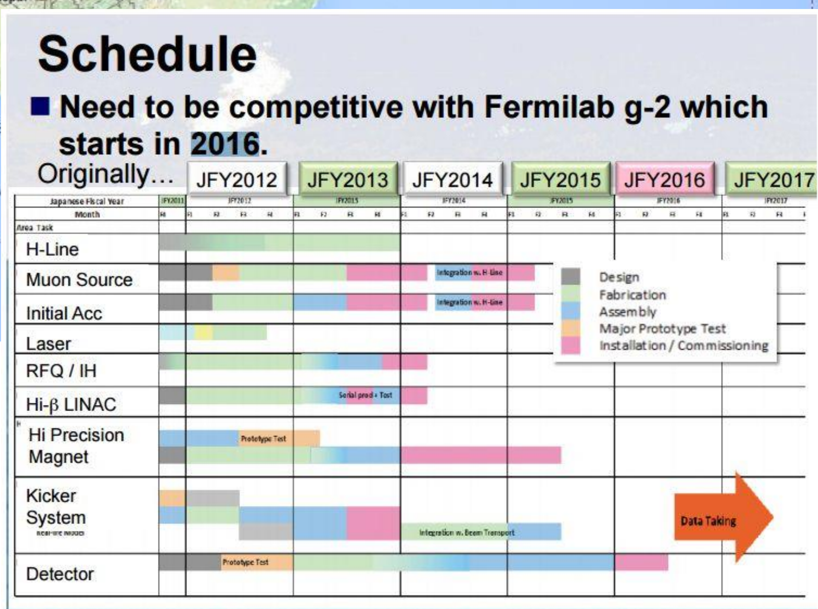
The discrepancy between the SM value and obs. is at $\sim 3\sigma$ level.

New experiments

New experiments

Both of new experiments will start SOON!





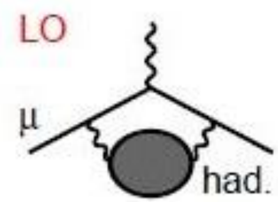
Schedule

2013	Magnet shipped to Fermilab
2014	Ring reassembly in progress
2015	Field shimming, detector installation
2016	Commissioning, first data
→2018	Data run

http://nuclpart.kek.jp/pac/1301/pdf/PAC16-Saito-v2.pptx.pdf
https://indico.in2p3.fr/event/10304/contribution/20/material/slides/0.pdf

Prospects of muon g-2 anomaly

- **SM value**

Dominant source of error comes from 

In the next 3-5 years the uncertainty on a_μ(HVP) is expected to drop by roughly a factor of two, relying on new results from *BABAR*, Belle, BES, and VEPP2000.

[1205.2671]

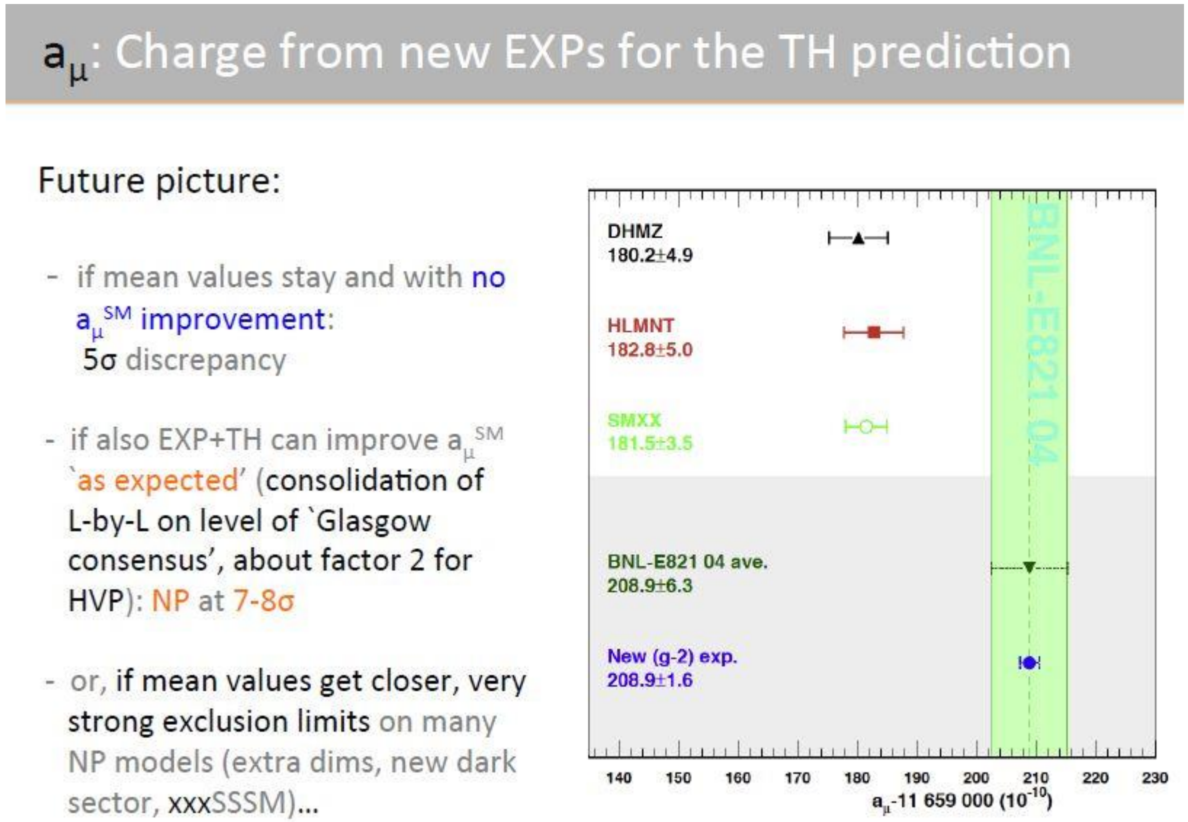
- **g-2 experiment**

Table 1.1: *Comparison of the previous experiment BNL-E821, FNAL-E989, and this experiment.*

	BNL-E821	FNAL-E989	This Experiment
Muon momentum	3.09 GeV/c		0.3 GeV/c
γ	29.3		3
Polarization	100%		> 90%
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	Electric Quad.		very-weak magnetic
Cyclotron period	149 ns		7.4 ns
Anomalous spin precession period	4.37 μs		2.11 μs
# of detected e^+	5.0×10^9	1.8×10^{11}	1.5×10^{12}
# of detected e^-	3.6×10^9	–	–
Statistical precision	0.46 ppm	0.1 ppm	0.1 ppm

[http://research.kek.jp/people/hiromi/MyHomePage/G-2_work_files/g-2EDM_CDR-part.pdf]

Prospects of muon g-2 anomaly



[a slide by Teubner, KAERU conference]

Both of error of SM value and experimental value will be reduced in a few years.
Muon g-2 anomaly may becomes more significant within a few years....

1. Introduction (Muon g-2 anomaly)

2. **Review on two Higgs doublet model**

3. Constraints on type-X (lepton-specific) THDM

4. Impact on Higgs physics

New physics?

$$\delta a_\mu = (26.1 \pm 8.0) \times 10^{-10}$$ [Hagiwara et. al.]

Naïve contribution of new one-loop diagram:

$$\delta a_\mu \sim \frac{\alpha}{4\pi}\frac{m_\mu^2}{M^2} \sim 20 \times 10^{-10} \times \frac{\alpha}{\alpha_2}\left(\frac{M}{100\ \mathrm{GeV}}\right)^{-2}$$

- Sizable coupling
- Electroweak scale
    - Two Higgs doublet model
    - MSSM
    - …

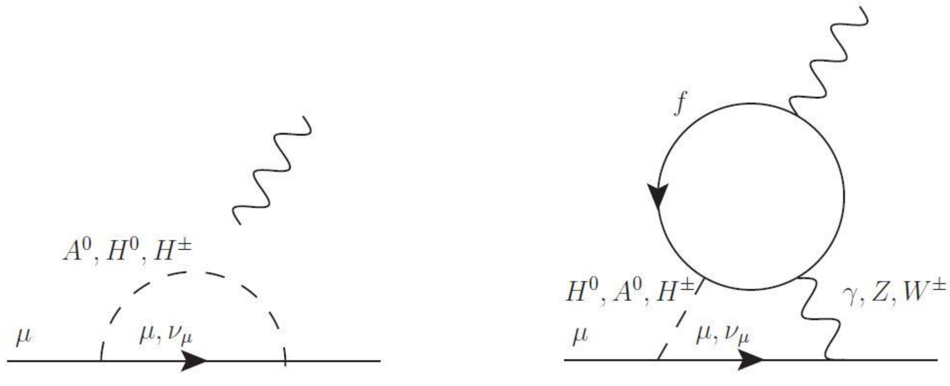
- Small coupling
- Small mass
    - Heavy photon
    - …

Two Higgs doublet model

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

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

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



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

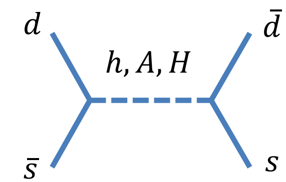
Two-loop Barr-Zee type diagram with A^0 is important to explain muon g-2 anomaly.
Large $A^0\bar{\ell}\gamma^5\ell$ coupling is important.

Two Higgs doublet model and FCNC

$$L \ni y_{d,1} H_1 q_L d_R^c + y_{d,2} H_2 q_L d_R^c \quad \Rightarrow \quad m_d = y_{d,1}\langle H_1 \rangle + y_{d,2}\langle H_2 \rangle$$

In general, $y_{d,1}$ and $y_{d,2}$ has off-diagonal components in a basis with diagonal m_d.
This is severely constrained.

ex) K^0-$\overline{K^0}$ mixing



Simple solution to prevent tree-level FCNC:

- Either $y_{d,1}$ or $y_{d,2}$ are taken as 0 (assuming Z2 parity)

ex) Z2 even : H_1, q_L, d_R^c
Z2 odd : H_2

$\Rightarrow \quad y_{d,1} \neq 0, \qquad y_{d,2} = 0$

This Z2 parity can be softly broken by Higgs potential and Higgs VEV.

Similar condition should be imposed for up-type quarks and leptons.

Two Higgs doublet model with Z2

We have four choices of the structure of Yukawa coupling.

$(y_{u,1} = 0 \text{ or } y_{u,2} = 0)$ and $(y_{d,1} = 0 \text{ or } y_{d,2} = 0)$ and $(y_{\ell,1} = 0 \text{ or } y_{\ell,2} = 0)$

Type-I : $L_{\text{yuk}} = -y_u \widetilde{H_2} q_L u_R^c + y_d H_2 q_L d_R^c + y_\ell H_2 \ell_L e_R^c$

Type-II : $L_{\text{yuk}} = -y_u \widetilde{H_2} q_L u_R^c + y_d H_1 q_L d_R^c + y_\ell H_1 \ell_L e_R^c$

Type-X (lepton-specific) : $L_{\text{yuk}} = -y_u \widetilde{H_2} q_L u_R^c + y_d H_2 q_L d_R^c + y_\ell H_1 \ell_L e_R^c$

Type-Y (flipped) : $L_{\text{yuk}} = -y_u \widetilde{H_2} q_L u_R^c + y_d H_1 q_L d_R^c + y_\ell H_2 \ell_L e_R^c$

$(\widetilde{H} = i\sigma^2 H^*)$

The assignment of Z2 parity :

	H_1	H_2	u_R^c	d_R^c	ℓ_R^c	Q_L, L_L
Type-I	$+$	$-$	$-$	$-$	$-$	$+$
Type-II	$+$	$-$	$-$	$+$	$+$	$+$
Type-X	$+$	$-$	$-$	$-$	$+$	$+$
Type-Y	$+$	$-$	$-$	$+$	$-$	$+$

Two Higgs doublet model with Z2

We have four choices of the structure of Yukawa coupling.

$(y_{u,1} = 0 \ \text{or} \ y_{u,2} = 0) \quad \text{and} \quad (y_{d,1} = 0 \ \text{or} \ y_{d,2} = 0) \quad \text{and} \quad (y_{\ell,1} = 0 \ \text{or} \ y_{\ell,2} = 0)$

Type-I : $L_{\rm yuk} = -\frac{\sqrt{2}m_u}{v\sin\beta}\widetilde{H_2}q_L u_R^c + \frac{\sqrt{2}m_d}{v\sin\beta}H_2 q_L d_R^c + \frac{\sqrt{2}m_\ell}{v\sin\beta}H_2 \ell_L e_R^c$

Type-II : $L_{\rm yuk} = -\frac{\sqrt{2}m_u}{v\sin\beta}\widetilde{H_2}q_L u_R^c + \frac{\sqrt{2}m_d}{v\cos\beta}H_1 q_L d_R^c + \frac{\sqrt{2}m_\ell}{v\cos\beta}H_1 \ell_L e_R^c$

Type-X (lepton-specific) : $L_{\rm yuk} = -\frac{\sqrt{2}m_u}{v\sin\beta}\widetilde{H_2}q_L u_R^c + \frac{\sqrt{2}m_d}{v\sin\beta}H_2 q_L d_R^c + \frac{\sqrt{2}m_\ell}{v\cos\beta}H_1 \ell_L e_R^c$

Type-Y (flipped) : $L_{\rm yuk} = -\frac{\sqrt{2}m_u}{v\sin\beta}\widetilde{H_2}q_L u_R^c + \frac{\sqrt{2}m_d}{v\cos\beta}H_1 q_L d_R^c + \frac{\sqrt{2}m_\ell}{v\sin\beta}H_2 \ell_L e_R^c$

$$\langle H_1\rangle = \frac{1}{\sqrt{2}}v\cos\beta$$
$$\langle H_2\rangle = \frac{1}{\sqrt{2}}v\sin\beta$$

$A^0\bar{f}\gamma^5 f$ Coupling

$$H_i = \begin{pmatrix} h_i^+ \\ (v_i + h_i - i a_i)/\sqrt{2} \end{pmatrix}, \qquad i = 1,2$$

$$\begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} G^0 \\ A^0 \end{pmatrix}$$

$A^0\bar{f}\gamma^5 f$ coupling is determined by $\tan\beta \equiv v_2/v_1$ and m_f.

Type-I : $L_{\text{yuk}} \ni -\frac{m_u}{v\tan\beta} iA^0\bar{u}\gamma^5 u + \frac{m_d}{v\tan\beta} iA^0\bar{d}\gamma^5 d + \frac{m_\ell}{v\tan\beta} iA^0\bar{\ell}\gamma^5 \ell$

Type-II : $L_{\text{yuk}} \ni -\frac{m_u}{v\tan\beta} iA^0\bar{u}\gamma^5 u + \frac{m_d\tan\beta}{v} iA^0\bar{d}\gamma^5 d + \frac{m_\ell\tan\beta}{v} iA^0\bar{\ell}\gamma^5 \ell$

Type-X (lepton-specific) : $L_{\text{yuk}} \ni -\frac{m_u}{v\tan\beta} iA^0\bar{u}\gamma^5 u + \frac{m_d}{v\tan\beta} iA^0\bar{d}\gamma^5 d + \frac{m_\ell\tan\beta}{v} iA^0\bar{\ell}\gamma^5 \ell$

Type-Y (flipped) : $L_{\text{yuk}} \ni -\frac{m_u}{v\tan\beta} iA^0\bar{u}\gamma^5 u + \frac{m_d\tan\beta}{v} iA^0\bar{d}\gamma^5 d + \frac{m_\ell}{v\tan\beta} iA^0\bar{\ell}\gamma^5 \ell$

To explain muon g-2 anomaly, Large $A^0\bar{\ell}\gamma^5\ell$ couping is required.

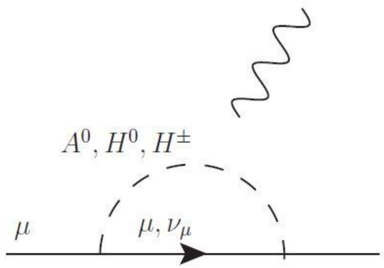
- $\tan\beta \ll 1$ in type-I/Y $\quad \rightarrow \quad$ Non-perturbative $A^0\bar{t}\gamma^5 t$ couping
- **$\tan\beta \gg 1$ in type-II/X**

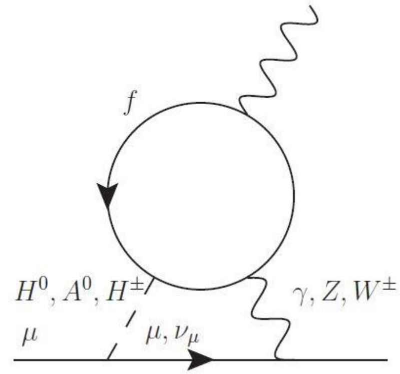
Type-II & X two Higgs doublet model

To explain muon g-2 anomaly:

- $m_A \sim O(10)$ GeV
- Large $\tan\beta$

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



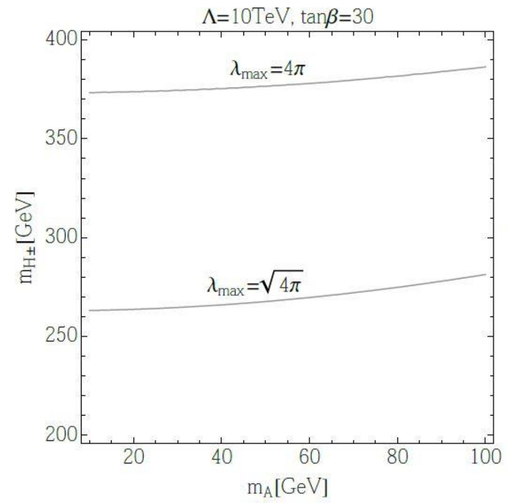


Large m_H or $m_{H^\pm}$ requires large λ's

[Broggino, Chun, Passera, Patel, Vempati (2014)]

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

$$V_{\text{Higgs}} \ni \lambda_4 |H_1^* H_2|^2 + \left(\frac{\lambda_5}{2}(H_1^* H_2)^2 + h.c.\right)$$



No Landau pole up to 10 TeV $\Rightarrow$ $m_{H^\pm}, m_H < 350$ GeV

Bound on Type-II two higgs doublet model

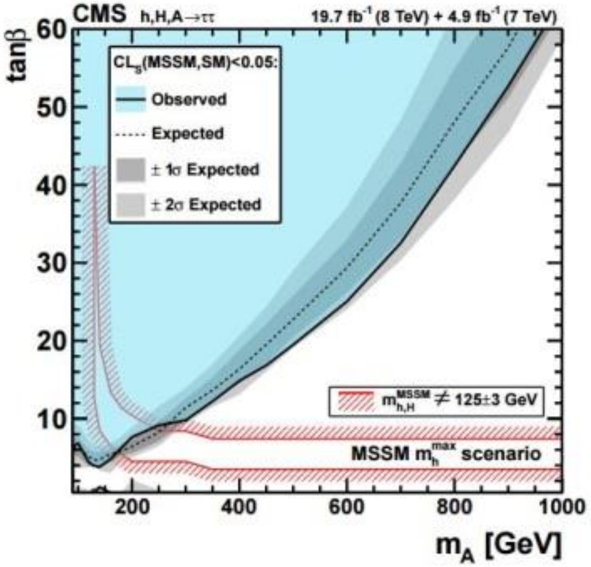
Type-II is severely constrained.

$m_{H^+} \leq 380$GeV is excluded by $b \to s\gamma$ measurement.

[Hermann, Misiak, Steinhauser (2012)]

To obtain $m_A = O(10)\ \mathrm{GeV}$, Landau pole appears at very low scale.

Direct search is also severe.



Type-X is the most favorable one to explain muon g-2 anomaly.

1. Introduction (Muon g-2 anomaly)

2. Review on two Higgs doublet model

3. Constraints on type-X (lepton-specific) THDM

4. Impact on Higgs physics

Type-X (lepton-specific) THDM

$$L_{\text{yuk}} = -Y_u \widetilde{H_2} q_L u_R^c + Y_d H_2 q_L d_R^c + Y_\ell H_1 \ell_L e_R^c$$

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

(Z2 parity is softly broken in m_{12}^2.)

Yukawa coupling of $A^0, H^0, H^\pm$ with SM leptons are enhanced by $\tan\beta$,
But coupling with SM quarks are suppressed by $\cot\beta$.

- Constraints from hadron physics (B physics etc.) is weak
- Direct production at the LHC is pair production via EW interactions.

Type-X THDM is less constrained.

Important constraints on type-X 2HDM

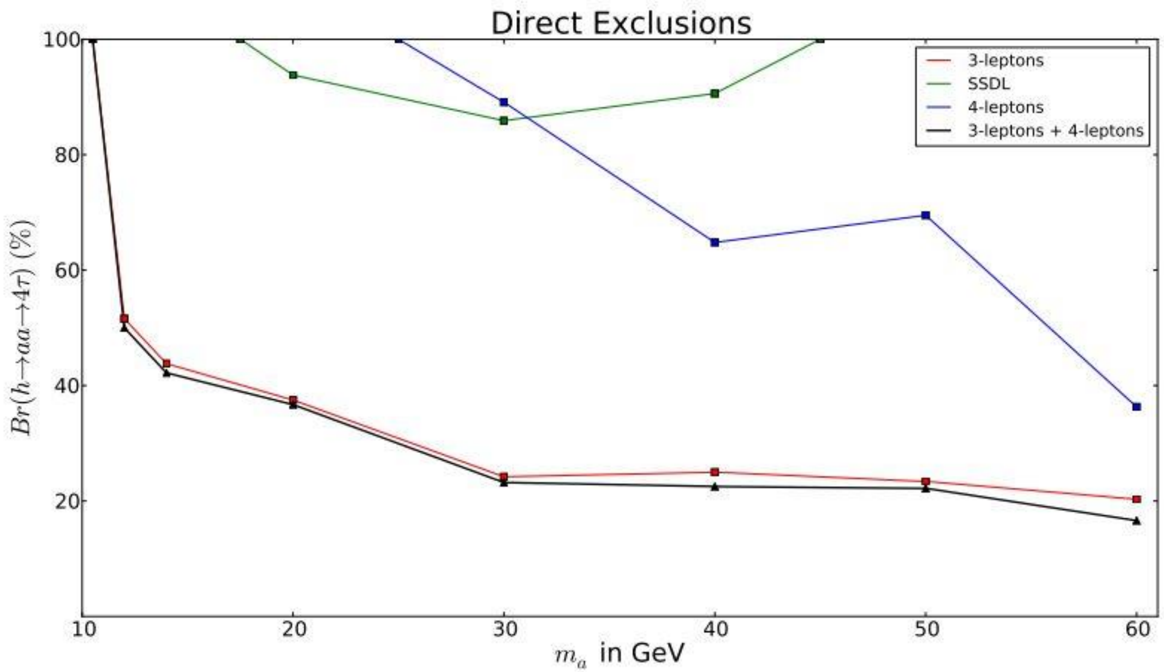
We need $m_A = O(10)\mathrm{GeV},\ \ \tan\beta = O(10)$

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

- LEP search ($e^+ \ e^- \to \tau\tau A^0$)
- Electroweak precision ($Z \to \tau\tau$, T parameter)
- $B_s \to \mu^+\mu^-$
- $h \to A^0 A^0 \to 4\tau$
- Decay of tau lepton (lepton universality)

$h \to A^0 A^0 \to 4\tau$

- If $m_A < m_h/2$, we have to care about $h \to A^0 A^0$
- Main decay mode of A^0 is $A^0 \to \tau\tau$



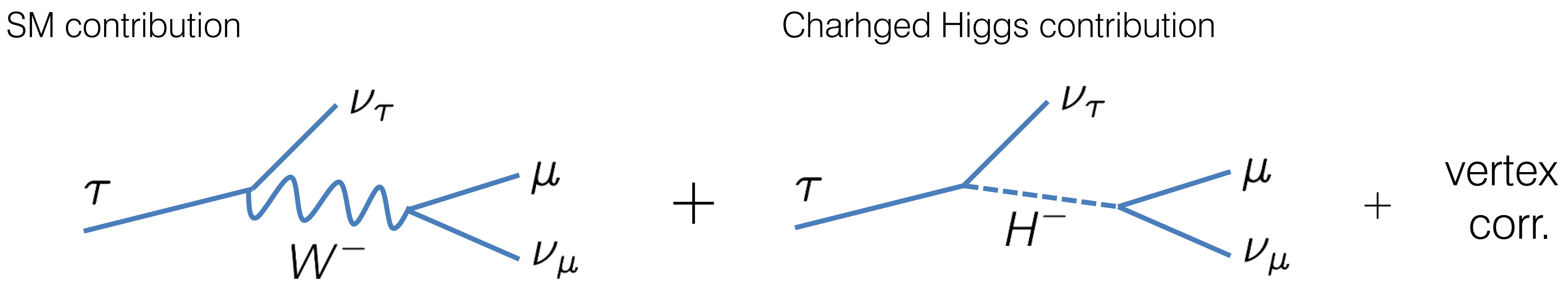
[Cutrin et al (2013)]

$\mathrm{Br}(h \to A^0 A^0) < 0.2$ ⇨ $\lambda_{hAA} < 6.7 \times 10^{-3}$, where $L \ni \lambda_{hAA} v\, h A^0 A^0$

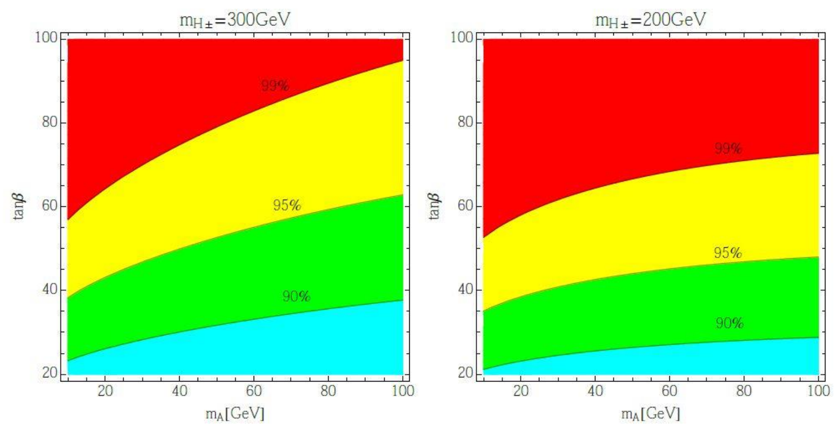
We take $\lambda_{hAA} = 0$. (In the case of large $\tan\beta$, $\lambda_{hAA} \simeq \lambda_3 + \lambda_4 - \lambda_5$)

Constraints from decay of τ

[Krawczyk, Temes (2004)]
[Logan, MacLennan, (2009)]

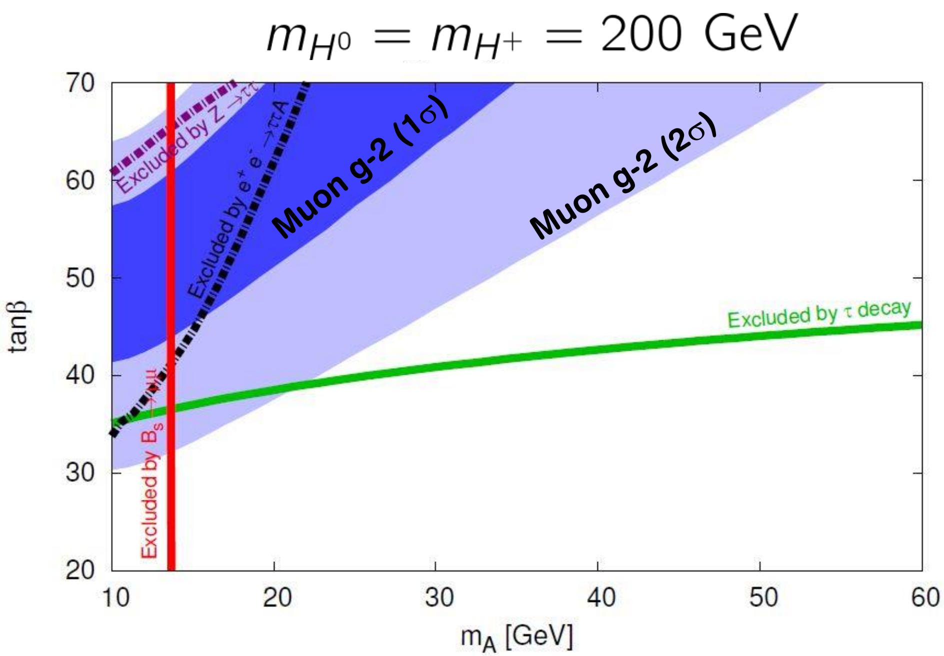


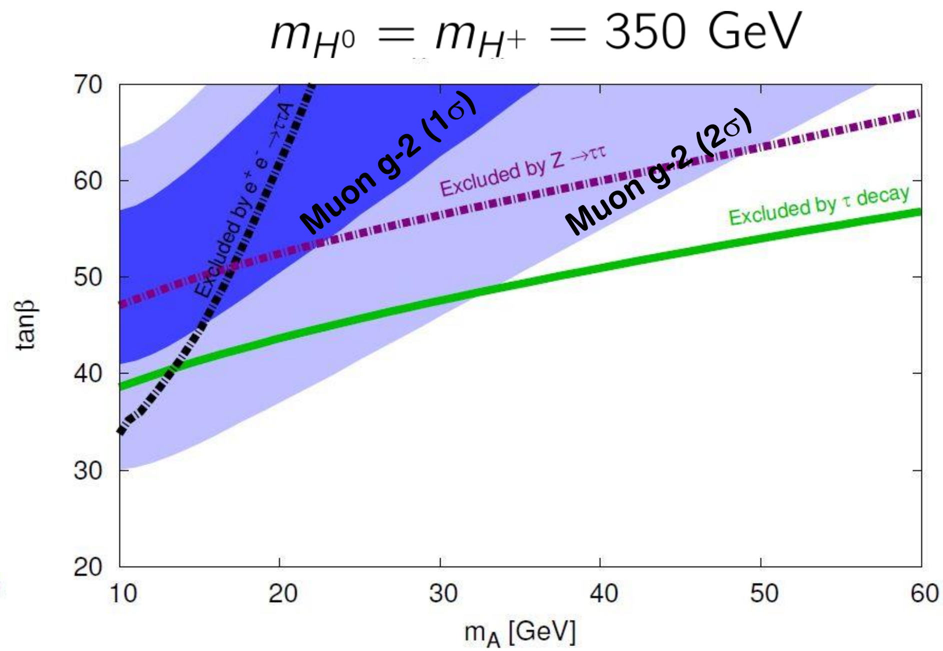
- Partial decay width (branching fraction)
- Momentum and angular distribution of decay products (Michel parameter)



- Partial decay width (branching fraction)
- Severe constraint on $m_{H^\pm} \sim 200\text{-}400$ GeV and $\tan\beta = O(10)$

Muon g-2 versus constraints





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

Smaller m_{H^+} → constrainted by lepton universality test (decay of tau lepton)

Larger m_{H^+} → constrained by triviality bound (perturbativity of quartic coupling)

1σ region is excluded by τ lepton decay.
2σ region is within reach of near future experiment (Higgs physics etc.).

1. **Introduction** (Muon g-2 anomaly)

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3. **Constraints on type-X** (lepton-specific) **THDM**

4. **Impact on Higgs physics**

Impacts on Higgs physics

Type-X THDM with $m_A = O(10)\ \mathrm{GeV}$ and large $\tan\beta$.

- $m_A = O(10)\ \mathrm{GeV}$
- $m_H, m_{H^\pm} = 200\text{-}350\ \mathrm{GeV}$
- large $\tan\beta$.

⇨

- Non-decoupling effect
- Decay mode including A^0

Significant impact on Higgs phyiscs.
This scenario can be discovered / completely excluded in near future.

- $h \to \tau\tau$
- $h \to \gamma\gamma$
- $h \to ZA^0$

$h \to \tau\tau$

$L \ni y_{h\tau\tau} h\bar{\tau}\tau$ $\Rightarrow$ $\kappa_\ell \equiv \dfrac{y_{h\ell\ell}}{y_{h\ell\ell,\mathrm{SM}}} \simeq -1 - \dfrac{m_h^2}{m_H^2} + \dfrac{2m_A^2}{m_H^2}$

- Opposite sign of $y_{h\ell\ell}$
- Enhancement of $|y_{h\ell\ell}|$

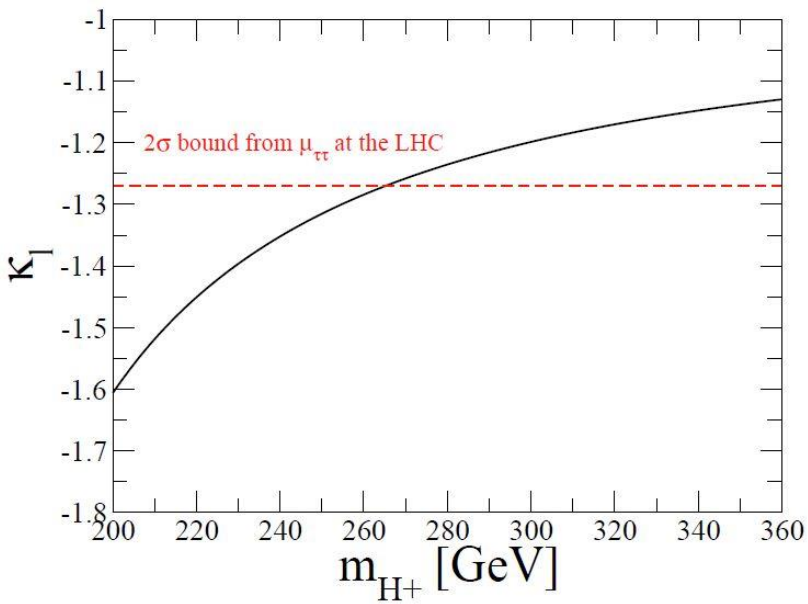
$\mu = 1.43^{+0.43}_{-0.37}$ (ATLAS)
$\mu = 0.91 \pm 0.28$ (CMS)

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

$\mu = 1.08 \pm 0.23$

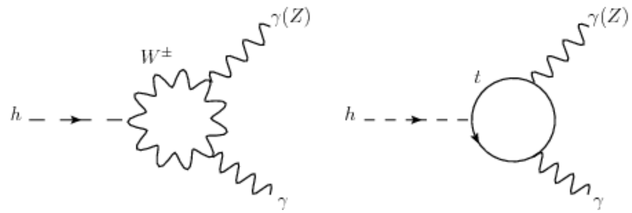
$\mu \simeq \kappa^2$ $\Downarrow$

$|\kappa_\ell| < 1.27$ at 95% C.L.



- Large $|y_{h\ell\ell}|$ has a tension with CMS, but favored by ATLAS.
- The region with $m_{H^+} < 270\ \mathrm{GeV}$ is excluded by naïve combination of ATLAS and CMS.

$h \to \gamma\gamma$



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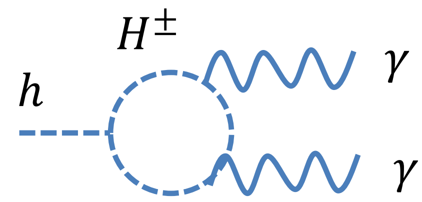
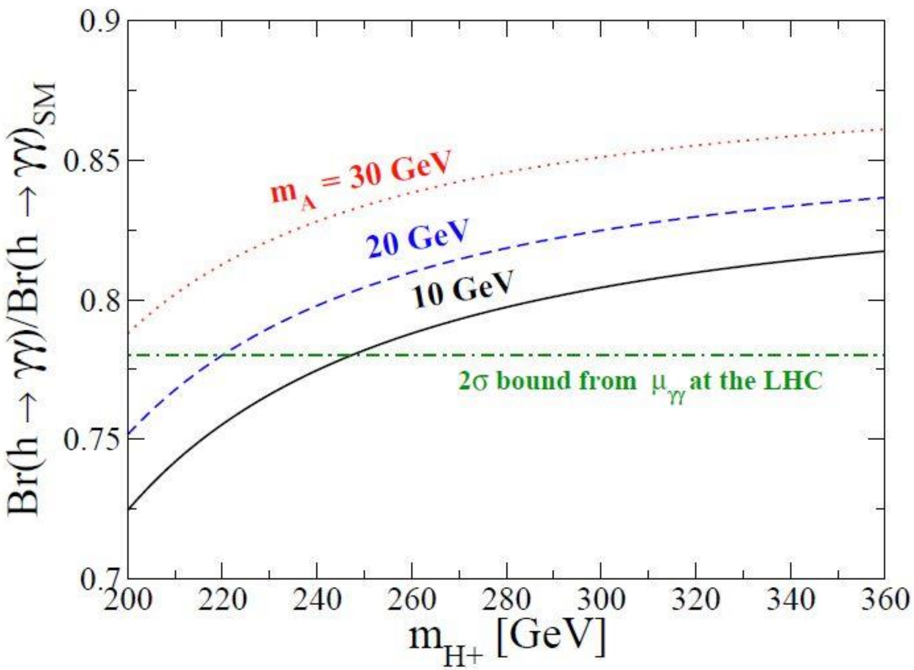


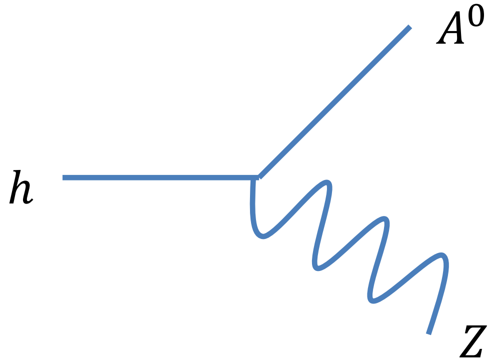
$\mu = 1.17 \pm 0.27$ [1408.7084, ATLAS]
$\mu = 1.12 \pm 0.24$ [CMS-PAS-HIG-14-009]

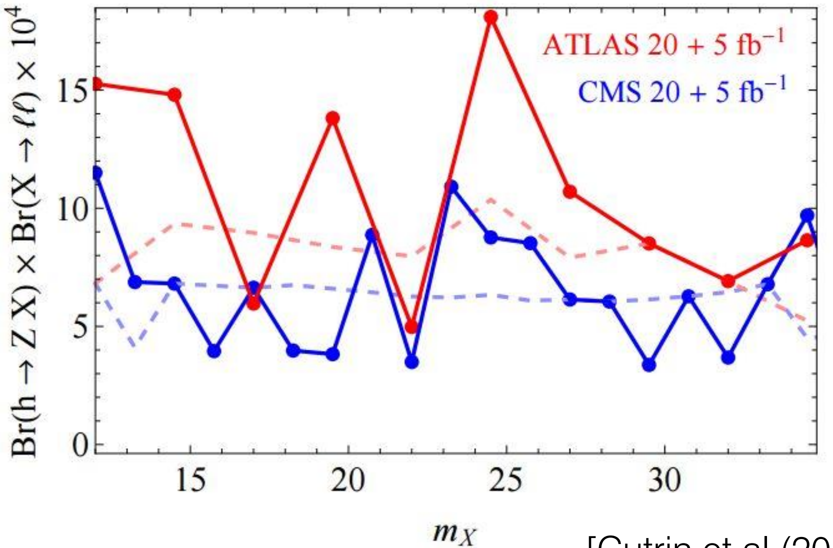
$\mu = 1.14 \pm 0.18$



Its constraint is weaker than $\tau\tau$-channel,
But a region with $m_{H^+} \sim 200\ \mathrm{GeV}$ is constrained.

$h \to ZA^0 \to Z\ell\ell$





[Cutrin et al (2013)]

$$\mathrm{Br}(h \to ZA) \times \mathrm{Br}(A \to \mu\mu) \; < \; 5\text{-}10 \times 10^{-4}$$

$$\mathrm{Br}(A \to \mu\mu) = \left(\frac{m_\mu}{m_\tau}\right)^2 = 0.036$$

$$\Rightarrow \quad \mathrm{Br}(h \to ZA) \; < 0.14\text{-}0.28$$

The current constraint is not so strong,
But four-lepton mode will constrain this model.

Summary

Type-X (Lepton-specific) Two Higgs doublet model is discussed
in the context of muon g-2 anomaly.

tau leptonic decay of tau excludes the region to explain muon g-2 anomaly
within 1σ level.

2σ region is within the reach of near future experiment.

- m_A $\sim$ 10-30 GeV
- m_H, m_{H^+} $\sim$ 200-350 GeV
- $\tan\beta$ $\sim$ 30-50

- O(10-100) % enhancement of $\tau\tau$ channel
- Branching fraction of $h \to ZA^0$ is a few percent for $m_A = 20\ \mathrm{GeV}$.

A. Backup slides

$h \to A^0 A^0 \to 4\tau$ and T-parameter

8 parameteres in Higgs potential :

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

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

$\Downarrow$

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, $\dfrac{g_{hWW}}{g_{hWW,SM}} - 1 = \mathcal{O}(\tan^{-2}\beta)$

λ_1 is almost irrelevant with phenomenology for large tanbeta.

Parameters of the Higgs sector

$\tan\beta \gg 1$

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

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

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

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

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

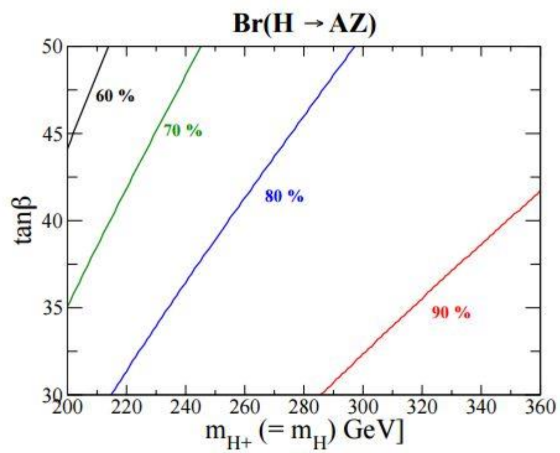
$$m_{H^\pm}^2 \sim m_{11}^2 + \frac{1}{2}\lambda_3 v^2$$

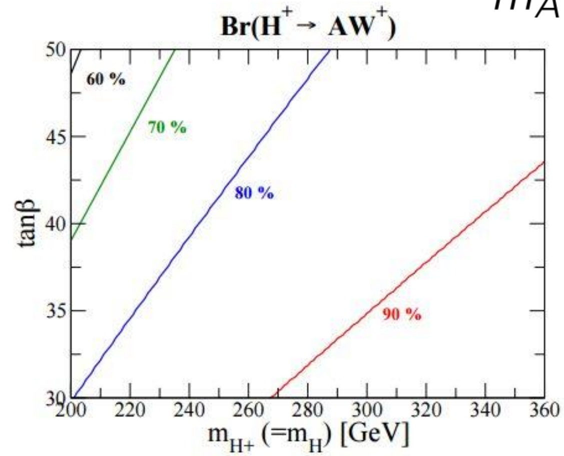
$$m_H^2 \sim m_{11}^2 + \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)v^2$$

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

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.

Yukawa interaction of THDM

Generic Yukawa interaction in THDM induce tree-level FCNC process.

	H_1	H_2	u_R^c	d_R^c	ℓ_R^c	Q_L, L_L	ξ_u	ξ_d	ξ_ℓ
Type-I	$+$	$-$	$-$	$-$	$-$	$+$	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type-II	$+$	$-$	$-$	$+$	$+$	$+$	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type-X	$+$	$-$	$-$	$-$	$+$	$+$	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type-Y	$+$	$-$	$-$	$+$	$-$	$+$	$\cot\beta$	$-\tan\beta$	$\cot\beta$

$$\begin{aligned}\mathcal{L}_{\text{Yukawa}} = &- \sum_{f=u,d,\ell} \frac{m_f}{v}\left(\xi_f^h\, h\bar{f}f + \xi_f^H\, H\bar{f}f - 2iT_f^3\xi_f\, A\bar{f}\gamma_5 f\right) \\ &+ \left[\sqrt{2}V_{ud}H^+\bar{u}\left(\frac{m_u\xi_u}{v}P_L - \frac{m_d\xi_d}{v}P_R\right)d - \frac{\sqrt{2}m_\ell\xi_\ell}{v}H^+\bar{\nu}P_R\ell + h.c.\right], \qquad (22)\end{aligned}$$

where $T_f^3 = +1/2\ (-1/2)$ for $f = u\ (d,\ell)$, and $V_{ff'}$ is the Cabibbo-Kobayashi-Maskawa matrix element. The ξ_f^h and ξ_f^H factors are defined by

$$\xi_f^h = s_{\beta-\alpha} + \xi_f c_{\beta-\alpha}, \quad \xi_f^H = c_{\beta-\alpha} - \xi_f s_{\beta-\alpha}. \qquad (23)$$

$$\mathcal{L}_{\text{Yukawa}} = -y_u\tilde{H}_u^T Q_L u_R^c - y_d H_d^\dagger Q_L d_R^c - y_\ell H_\ell^\dagger L_L e_R^c + h.c.,$$

example) Type-II two Higgs doublet model

$$\mathcal{L}_{\text{Yukawa}} = -y_u \tilde{H}_2 Q_L u_R^c \; + y_d H_1 Q_L d_R^c \; + y_\ell H_1 \ell_L e_R^c \; + h.c..$$

$$H_i = \begin{pmatrix} h_i^+ \\ (v_i + h_i - i a_i)/\sqrt{2} \end{pmatrix}$$

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

$$v_1^2 + v_2^2 = v^2 = (246\ \text{GeV})^2, \qquad \frac{v_2}{v_1} = \tan\beta$$

$$\begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} G^0 \\ A \end{pmatrix}$$

$$\begin{pmatrix} h_1^\pm \\ h_2^\pm \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix}$$

$$y_u = \frac{\sqrt{2m_u}}{v\sin\beta}, \quad y_d = \frac{\sqrt{2m_d}}{v\cos\beta}, \quad y_\ell = \frac{\sqrt{2m_u}}{v\cos\beta}$$

$$\mathcal{L}_{\text{Yukawa}} \supset \frac{im_u}{v}\frac{1}{\tan\beta}A^0\bar{u}\gamma^5 u \; - \frac{im_d}{v}\frac{1}{\tan\beta}A^0\bar{d}\gamma^5 d \; - \frac{im_\ell}{v}\tan\beta A^0\bar{\ell}\gamma^5\ell$$

For type-II THDM, Large $\tan\beta$ $(v_2 \gg v_1)$ induce large $A\ell\ell$ coupling.

Impacts on Higgs physics

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

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]

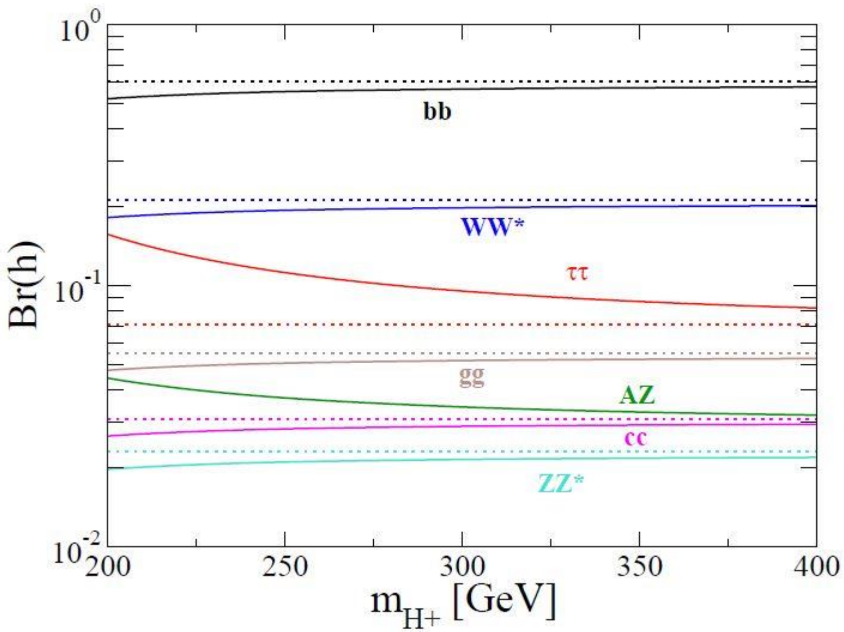
Exotic channel : $h^0 \to ZA$

- 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

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



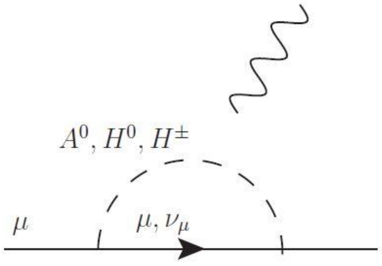
$m_A = 20$ GeV, $\tan\beta = 35$

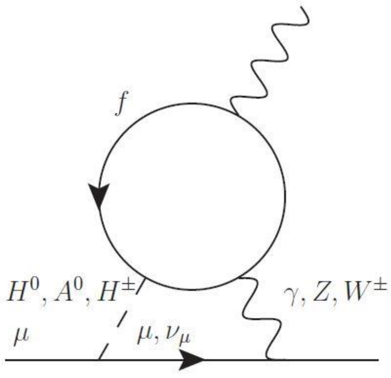
Type-II & X two Higgs doublet model

To explain muon g-2 anomaly:

- $m_A \sim O(10)$ GeV
- Large $\tan\beta$

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



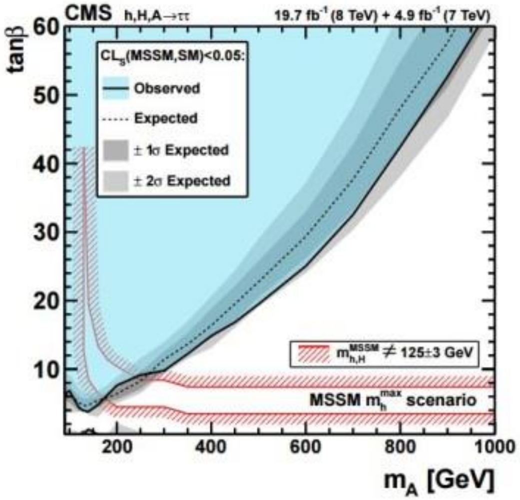


Type-II is severely constraint.

$m_{H^+} \leq 380$GeV is excluded by $b \to s\gamma$ measurement.

[Hermann, Misiak, Steinhauser (2012)]

Direct search is also severe.



Type-X is the most favorable one to explain muon g-2 anomaly.

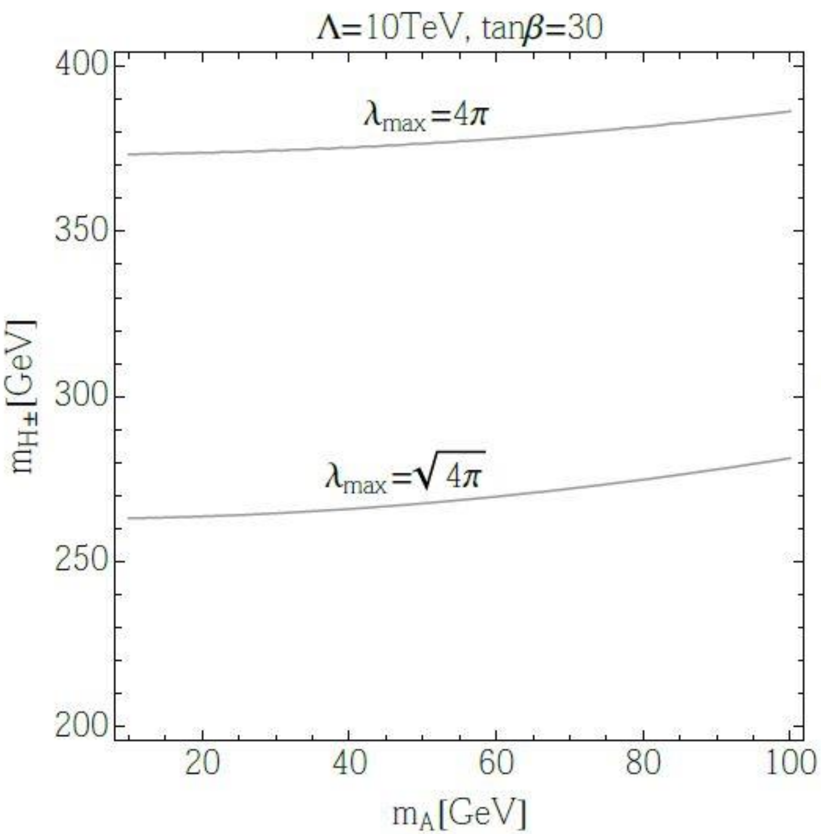
Triviality bound

We have upperbound on m_H and $m_{H^\pm}$

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

$$V_{\text{Higgs}} \ni \lambda_4 |H_1^* H_2|^2 + \left(\frac{\lambda_5}{2}(H_1^* H_2)^2 + h.c.\right)$$

In the case of small m_A,
Large $m_H, m_{H^\pm}$ means large λ's



For $m_A = O(10)\text{GeV}$ and there is no Landau pole up to $\mathbf{10\ TeV}$,
upper bound on charged (& heavier CP-even) Higgs mass : $m_{H^\pm} < 350\ \text{GeV}$

Custodial symmetry

$$H = \cos\beta\, H_1 + \sin\beta\, H_2$$
$$H' = -\sin\beta\, H_1 + \cos\beta\, H_2$$

$$\Big\Downarrow \quad \sin(\beta - \alpha) \simeq 1$$

$$H = \begin{pmatrix} G^+ \\ (v + h + iG^0)/\sqrt{2} \end{pmatrix},$$

$$H' = \begin{pmatrix} H^+ \\ (H^0 + iA^0)/\sqrt{2} \end{pmatrix}$$

- Custodial symmetry 1, $m_A = m_{H^+}$

  Triplet : $A^0, H^{\pm}$
  Singlet: H^0, h

- Custodial symmetry 2, $m_H = m_{H^+}$

  (Broken by $\sin(\beta - \alpha) - 1,\ 1/\tan\beta$)

  Triplet : $H^0, H^{\pm}$
  Singlet: A^0, h