Lepton-Specific two-Higgs doublet model as a solution of the muon g-2 anomaly

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KMI topics
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Success of the Standard Model

gauge symmetry

strong — electroweak

$SU(3)_c \times SU(2)_L \times U(1)_Y$

$SU(2)_L \times U(1)_Y \rightarrow U(1)_{QED}$

Higgs mechanism

Yukawa interaction

$$-\bar{q}^i_L \tilde{H} y^{ij}_u u^j_R - \bar{q}^i_L H y^{ij}_d d^j_R - \bar{\ell}^i_L H y^{ij}_e e^j_R$$

- ⋆ fermion mass
- ⋆ CKM matrix
- ⋆ CP violation

Higgs potential

$$V = \mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

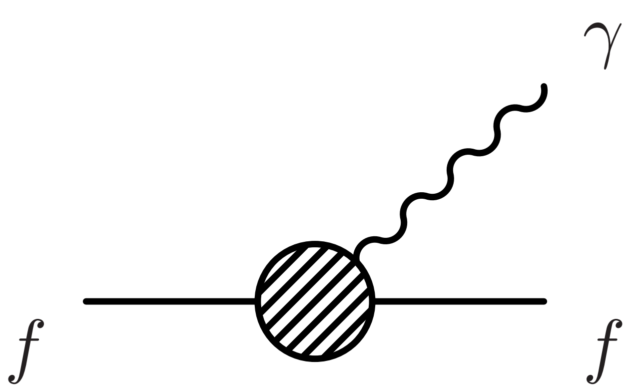
- ⋆ spontaneous symmetry breaking
- ⋆ Higgs mass

We need a model beyond the Standard Model

- **SM cannot explain that**
  - ★ dark matter
  - ★ baryon asymmetry (matter >> anti-matter in the universe)
  - ★ the origin of neutrino mass
  - ★ **muon g-2**
  - ★ …

Muon g-2

- **the property of muon as *a magnet***



$$i\mathcal{M} = -i\bar{u}_f e Q_f \left(F_1(q^2)\gamma^\mu + F_2(q^2) i \frac{\sigma^{\mu\nu} q_\nu}{2m_f} \right) u_f$$

$$a_f = \frac{g_f - 2}{2} = F_2(0)$$

- **Status: more than 3σ deviation**

$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (28.7 \pm 8.0) \times 10^{-10},$$ Davier et.al. (2011)

$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (26.1 \pm 8.0) \times 10^{-10},$$ Hagiwara et.al. (2011)

- **three interpretations:**
  - ★ error in experiments
  - ★ error in theoretical prediction
  - ★ ***new physics***

Muon g-2 and new physics scale

SM + dim. 6 operators

$$+\frac{c'}{(4\pi)^2}\frac{g'}{\Lambda'^2}\left(\bar{\ell}_L\sigma^{\mu\nu}He_R B_{\mu\nu}\right)-\frac{c}{(4\pi)^2}\frac{g}{\Lambda^2}\left(\bar{\ell}_L\sigma^{\mu\nu}W_{\mu\nu}He_R\right)+(h.c.)$$

$$\mathrm{Amp}\sim\bar{u}i\sigma^{\mu\nu}q_\nu\epsilon_\mu\frac{\delta a_\mu}{2m_\mu}u$$

$$\delta a_\mu=2m_\mu\frac{v}{\sqrt{2}}\frac{1}{(4\pi)^2}\left(2\frac{c'}{\Lambda'^2}+\frac{c}{\Lambda^2}\right)$$

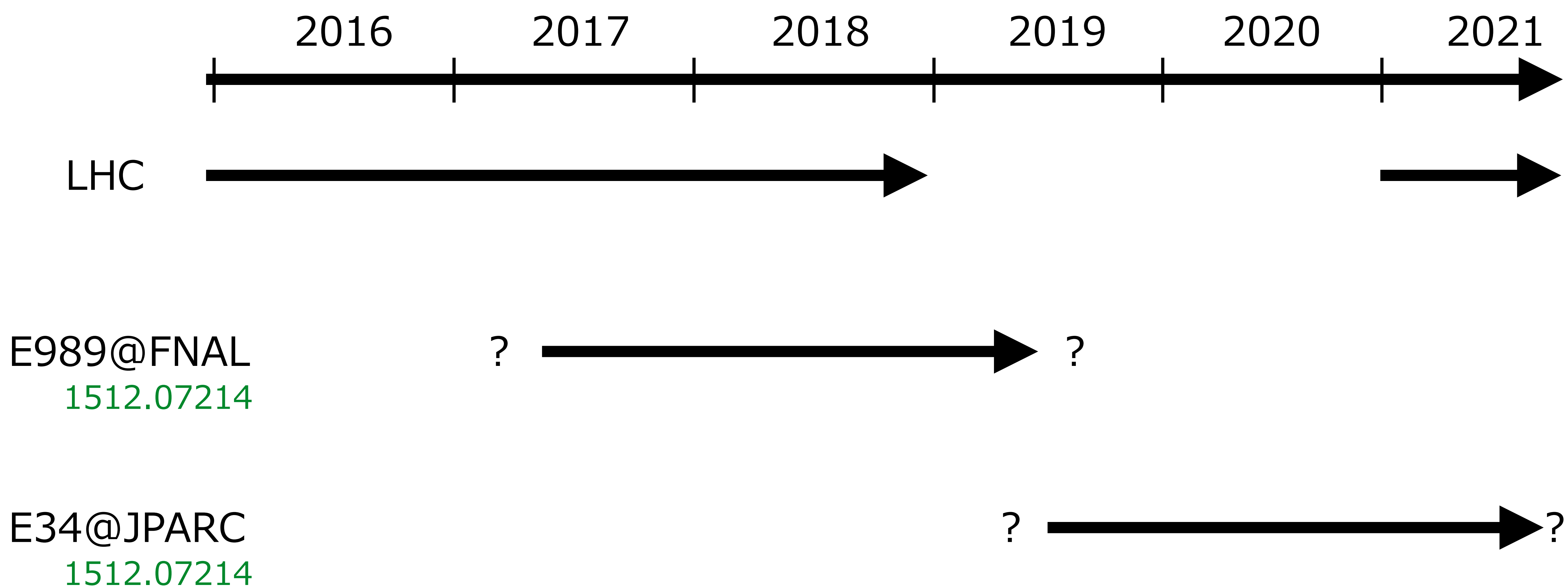
ex) c = 0

c’	1	0.1	0.01	0.001
Λ’[TeV]	13	4.2	1.3	0.42

strong expectation of the existence new physics

around TeV scale

exp. schedule



http://agenda.linearcollider.org/event/6772/contributions/33275/attachments/27394/41633/muon_g-2EDM_MS.pdf

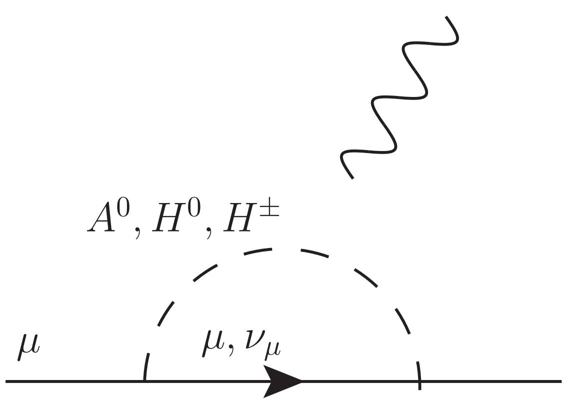
Now is the time for g-2

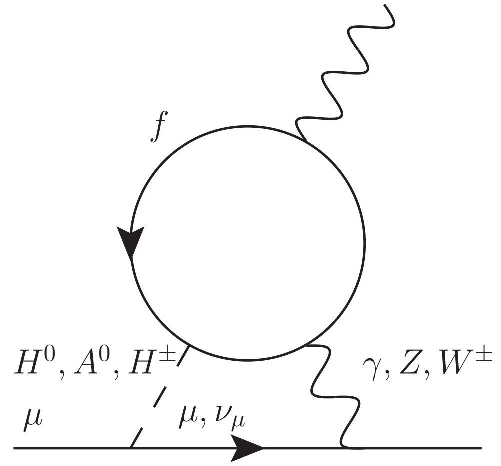
Muon g-2 and new physics

What kind of models are preferred?

- ⋆ new particle must coupling to lepton (muon)
- ⋆ simple model
- ⋆ verifiable model in the near future

two-Higgs doublet model

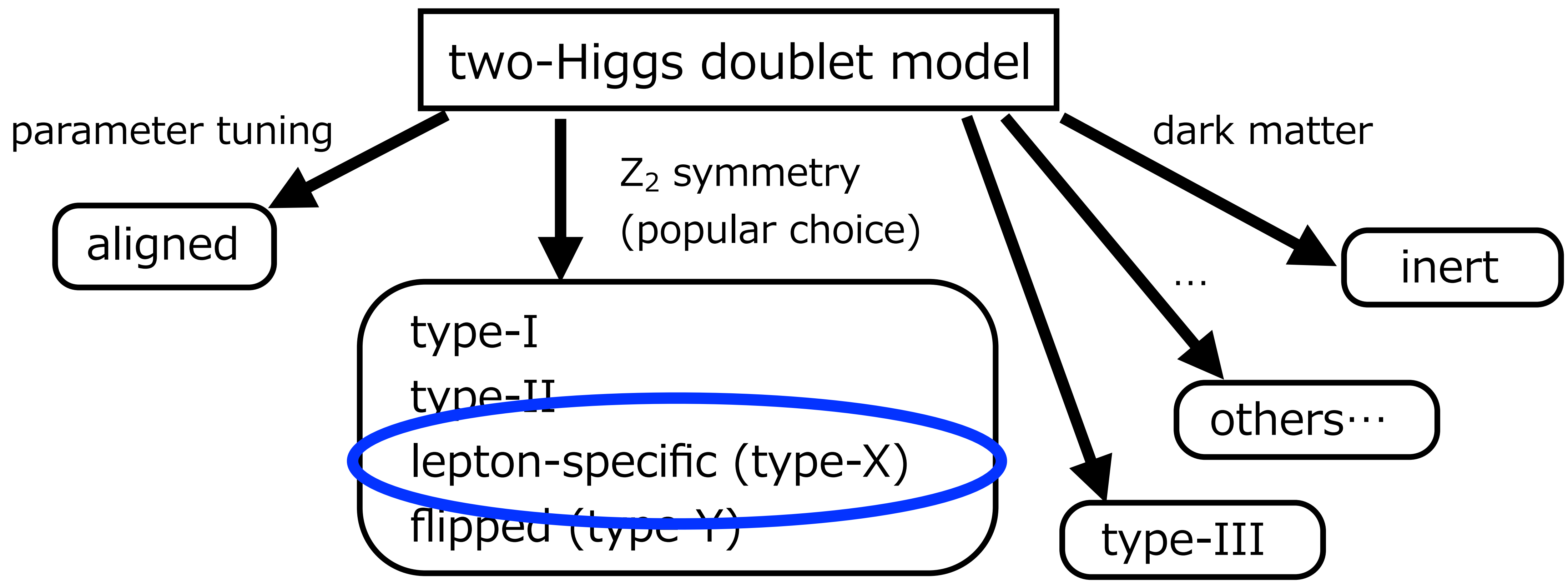




- ⋆ simple extension from SM
- ⋆ new scalar particles (H^0, A^0, $H^\pm$)
- ⋆ mass ~ O(10)- O(1000)GeV
- ⋆ large coupling to leptons
- ⋆ the great candidate for muon g-2!

two-Higgs doublet model

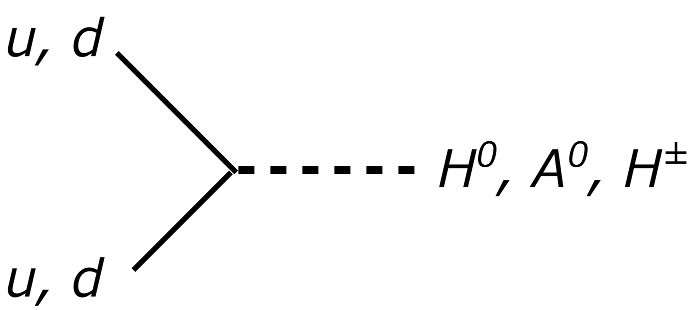
- "two-Higgs doublet model" = a set of many models
- Many models exist for different structure of Yukawa interactions
  - ★ different names for different models



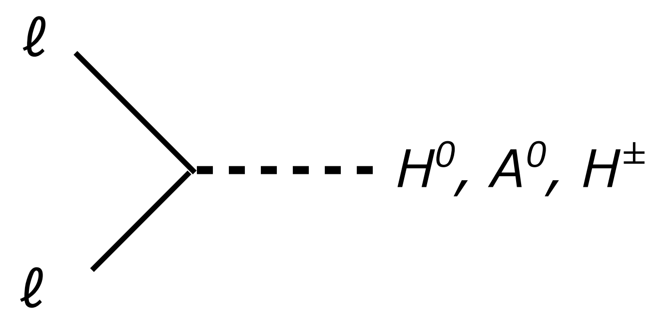
A viable model for muon g-2 !

lepton specific two-Higgs doublet model

- SM + one more Higgs doublet
- two Higgs : H_1 and H_2
  - ★ SM-like Higgs (h)
  - ★ new scalars (H^0, A^0, $H^\pm$)
- important parameter: **tanβ** ($1 < \tan\beta < 100$)
- the lepton Yukawa interactions are enhanced by tanβ



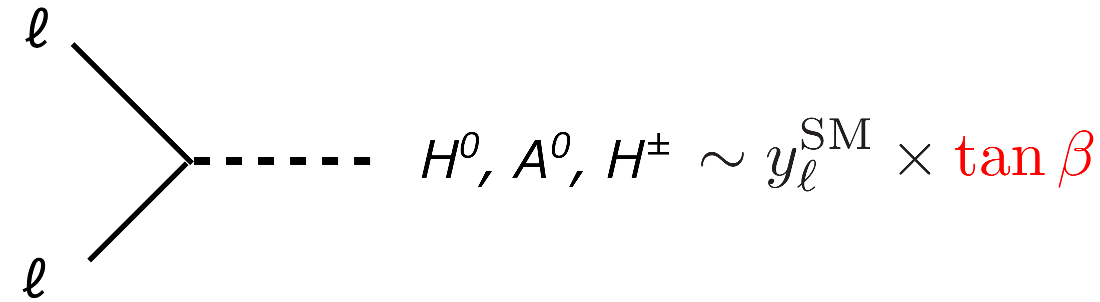
$$\sim y_{u,d}^{\mathrm{SM}} \times \frac{1}{\tan\beta}$$



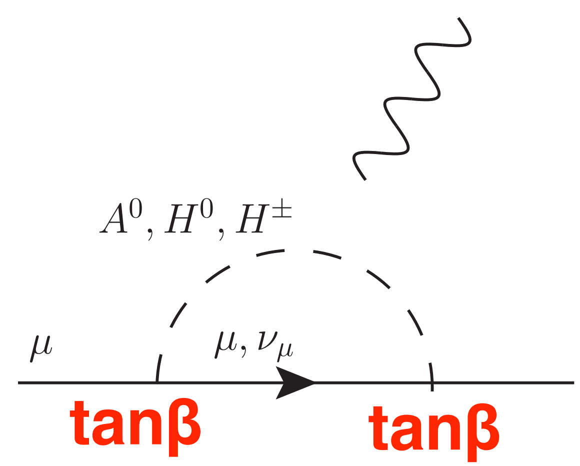
$$\sim y_{\ell}^{\mathrm{SM}} \times \tan\beta$$

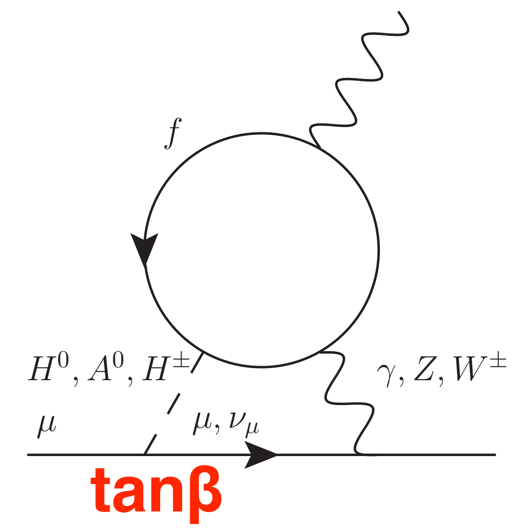
lepton physics

- new particles affect to all the physics with leptons



- **good point :** muon g-2

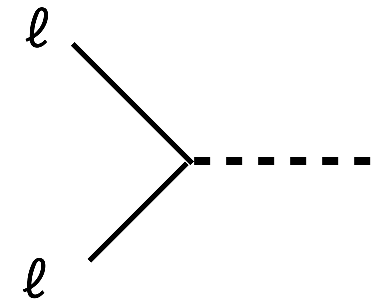




- **On the other hand,** constraints on the lepton couplings are important
  - ★ $Z \to \tau\tau$
  - ★ $Z \to \tau\tau A^0$
  - ★ $\tau \to \mu\nu_\tau\bar{\nu}_\mu, \ \tau \to e\nu_\tau\bar{\nu}_e$
    - ✳ Michel parameters
    - ✳ lepton coupling universality

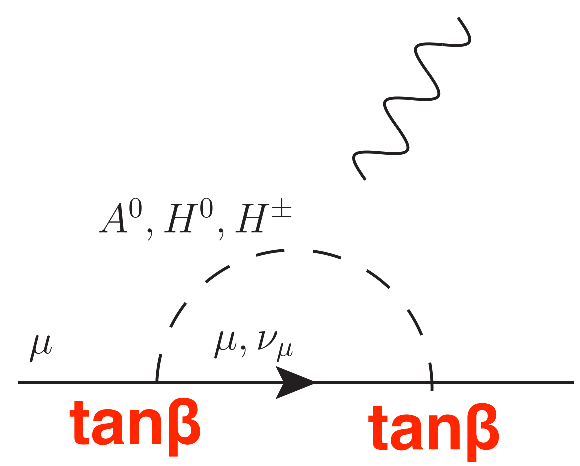
lepton physics

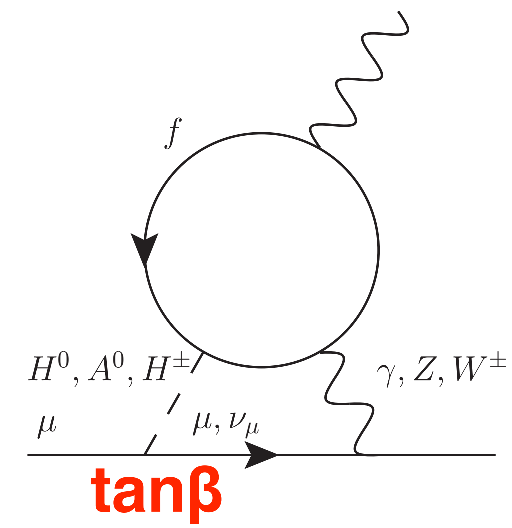
- new particles affect to all the physics with leptons



$H^0, A^0, H^\pm \sim y_\ell^{\rm SM} \times \tan\beta$

- **good point :** muon g-2





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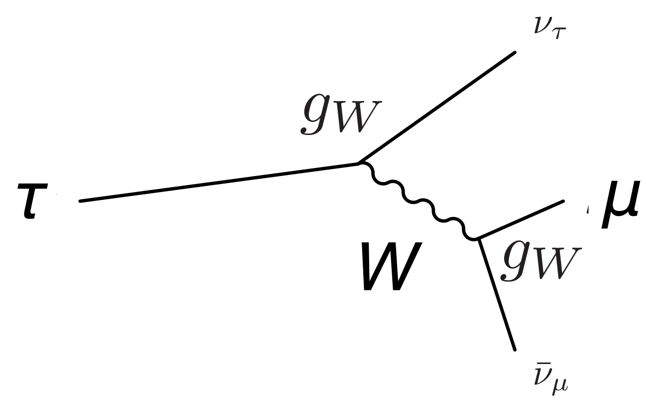
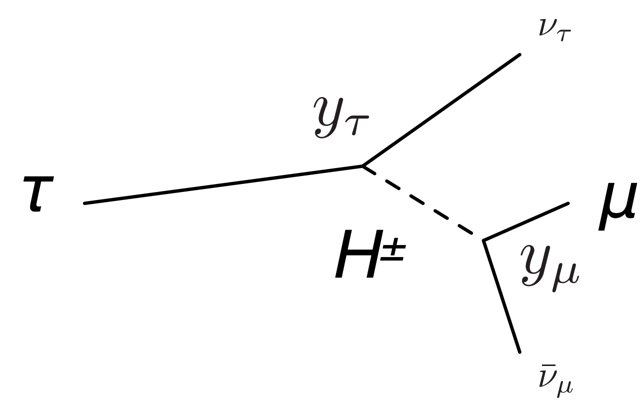
    - ✳ Michel parameters
    - ✳ **lepton coupling universality**

the most stringent bound

lepton β decays

- $H^{\pm}$ breaks lepton universality



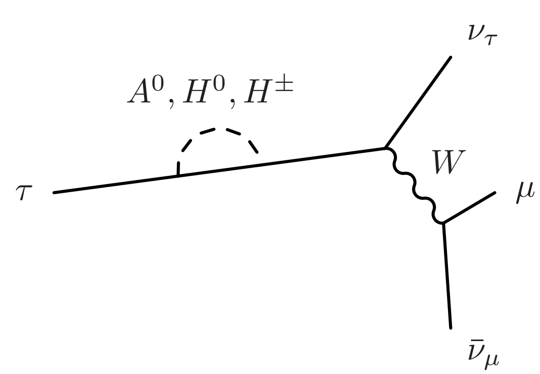


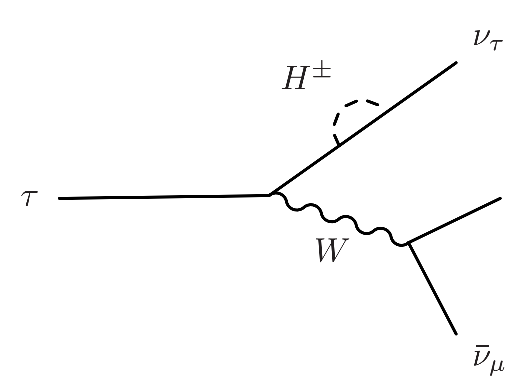
<u>flavor universal interaction</u>

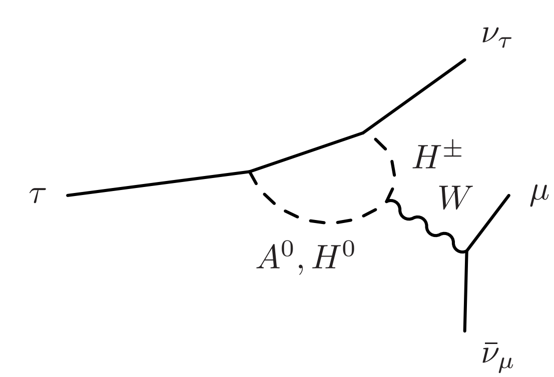
<u>flavor dependent interaction (Yukawa)</u>

- large contributions in τ→μνν process
- small contributions in μ→eνν process

- loop diagrams also there







constraint from lepton coupling universality

- define $G_{\mu\tau}$, $G_{e\tau}$, $G_{e\mu}$

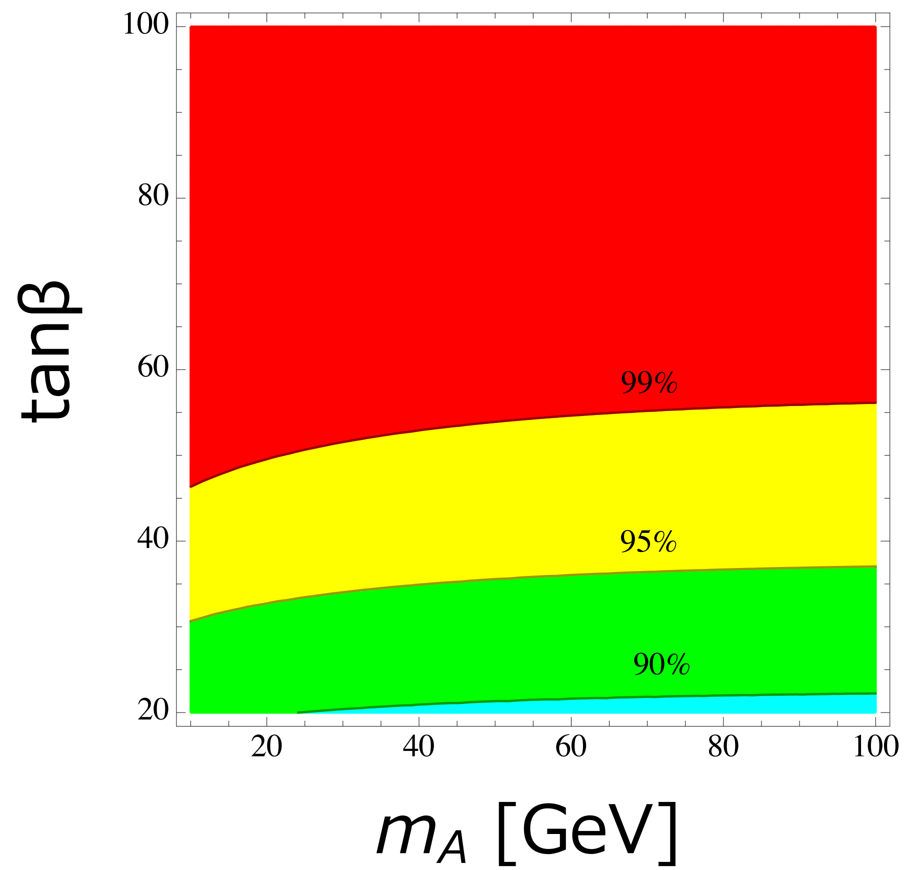
$$\left(\frac{G_{\mu\tau}}{G_F}\right)^2 \equiv \frac{\Gamma(\tau \to \mu\nu\nu)_{\rm 2HDM}}{\Gamma(\tau \to \mu\nu\nu)_{\rm SM}}$$

- constraints HFAG (1412.7515)

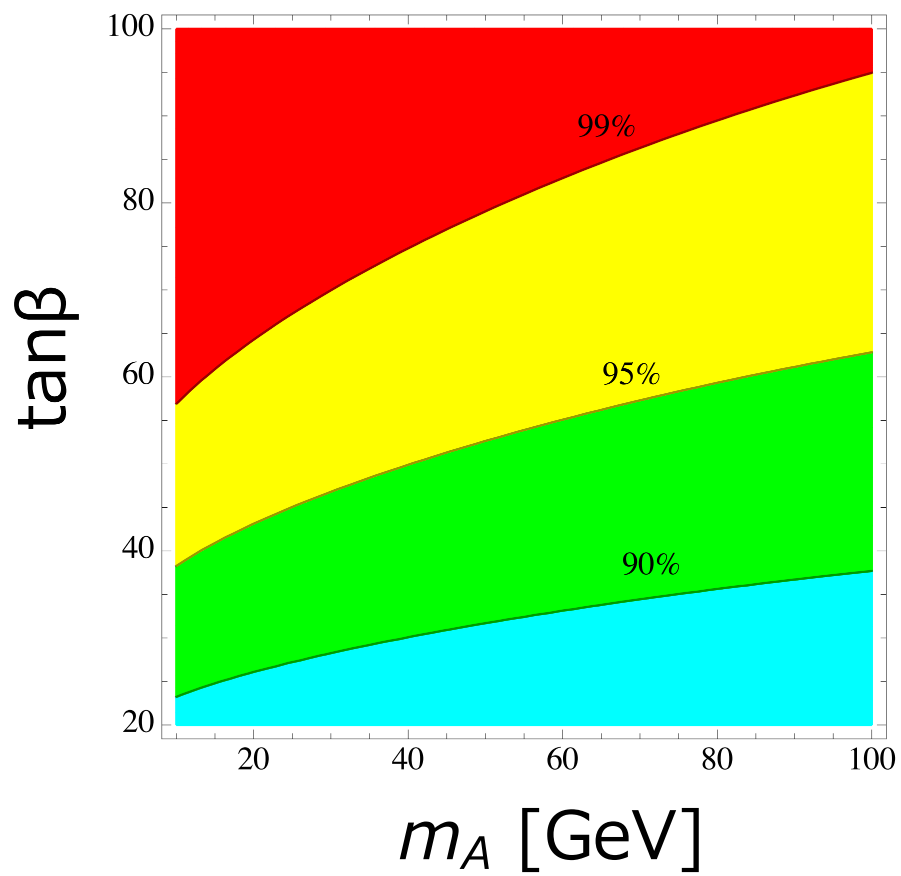
$$\frac{G_{\mu\tau}}{G_{e\mu}} = 1.0029 \pm 0.0015, \quad \frac{G_{\mu\tau}}{G_{e\tau}} = 1.0018 \pm 0.0014,$$

- we find severe constraint on **tanβ** (large **tanβ** is excluded!)

$m_{H\pm}$ = 150 GeV



$m_{H\pm}$ = 300 GeV



tanβ dilemma

new particle couplings to lepton is enhanced by tanβ

- **large tanβ** is better for muon g-2

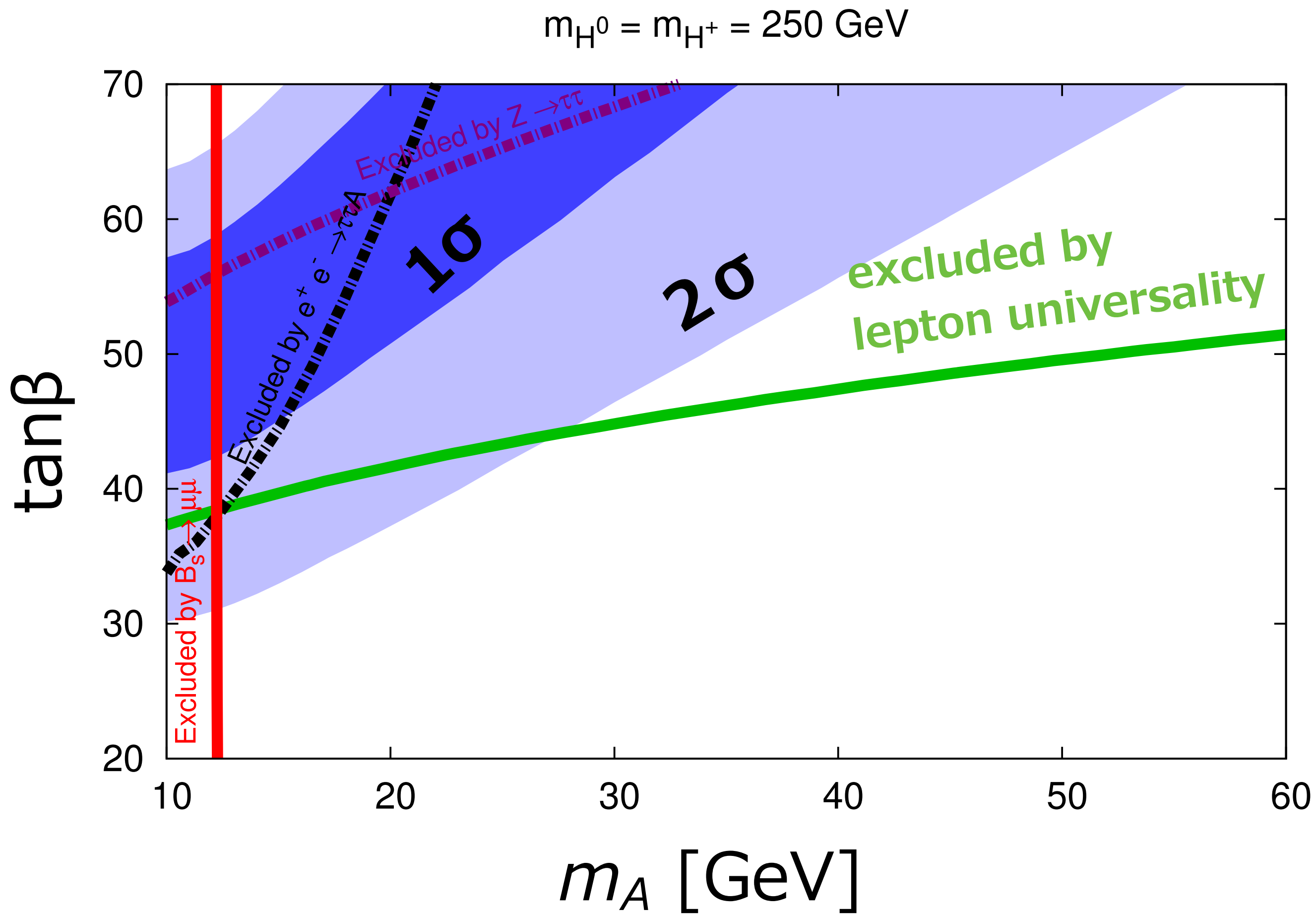
strong constraint from lepton coupling universality

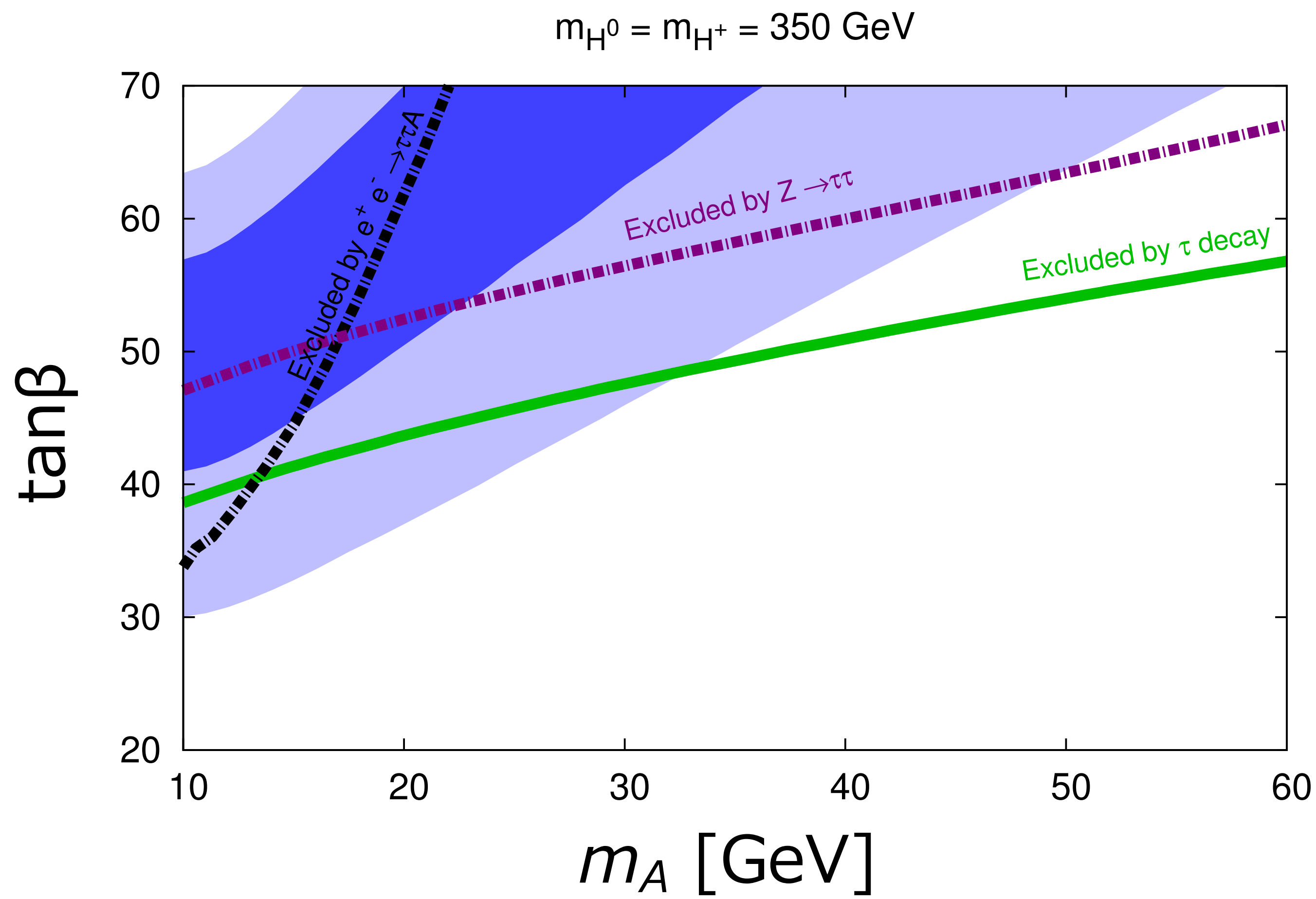
- **small tanβ** is required to avoid the constraint

- tanβ is in a dilemma between **g-2** and **lepton flavor universality**

- Is it possible to explain muon g-2 in this model?
  (→ see next slide !)

Result: g-2 with constraints



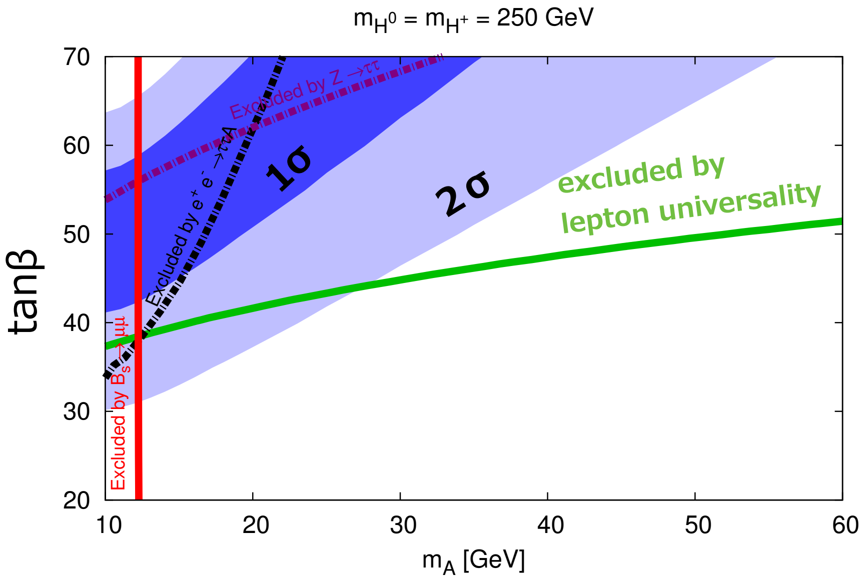


- **g-2 within 1σ region (dark blue)** is completely excluded!
- **g-2 within 2σ region (light blue)** is survive!
- constraint from **lepton universality** is strong.

short summary

- lepton specific two-Higgs doublet model can explain muon g-2 within 2σ

- **parameters for the muon g-2**
  - ★ 10 GeV < m_A < 30 GeV
  - ★ 250 GeV < $m_{H\pm}$ < 350 GeV
  - ★ $m_{H0} = m_{H\pm}$
  - ★ 30 < tanβ < 40

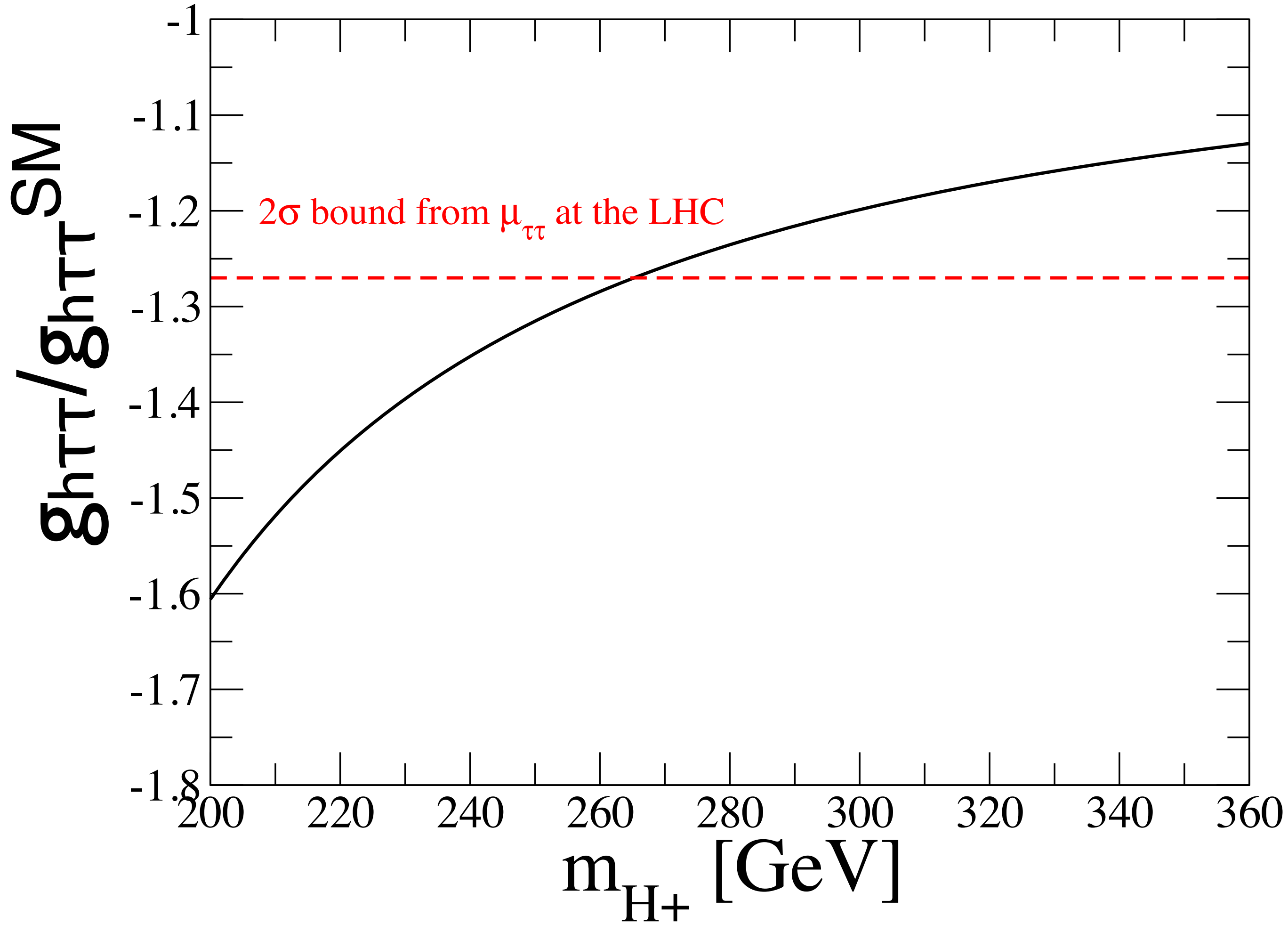


- **What else …?**
- **phenomenology at the LHC is a good complement**

Collider physics

h(125) couplings (1)

- **hττ** : ***more than 10% deviation*** from the SM prediction

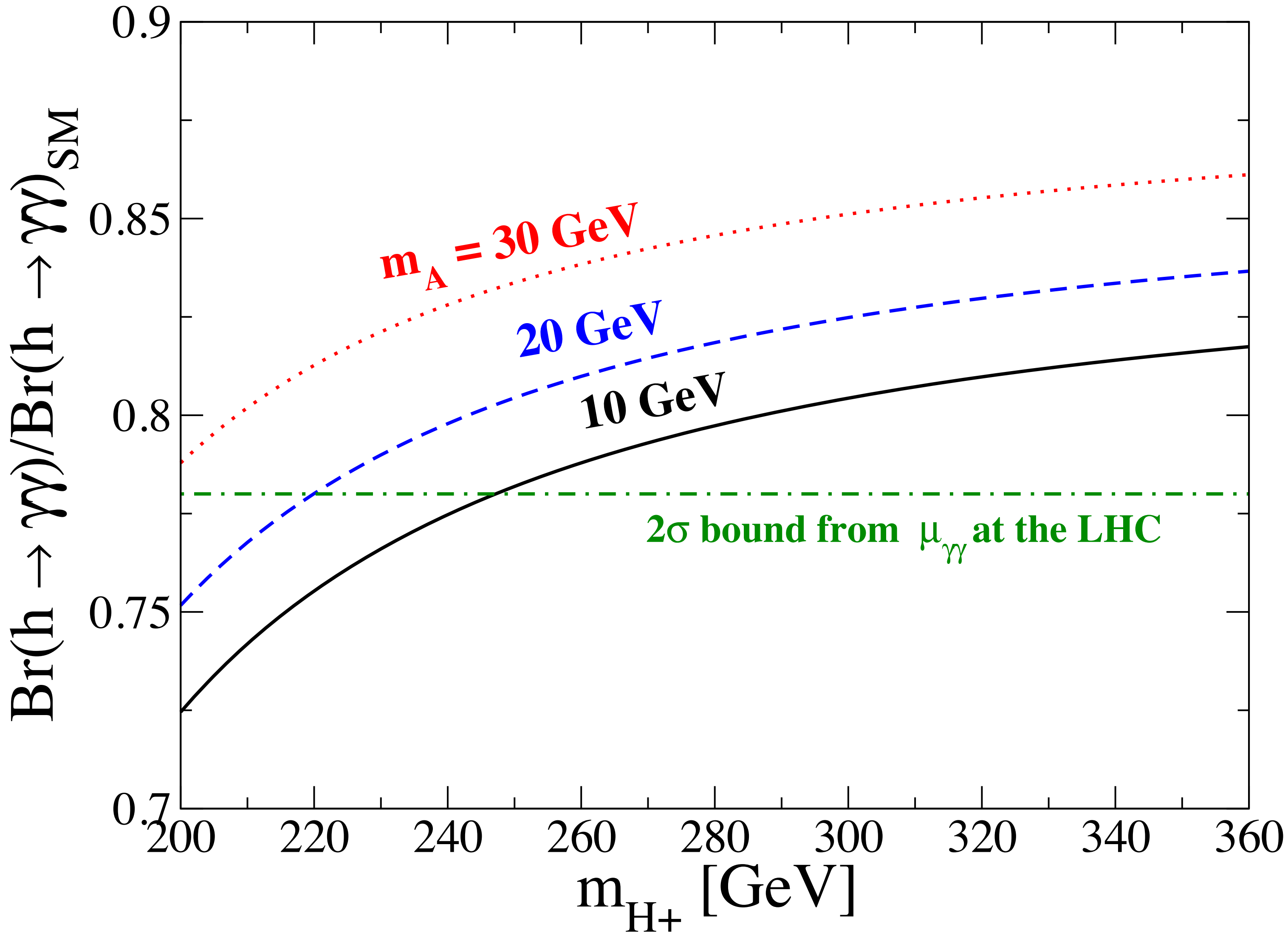


$$\kappa_\ell \simeq -1 - \frac{m_h^2}{m_{H^\pm}^2} + \frac{2m_A^2}{m_{H^\pm}^2}$$

$$\kappa_X = g_{hXX}/g_{hXX}^{\rm SM}$$

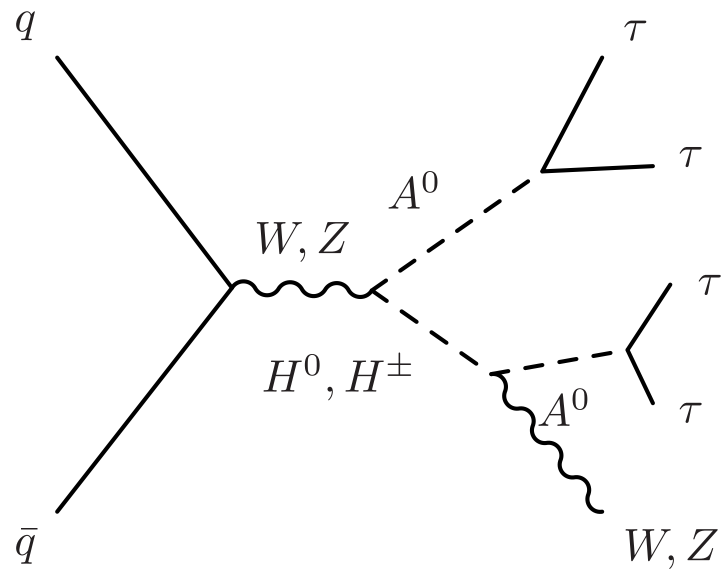
h(125) couplings (2)

- **hγγ** : ***more than 10% deviation*** from the SM prediction



H^0, A^0, $H^\pm$ at the LHC

- ***many tau leptons* are produced** at the LHC 14TeV



- xsec [fb]

$m_{H^\pm}$ [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

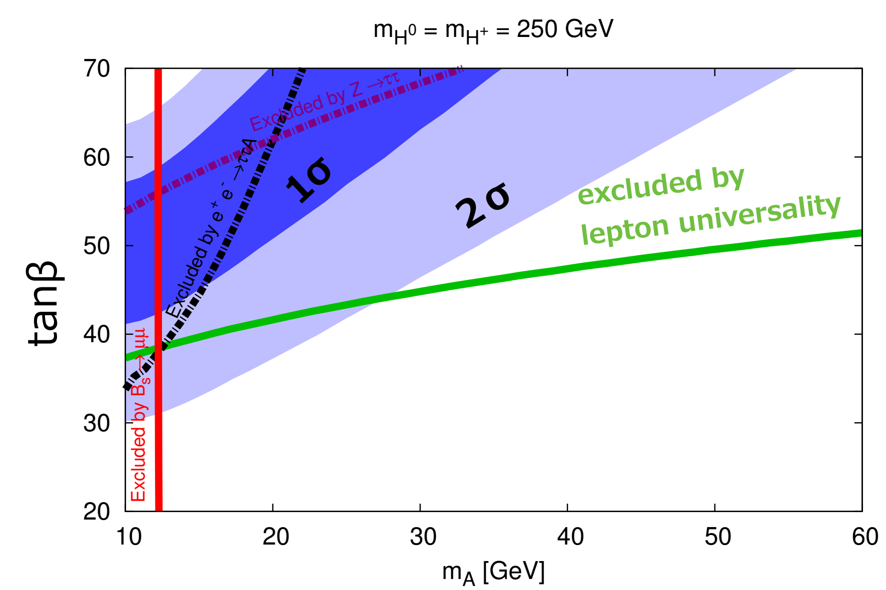
Table 2: Cross sections of the electroweak production processes expressed in Eq. (65), and those of the multi-tau processes expressed in Eqs. (67)-(70) at $\sqrt{s} = 14$ TeV in the unit of fb. We take $m_A = 20$ GeV, $m_H = m_{H^\pm}$, $\sin(\beta-\alpha) = 1$ and $\tan\beta = 35$.

Summary

Summary

- **lepton specific two-Higgs doublet model**
  - ★ simple extension from the SM
  - ★ large new particle couplings to the leptons by **tanβ**
  - ★ **tanβ** is in a dilemma between **g-2** and **lepton flavor universality**
  - ★ **can explain muon g-2 within 2σ**

- **parameters for the muon g-2**
  - ★ 10 GeV < m_A < 30 GeV
  - ★ 250 GeV < $m_{H\pm, H0}$ < 350 GeV
  - ★ 30 < tanβ < 40



- **LHC phenomenology**
  - ★ **more than 10%** deviation in **hττ** and **hγγ** couplings (within the reach of LHC14TeV 300fb-1 (year 2022?))
  - ★ **O(10) fb multi-τ events** will be observed