Flavor Physics
in general two Higgs doublet model

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KMI 2017, Jan. 5, 2017

References:

- Y. Omura, E. Senaha, K. Tobe , JHEP 1505, 028 (2015) [1502.07824], Phys. Rev. D94 (2016) 055019 [1511.08880]
- K. Tobe, JHEP 1610 (2016) 114 [1607.04447]

Introduction

The Standard model (SM) of elementary particle physics is very successful

- consistent with almost all experimental data
- discovery of Higgs boson

On the other hand, unfortunately, no discovery of SUSY, extra-dimension or little Higgs ⋯ at LHC, so far.

Where is new physics?

Introduction

Anomalies in flavor physics??

- muon physics

  muon anomalous magnetic moment (muon g-2)

$$a_\mu^{\mathrm{Exp}} - a_\mu^{\mathrm{SM}} = (26.1 \pm 8.0) \times 10^{-10} \qquad (\sim 3\sigma)$$

- Higgs physics

$$\mathrm{BR}(h \to \mu\tau) = (0.84^{+0.39}_{-0.37})\ \% \qquad (\sim 2.4\sigma,\ \mathrm{CMS\ run\ 1})$$

- B physics

$$R(D^{(*)}) = \frac{\mathrm{BR}(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\mathrm{BR}(\bar{B} \to D^{(*)}l\bar{\nu})} \qquad (\sim 4\sigma)$$

$$R_K = \frac{\mathrm{BR}(B^+ \to K^+\mu^+\mu^-)}{\mathrm{BR}(B^+ \to K^+e^+e^-)} \qquad (\sim 2.6\sigma)$$

lepton flavor non-universality?

- more…

These data may be a good hint for new physics

In the standard model, “flavor” is still mystery.

No principle nor symmetry in flavor structure

“Flavor” may be a good window to new physics.

It could be sensitive to high scale physics.

Two Higgs doublet model

- One of simplest extensions of the SM
- predicts extra flavor violation

In this talk, $h \to \mu\tau$

$\updownarrow$ Maybe related?

muon g-2 anomaly

Interplay between LHC physics and flavor physics is interesting

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✦Introduction

✦General Two Higgs double model

✦h→μ τ and muon g-2 in 2HDM

✦Any Predictions in this scenario?

$$\tau \to \mu\gamma$$

$$\tau \to \mu\nu\bar{\nu}$$

✦Summary

General Two Higgs doublet model

(both Higgs doublets couple to all fermions)

A basis where one Higgs doublet has vev ("Higgs basis")

$$H_1 = \begin{pmatrix} G^+ \\ \frac{v+\phi_1+iG}{\sqrt{2}} \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ \frac{\phi_2+iA}{\sqrt{2}} \end{pmatrix},$$

$G^+,\ G$: Nambu-Goldstone bosons
$H^+,\ A$: charged and CP-odd Higgs bosons

In fermion mass eigenbasis (lepton sector)

$$\mathcal{L} = -\bar{L}^i_L H_1 y^i_e e^i_R - \bar{L}^i_L H_2 \rho^{ij}_e e^j_R$$

$$L = \begin{pmatrix} V_{\mathrm{MNS}} \nu_L \\ e_L \end{pmatrix}$$

$\rho_f\ (f = d,\ u,\ e)$: flavor violating Yukawa couplings

scalar mixing

$$\begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\beta\alpha} & \sin\theta_{\beta\alpha} \\ -\sin\theta_{\beta\alpha} & \cos\theta_{\beta\alpha} \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}.$$

mass eigenstates

SM limit
$c_{\beta\alpha} \to 0$

$s_{\beta\alpha} = \sin\theta_{\beta\alpha},\ c_{\beta\alpha} = \cos\theta_{\beta\alpha}$

General 2HDM predicts

Flavor-changing phenomena mediated by neutral Higgs bosons

Bjorken and Weinberg, PRL 38, 622 (1977)

This may be a problem if we do not observe any flavor-changing phenomena beyond the SM.

But, now....

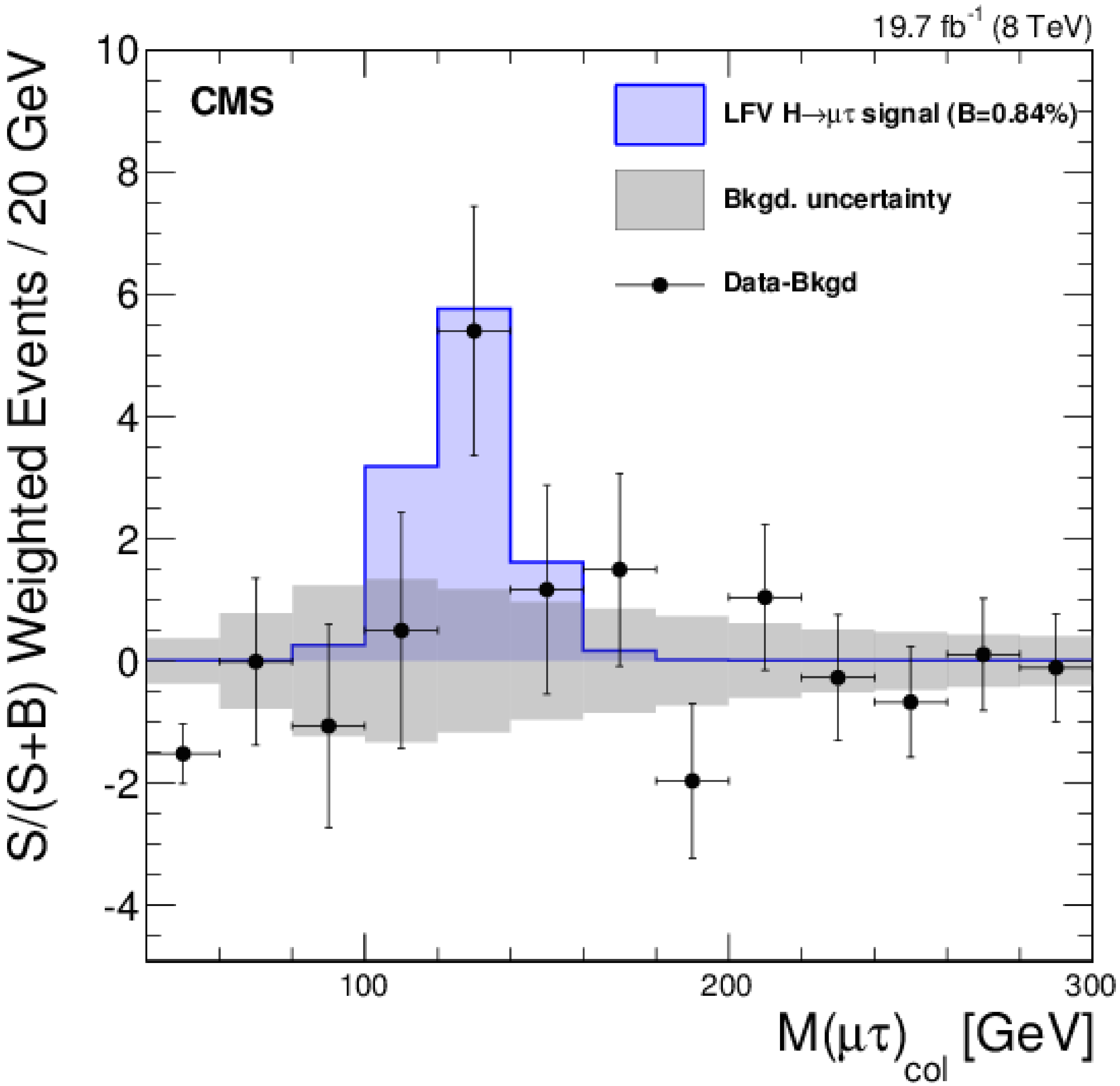
Various data suggest there may be extra flavor violation

e.g. $$\mathrm{BR}(h \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$$

h$\rightarrow\mu\tau$ and muon g-2 in 2HDM

CMS collaboration has reported an excess in $h \to \mu\tau$

CMS: Phys. Lett. B749, 337 (2015) [arXiv: 1502.07400]



CMS best fit:

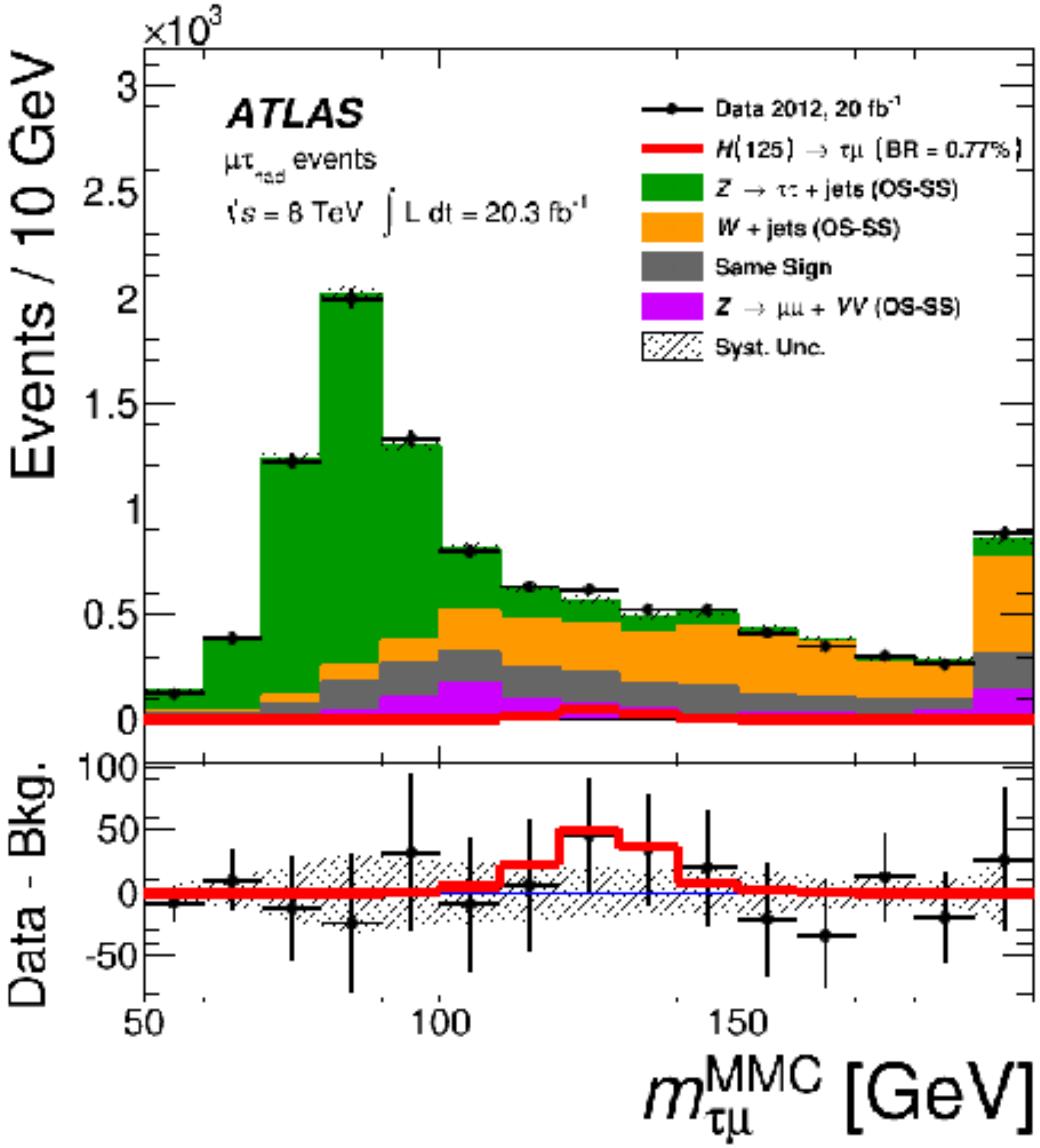
$$\mathrm{BR}(h \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$$

$$(\mathrm{BR}(h \to \mu\tau) < 1.51\%,\ 95\%\mathrm{CL})$$

2.4 σ excess

Hint for new physics?

Current status



ATLAS

$$\mathrm{BR}(h \to \mu\tau) = (0.77 \pm 0.62)\%$$

ATLAS: JHEP 1511, 211 (2015) [arXiv: 1508.03372]

In Moriond EW 2016 [arXiv: 1604.07730]

ATLAS:
BR = 0.53 ± 0.51% < 1.43% (95% CL)

consistent with CMS

CMS best fit:

$$\mathrm{BR}(h \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$$

2.4 σ excess

ATLAS: arXiv: 1508.03372

New 13 TeV result from CMS

CMS PAS HIG-16-005

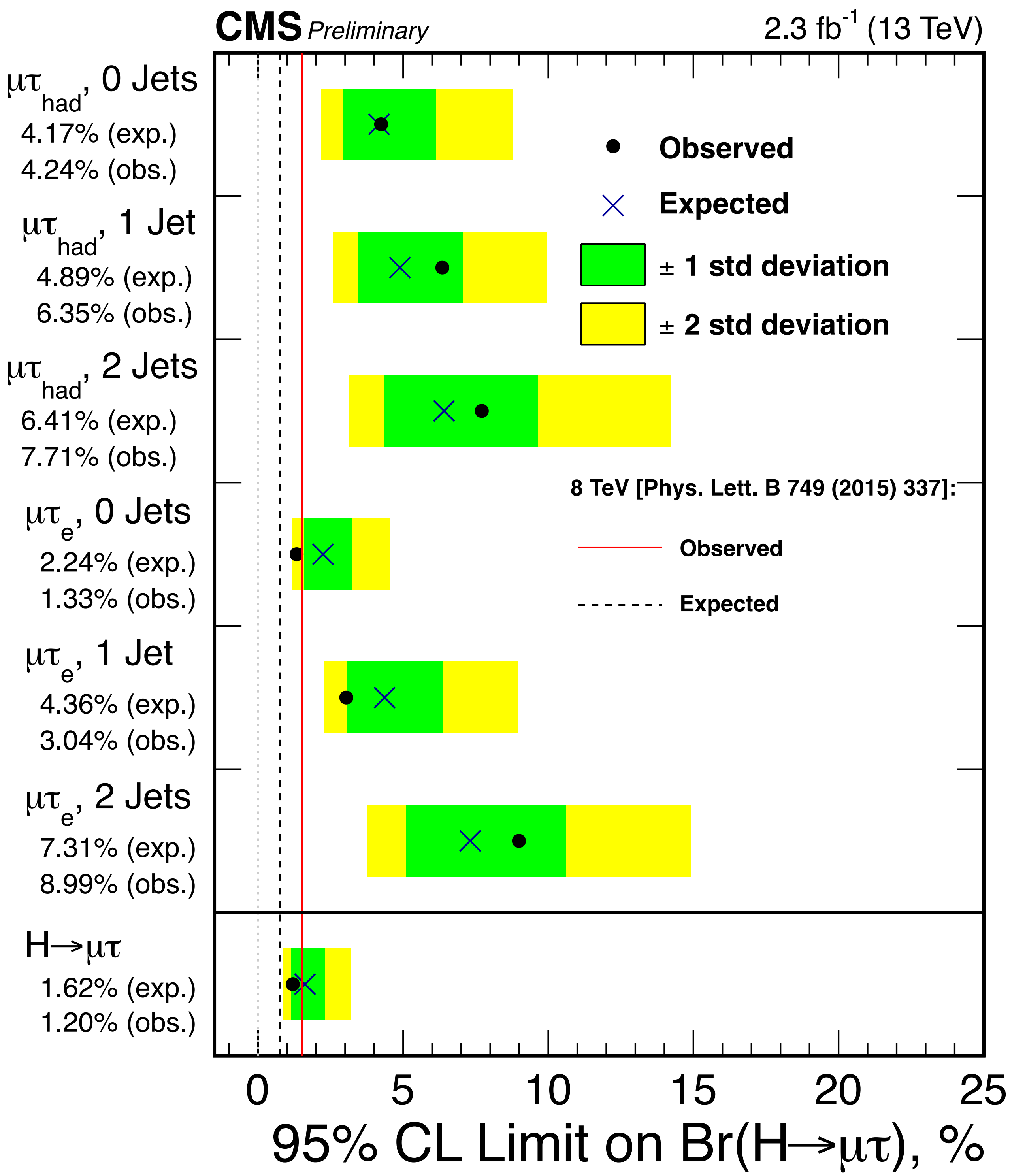


Figure 4: Observed and expected 95% CL upper limits on the $\mathcal{B}(\mathrm{H} \to \mu\tau)$ for each individual category and combined. The solid red and dashed black vertical lines correspond, respectively, to the observed and expected 95% CL upper limits obtained at $\sqrt{s} = 8$ TeV [23].

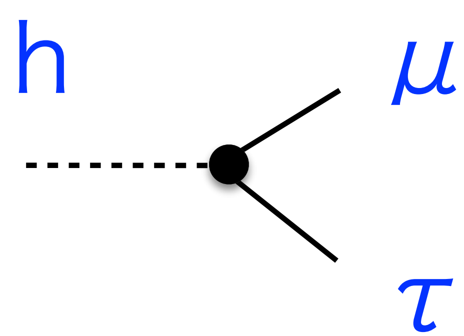
No excess is observed

$\mathrm{BR}(h \to \mu\tau) < 1.20\%$ (95% CL)

It is not enough to exclude the 8 TeV result. More data are needed.

Wait for full 2016 data!

Two Higgs doublet model (2HDM) can explain it easily.



$$y_{hij} = \frac{m_f^i}{v} s_{\beta\alpha}\delta_{ij} + \frac{\rho_f^{ij}}{\sqrt{2}} c_{\beta\alpha},$$

$h \to \mu\tau$

Sierra and Vicente, 1409.7690, Crivellin et al., 1501.00993, Lima et al., 1501.06923, Dorsner et al., 1502.07784, ……
Even before the CMS excess, see Pilaftsis, PLB 285, 68 (1992); Assamagan et al, PRD 67, 035001 (2003); Brignole and Rossi, PLB 566, 217 (2003); Kanemura et al, PLB 599, 83 (2004); Arganda et al, PRD 71, 035011 (2005); ……, Blankenburg, Ellis, Isidori, PLB712, 386 (2012),……

CMS result

$$\mathrm{BR}(h \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$$

2HDM prediction

$$\mathrm{BR}(h \to \mu\tau) = \frac{c_{\beta\alpha}^2 (|\rho_e^{\mu\tau}|^2 + |\rho_e^{\tau\mu}|^2) m_h}{16\pi\Gamma_h},$$

Result

$$\bar{\rho}^{\mu\tau} \equiv \sqrt{\frac{|\rho_e^{\mu\tau}|^2 + |\rho_e^{\tau\mu}|^2}{2}}$$

$$\simeq 0.26 \left(\frac{|0.01|}{c_{\beta\alpha}}\right) \sqrt{\frac{\mathrm{BR}(h \to \mu\tau)}{0.84 \times 10^{-2}}}.$$

General 2HDM can explain it easily

muon g-2 anomaly

Discrepancy between the experimental value
and the SM prediction

$a_\mu^{\rm Exp}$ $[10^{-10}]$	$\delta a_\mu = a_\mu^{\rm Exp} - a_\mu^{\rm SM}$ $[10^{-10}]$	
11659208.9 ± 6.3 (~0.54 ppm)	26.1 ± 8.0 (3.3σ)	HLMNT11
	31.6 ± 7.9 (4.0σ)	THLMN10
	33.5 ± 8.2 (4.1σ)	BDDJ12
	28.3 ± 8.7 (3.3σ)	JS11
	29.0 ± 9.0 (3.2σ)	JN09
	28.7 ± 8.0 (3.6σ)	DHMZ12

3-4 σ deviation

possibly an evidence of new physics

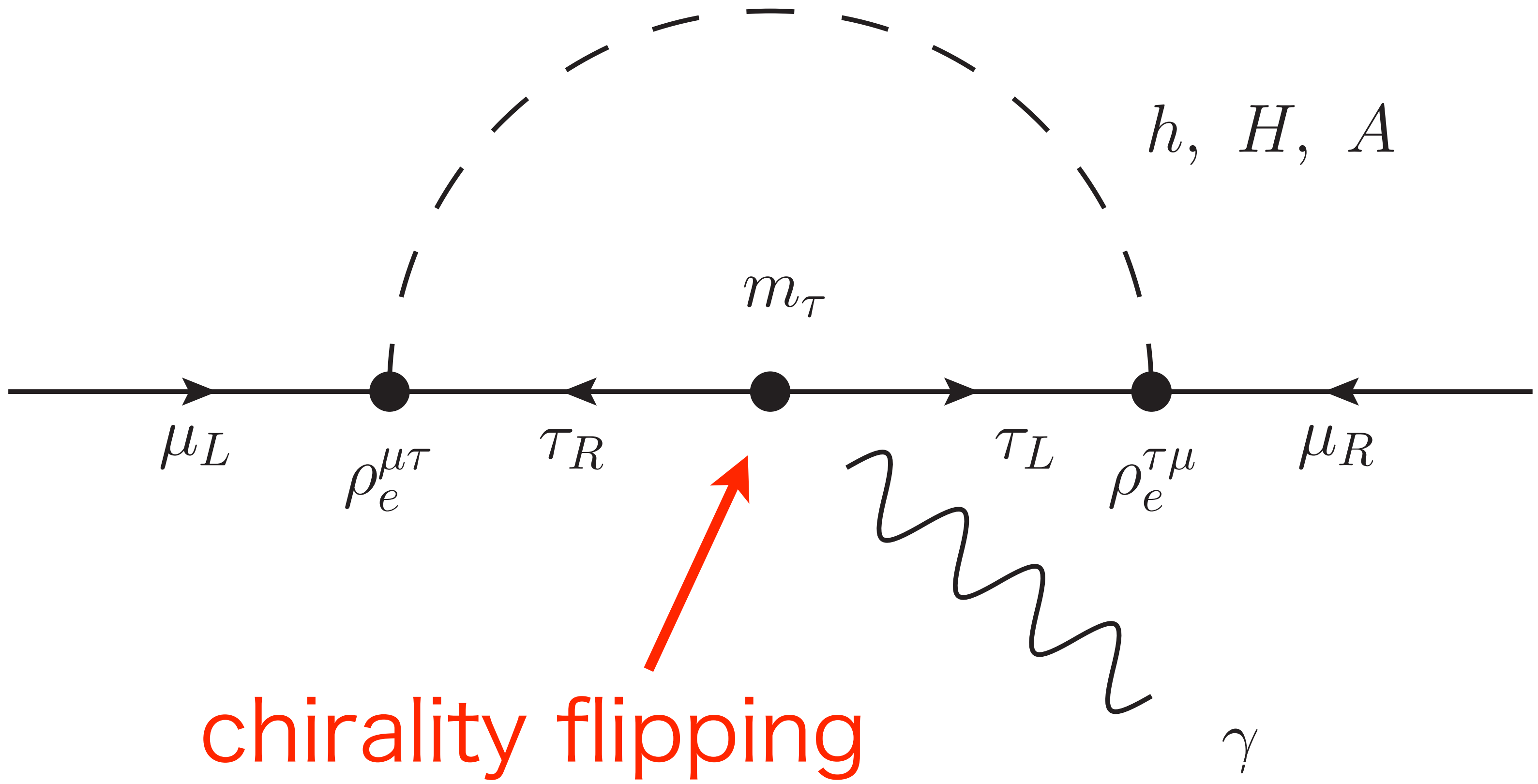
The size of anomaly is comparable to the EW contribution

$$a_\mu^{\rm EW} = (15.4 \pm 0.1) \times 10^{-10}$$

Naively we expect new particles with EW scale mass

muon g-2 in 2HDM,

induced by the μ-τ flavor violating coupling

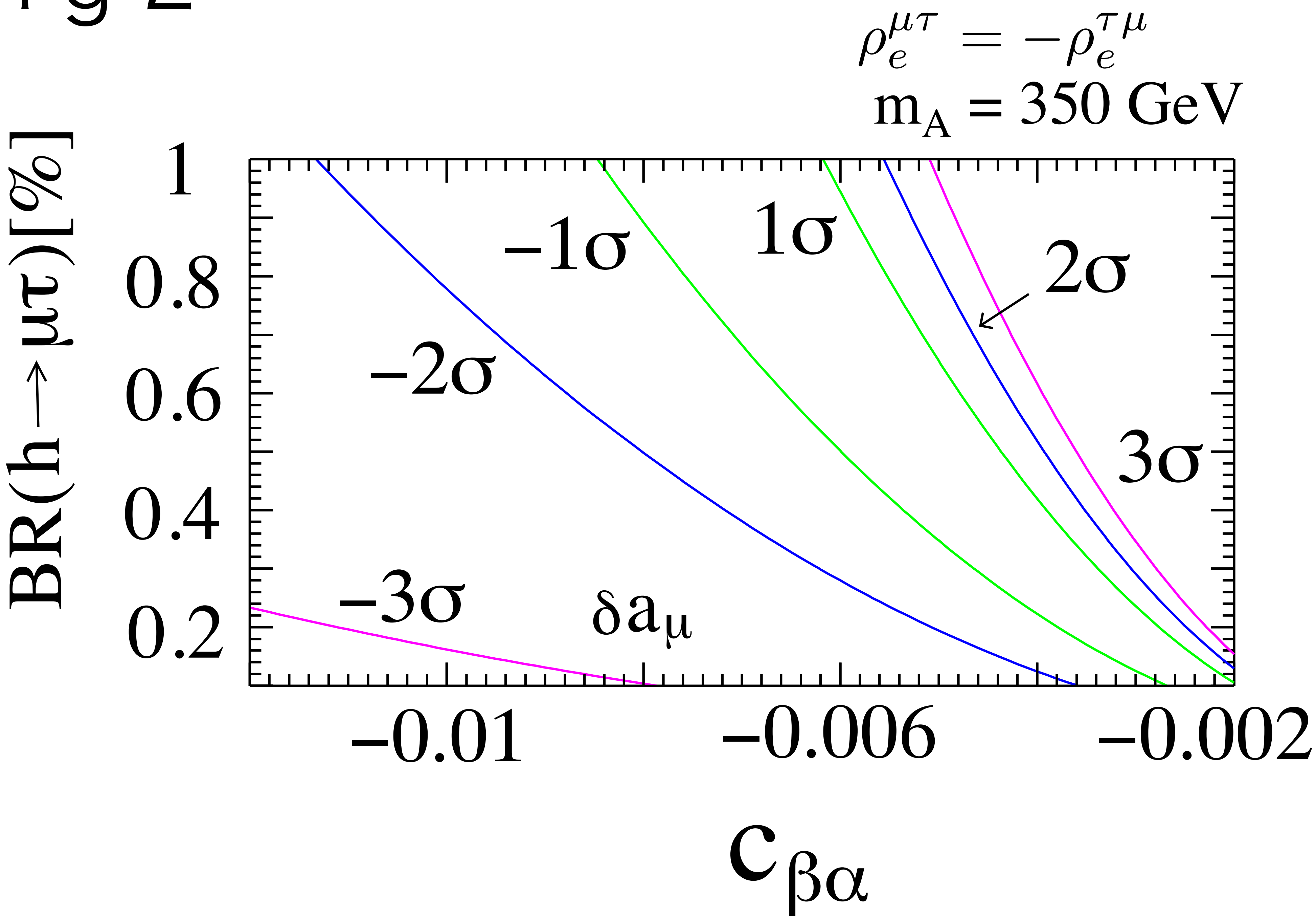


$O\left(\frac{m_\tau}{m_\mu}\right)$ enhancement

The $\mu - \tau$ flavor-violating coupling can generate large contribution to the muon g-2

muon g-2

Omura, Senaha, Tobe (2015)



Both anomalies in the muon g-2 and $h \to \mu\tau$ can be accommodated in the general 2HDM

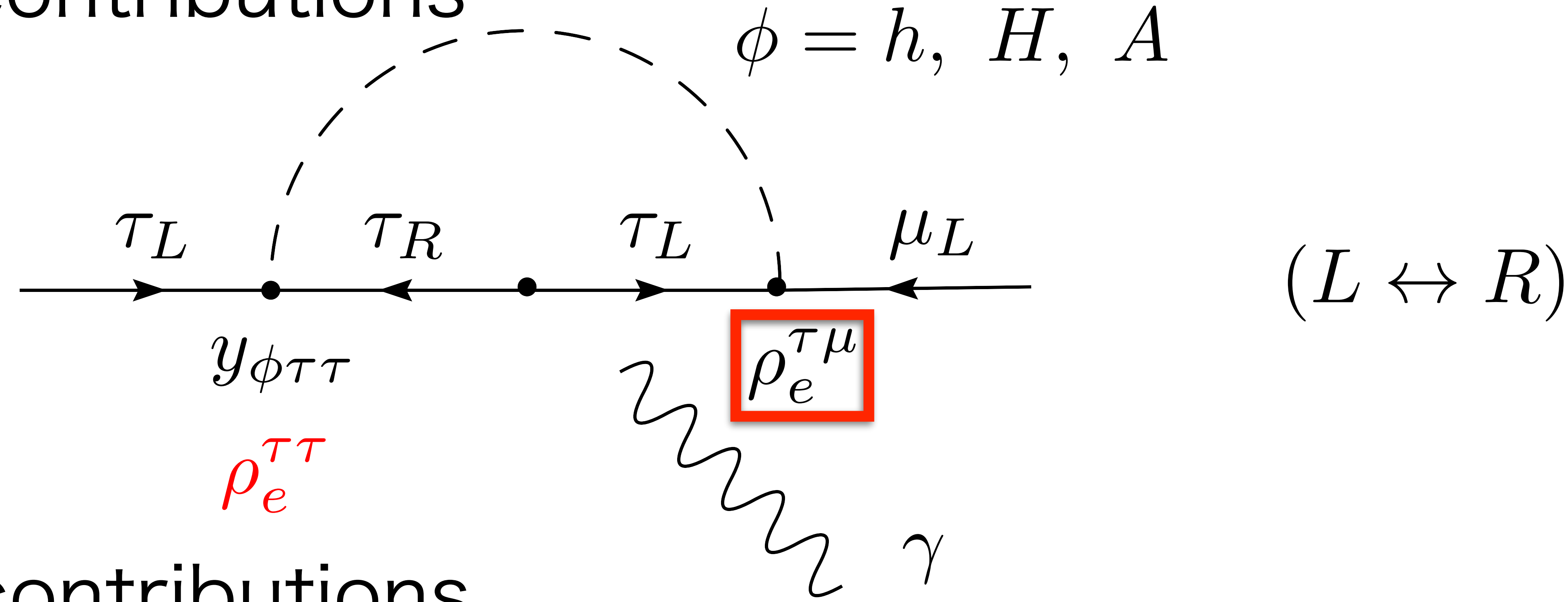
Any Predictions in this scenario?

$$\tau \to \mu\gamma$$

$$\tau \to \mu\nu\bar{\nu}$$

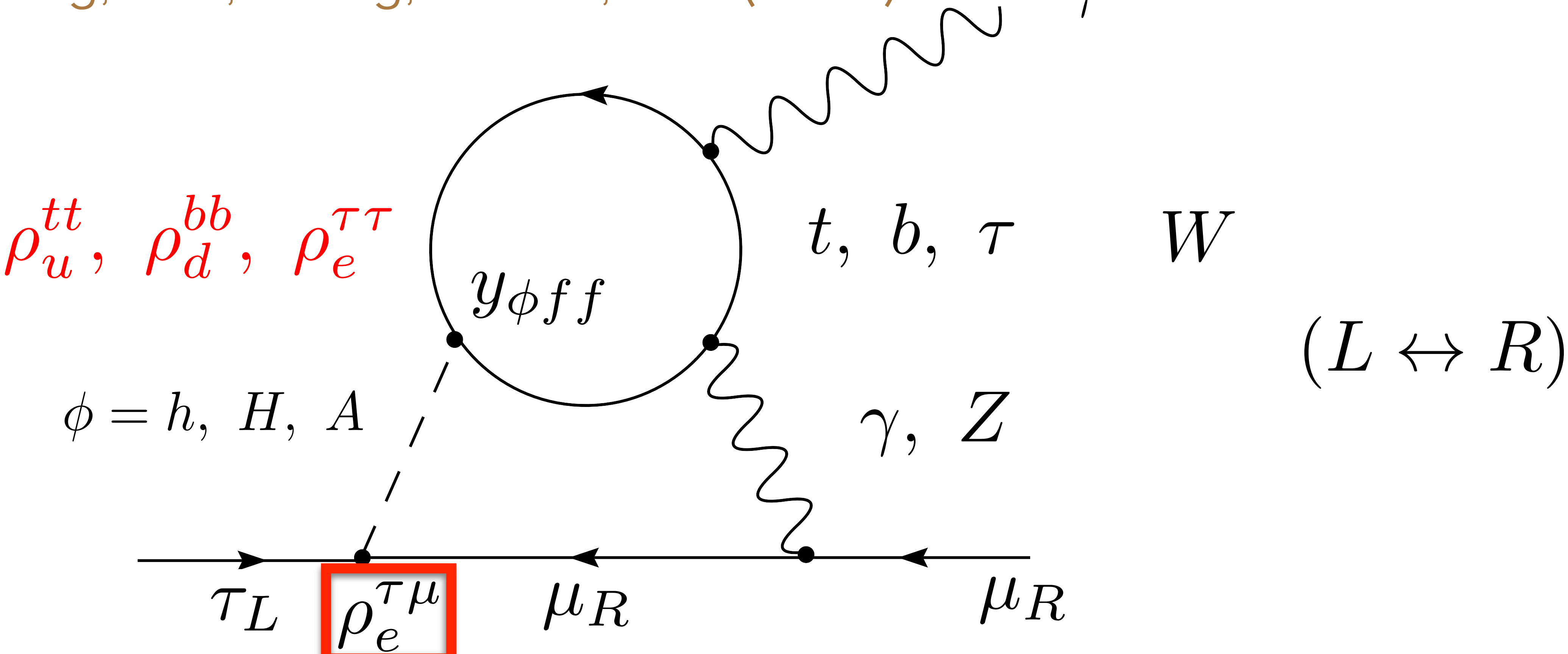
$\tau \to \mu\gamma$

1-loop contributions

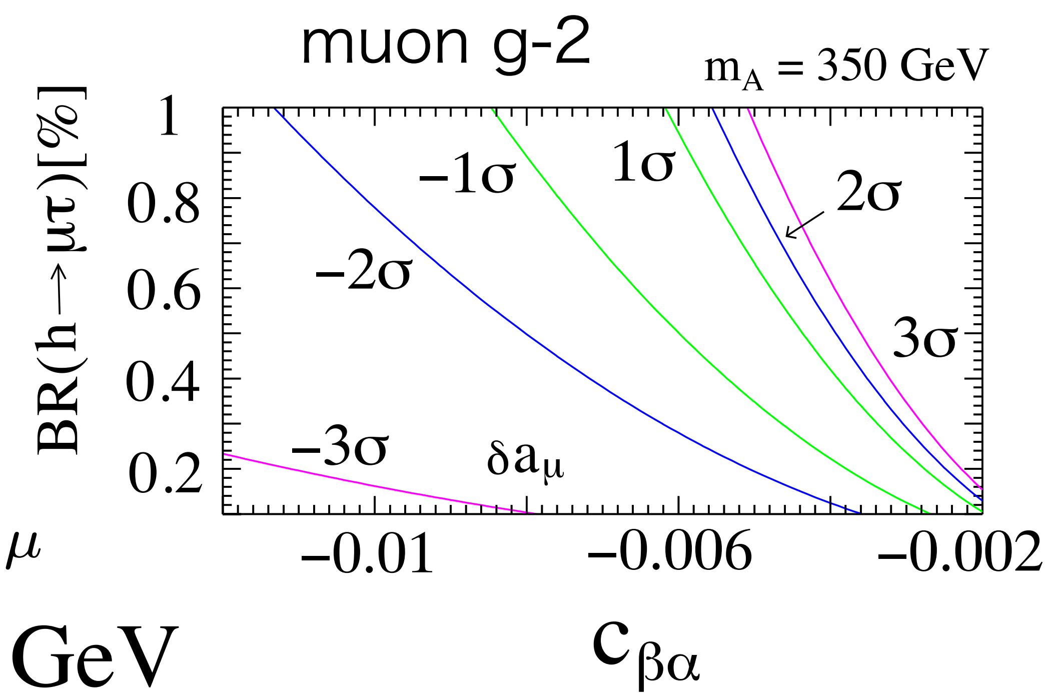


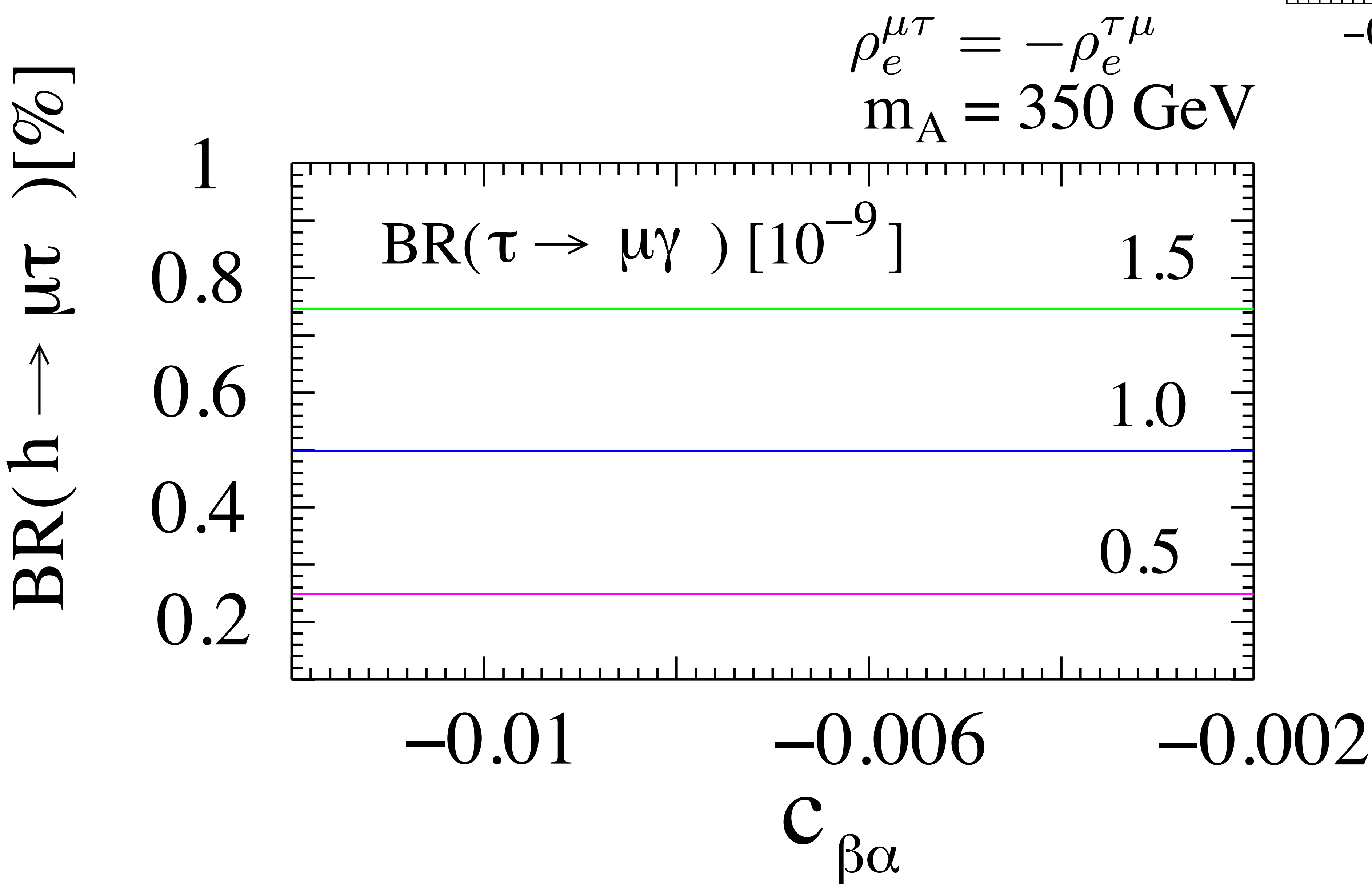
2-loop contributions

Chang, Hou, Keung, PRD48, 217 (1993)



For a case with $\rho_e^{\tau\tau} = \rho_u^{tt} = 0$





$\mathrm{BR}(\tau \to \mu\gamma)_{\mathrm{exp.}} < 4.4 \times 10^{-8}$

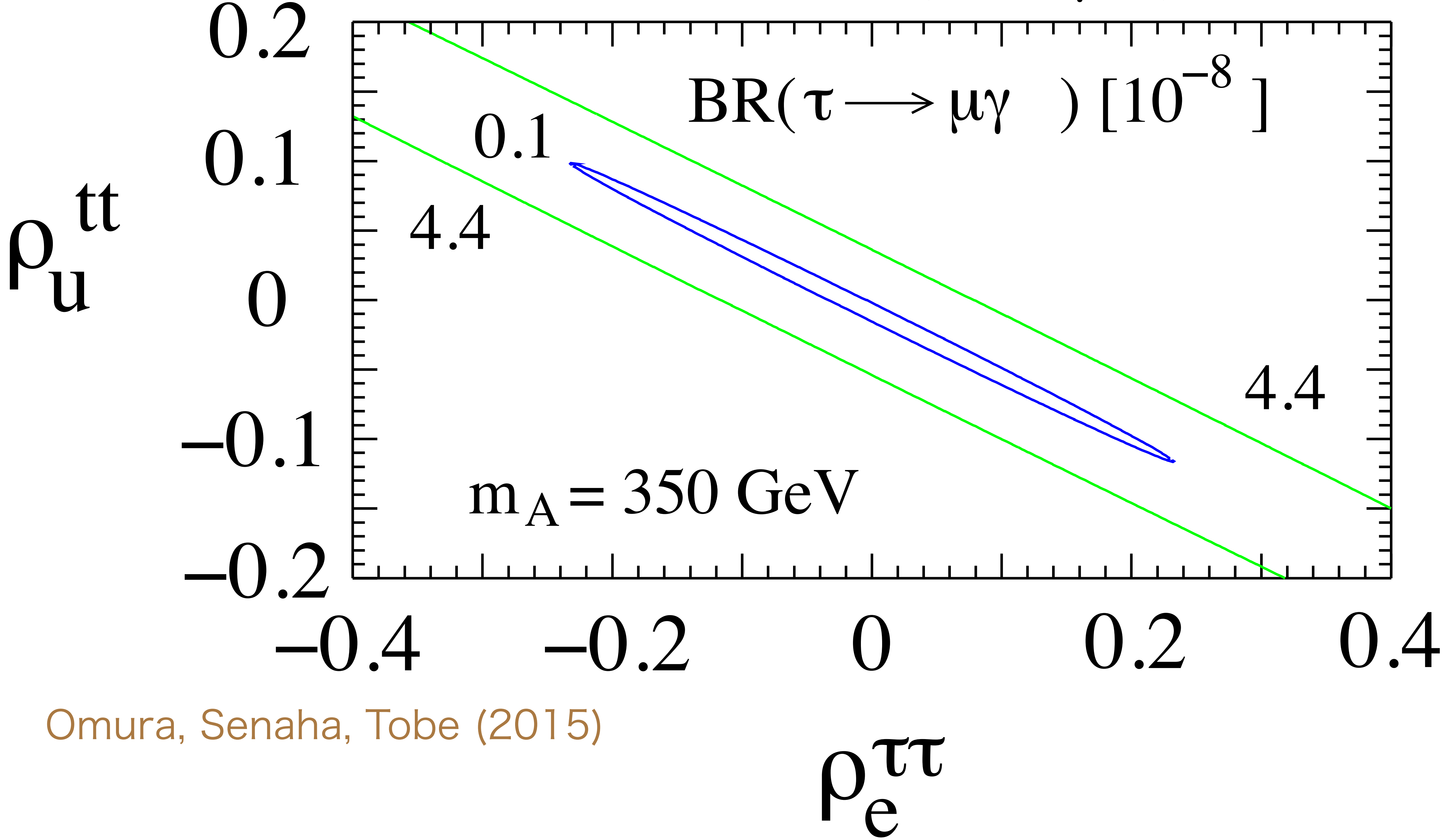
Omura, Senaha, Tobe (2015)

For a case with $\rho_e^{\tau\tau} \neq 0,\ \rho_u^{tt} \neq 0$

$$c_{\beta\alpha} = -0.007$$

$$\delta a_\mu = 2.2 \times 10^{-9}$$

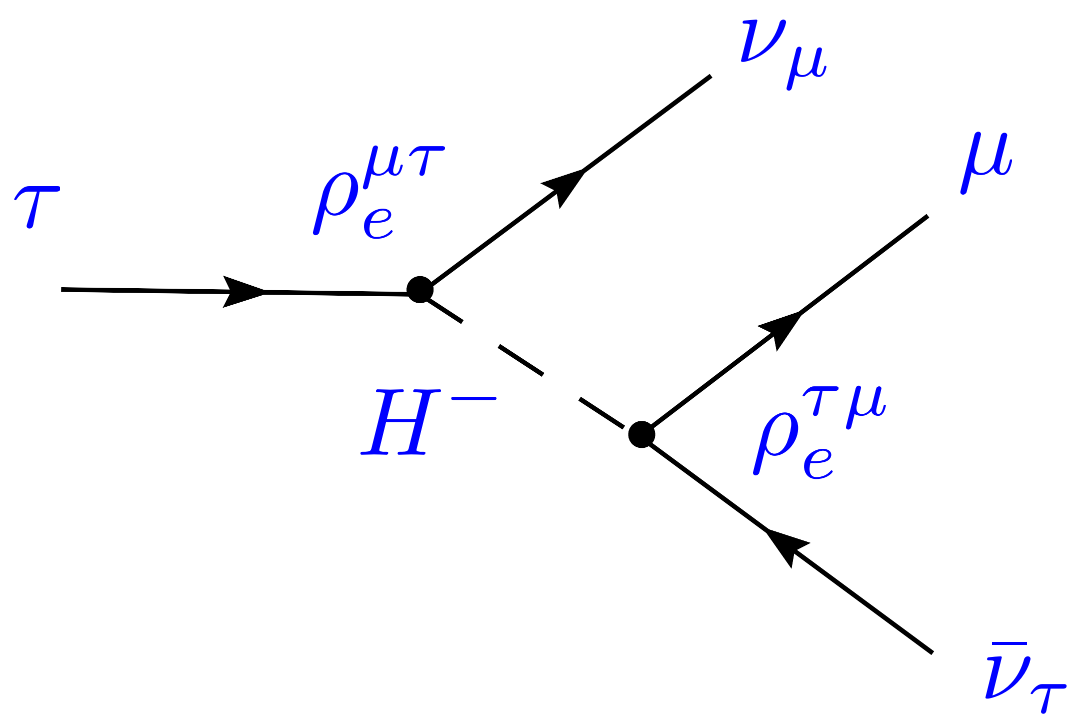
$\mathrm{BR}(h \to \mu\tau) = 0.84\%$



Omura, Senaha, Tobe (2015)

The size of the rate can be within the reach of the future B-factory

Correction to $\tau \to \mu\nu\bar{\nu}$ decay



$$\Gamma(\tau \to \mu\nu\bar{\nu}) = \frac{m_\tau^5 G_F^2}{192\pi^3}(1+\delta),$$

$$\delta = \frac{|\rho_e^{\mu\tau}|^2 |\rho_e^{\tau\mu}|^2}{32 G_F^2 m_{H^+}^4}.$$

Omura, Senaha, Tobe (2015)

Michel parameters in τ decay

$$\frac{d\Gamma(\tau^- \to \mu^-\nu\bar{\nu})}{dx\, d\cos\theta_\mu} = \frac{m_\tau w^4}{2\pi^3}\sqrt{x^2 - x_0^2}\, G_{F_\mu}^2 \left[F_1(x) - F_2(x)\mathcal{P}_\tau \cos\theta_\mu\right]$$

$$F_1(x) = x(1-x) + \frac{2\rho}{9}(4x^2 - 3x - x_0^2) + \eta x_0(1-x)$$

$$F_2(x) = -\frac{\xi\sqrt{x^2 - x_0^2}}{3}\left[1 - x + \frac{2\delta(4x - 4 + \sqrt{1 - x_0^2})}{3}\right]$$

$$w = \frac{m_\tau^2 + m_\mu^2}{2m_\tau} \qquad x = E_\mu/w,\ x_0 = m_\mu/w \qquad \mathcal{P}_\tau: \text{ tau polarization}$$

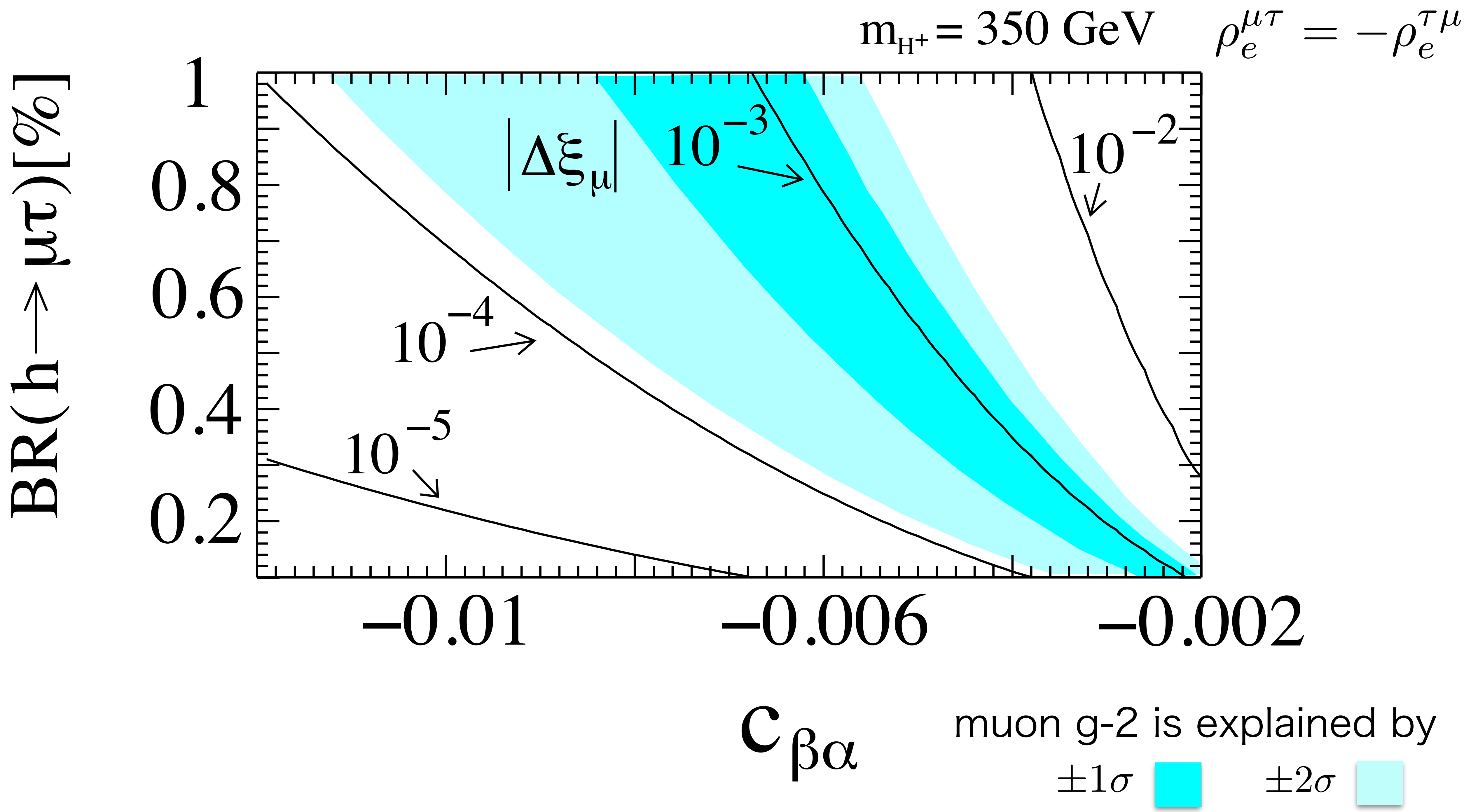
$$\underline{\xi \simeq 1 - 2\delta}$$

K. Tobe (2016)

Note: flavor conserving case

$$\Delta\xi \simeq -2(\Delta\eta)^2,\ (|\Delta\eta| \gg |\Delta\xi|)$$

Michel parameter $|\Delta\xi|$ $(\Delta\xi < 0)$



There is interesting correlation between muon g-2 and $\Delta\xi$

The precise measurement of the Michel parameter at the level of $10^{-4} - 10^{-2}$ would be very important for this scenario

lepton universality measurement

BABAR collaboration +others

PRL 105, 051602 (2010)

$$\left(\frac{g_\mu}{g_e}\right)_\tau^2 = \frac{\mathrm{BR}(\tau\to\mu\bar{\nu}\nu)}{\mathrm{BR}(\tau\to e\bar{\nu}\nu)}\frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)} = 1 \quad \text{for} \quad \mathrm{SM}$$

f: phase space factor

$$\begin{aligned}\left(\frac{g_\mu}{g_e}\right)_\tau &= 1.0036 \pm 0.0020 \ (\text{BaBar}) \\ &= 1.0018 \pm 0.0014 \ (\text{world average}) \\ &\simeq 1 - \frac{\Delta\xi}{4} \ (\text{2HDM})\end{aligned}$$

Omura, Senaha, Tobe (2015)

The precise measurement is also important.

Belle and future B-factory result would be very interesting.

✦ Summary

★ General 2HDM predicts the flavor-violating phenomena, mediated by neutral Higgs bosons

★ The CMS excess in $h \to \mu\tau$ decay can be explained by the general 2HDM.

More data from LHC will be important.

★ We have found that the flavor-violating interactions relevant to the CMS excess enhance the neutral Higgs contributions to the muon g-2 and it can resolve the muon g-2 anomaly.

★ This scenario predicts

- $\tau \to \mu\gamma$ (which depends on $\mathrm{BR}(h \to \mu\tau)$)
- sizable correction to $\tau \to \mu\nu\bar{\nu}$ (interesting correlation to muon g-2)

★ Interesting effects on hadronic processes?

B-physics ($R(D^{(*)})$)

Iguro, Nakano, Sakurai, Tobe, work in progress

★ Direct detection of extra heavy Higgs bosons at LHC?

need the information on quark Yukawa couplings

Interplay between various physics would be important

Backup

neutral Higgs mass spectrum from tree level potential

potential

$$V = M_{11}^2 H_1^\dagger H_1 + M_{22}^2 H_2^\dagger H_2 - \left(M_{12}^2 H_1^\dagger H_2 + \mathrm{h.c.}\right)$$
$$+ \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1)$$
$$+ \frac{\lambda_5}{2}(H_1^\dagger H_2)^2 + \left\{\lambda_6 (H_1^\dagger H_1) + \lambda_7 (H_2^\dagger H_2)\right\}(H_1^\dagger H_2) + \mathrm{h.c.}.$$

relations among Higgs masses

$$m_{H^+}^2 = M_{22}^2 + \frac{v^2}{2}\lambda_3,$$
$$m_A^2 - m_{H^+}^2 = -\frac{v^2}{2}(\lambda_5 - \lambda_4),$$
$$(m_H^2 - m_h^2)^2 = \left\{m_A^2 + (\lambda_5 - \lambda_1)v^2\right\}^2 + 4\lambda_6^2 v^4,$$
$$\sin 2\theta_{\beta\alpha} = -\frac{2\lambda_6 v^2}{m_H^2 - m_h^2}.$$

Now, $c_{\beta\alpha} \ll 1 \longrightarrow \lambda_6 \ll 1$

$$m_h^2 \simeq \lambda_1 v^2,$$

$$m_H^2 \simeq m_A^2 + \lambda_5 v^2,$$

$$m_{H^+}^2 = m_A^2 - \frac{\lambda_4 - \lambda_5}{2} v^2,$$

$$m_A^2 = M_{22}^2 + \frac{\lambda_3 + \lambda_4 - \lambda_5}{2} v^2.$$

Note: correction to Peskin-Takeuchi T parameter

When $m_A \simeq m_{H^+}$,

the small $c_{\beta\alpha}$ suppresses the correction

Here, we mainly consider a case with $\lambda_4 = \lambda_5 = 0.5$