Lepton-flavor-violating Higgs decay $h \to \mu\tau$ and muon g-2 in general two Higgs doublet model

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arXiv:1502.07824 (JHEP 1505, 028 [2015])
and arXiv:1511.08880

Introduction

muon g-2 anomaly

Mibe-San's talk
(See also Saito-san's talk)

Difference between the experimental value
and the SM prediction

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

3-4 σ deviation

possibly an evidence of new physics

If this anomaly is due to new physics, ...

The size of anomaly

$$\delta a_\mu = (26.1 \pm 8.0) \times \ 10^{-10}$$

is comparable to the electroweak contribution

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

we expect new particles with EW scale mass

→ strong constraints from EW precision data

→ good target at near future experiments

We may be able to discover the new physics before new experiment or/and new (improved) calculation for muon g-2 are done.

So, we should study it NOW!

S. Kanemitsu and K. Tobe PRD86, 095025 (2012)

Effective operator for the muon g-2

$$\mathcal{L} = \frac{y\langle H\rangle}{\Lambda^2}\underline{\bar{\mu}_R}\sigma^{\mu\nu}\underline{\mu_L}F_{\mu\nu} + \text{h.c.}$$

★ muon chirality has to be flipped

If there is a large chirality flipping, the muon g-2 can be enhanced and the new physics scale can be larger and hence the EW constraints are avoided.

We find that the muon g-2 anomaly can be explained by the μ-τ flavor-violating Higgs couplings in general two Higgs doublet model

$h \to \mu\tau$ ← motivated by the CMS excess

↕

muon g-2

The $\mu - \tau$ flavor-violating coupling can enhance the muon g-2

General 2HDM can explain both anomalies.

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- ✦ Introduction
- ✦ General two Higgs doublet model (2HDM)
- ✦ h $\rightarrow \mu\ \tau$ and muon g-2 in general 2HDM
- ✦ Predictions (constraints)

$$\tau \rightarrow \mu\gamma,\ \tau \rightarrow \mu\nu\bar{\nu},\ \cdots$$

- ✦ Summary

General two Higgs doublet model (2HDM)

(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)

$$\mathcal{L} = -\bar{L}_L^i H_1 y_e^i e_R^i - \bar{L}_L^i H_2 \rho_e^{ij} e_R^j$$

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

$\rho_f\ (f = d,\ u,\ e)$: 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

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

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

neutral Higgs mass spectrum from tree level potential

For $c_{\beta\alpha} \ll 1$

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

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

$\lambda_{4,5}$; Higgs quartic couplings

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 $\lambda_4 = \lambda_5 = 0.5$

General 2HDM predicts

Flavor-changing phenomena mediated
by neutral Higgs bosons

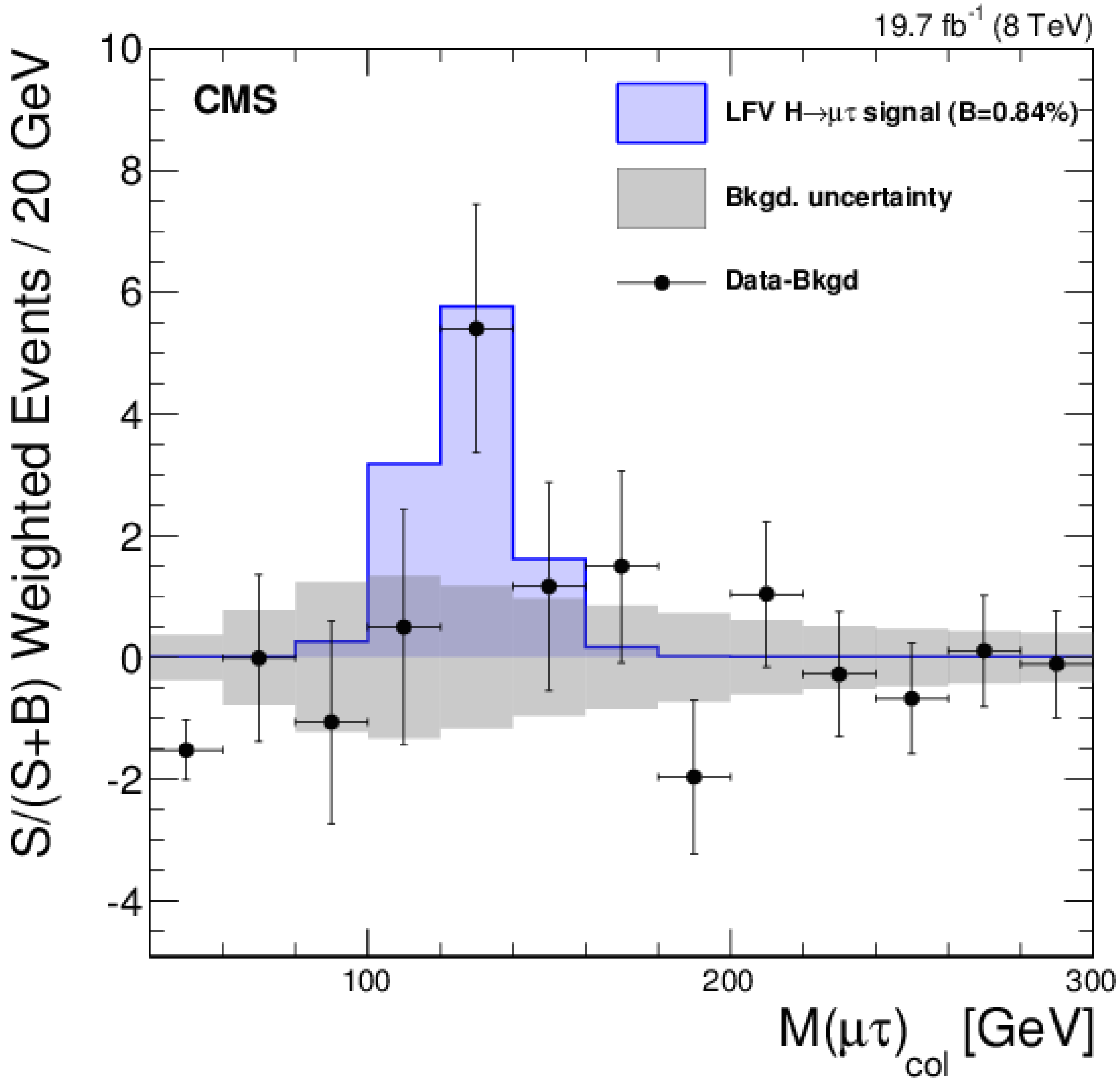
Bjorken and Weinberg, PRL 38, 622 (1977)

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

But, now....

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

CMS: arXiv: 1502.07400

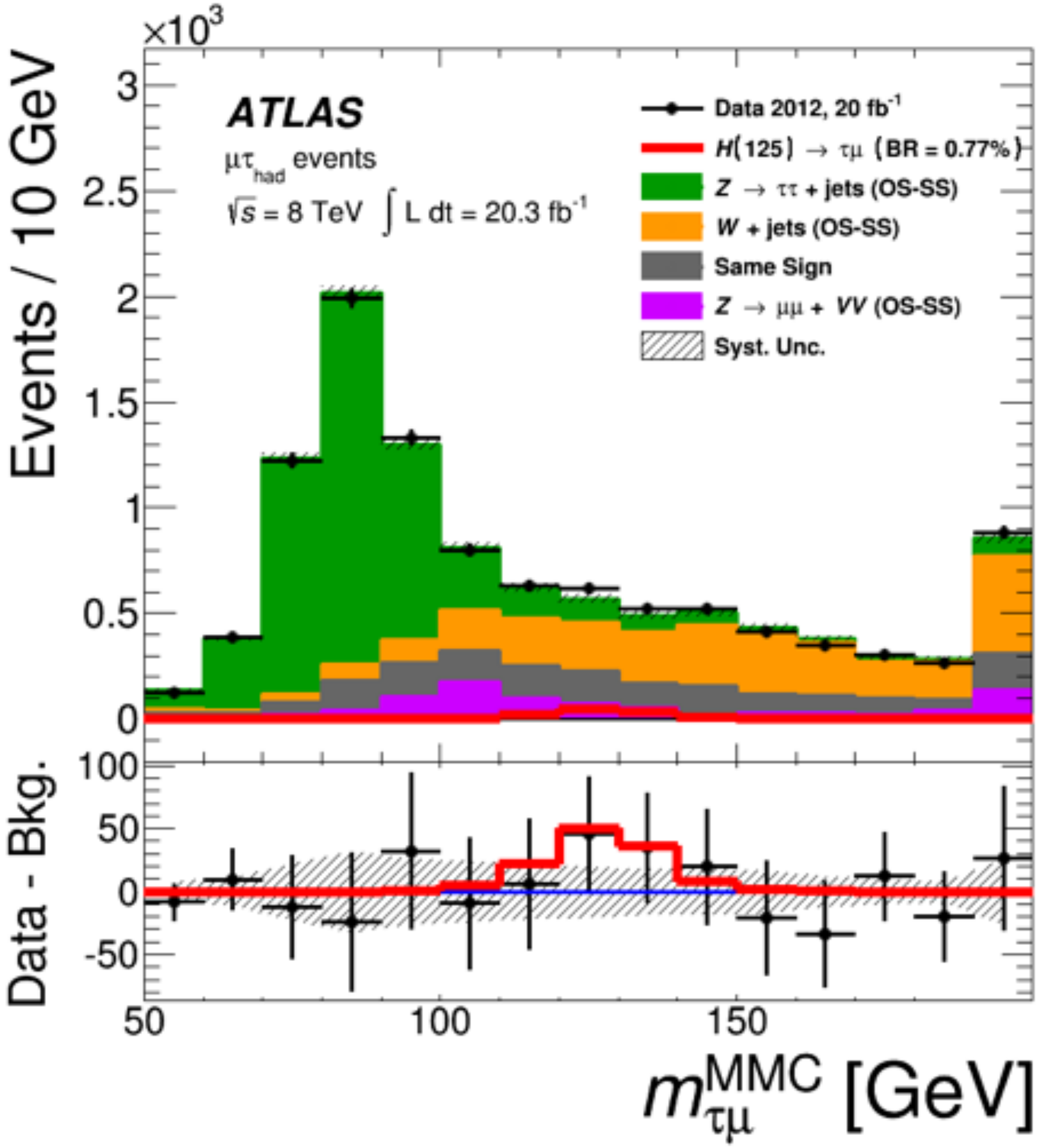


CMS best fit:

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

2.4 σ excess

Talk by P. Onyisi @FPCP 2015



ATLAS: arXiv: 1508.03372

ATLAS

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

ATLAS: arXiv: 1508.03372

consistent with CMS

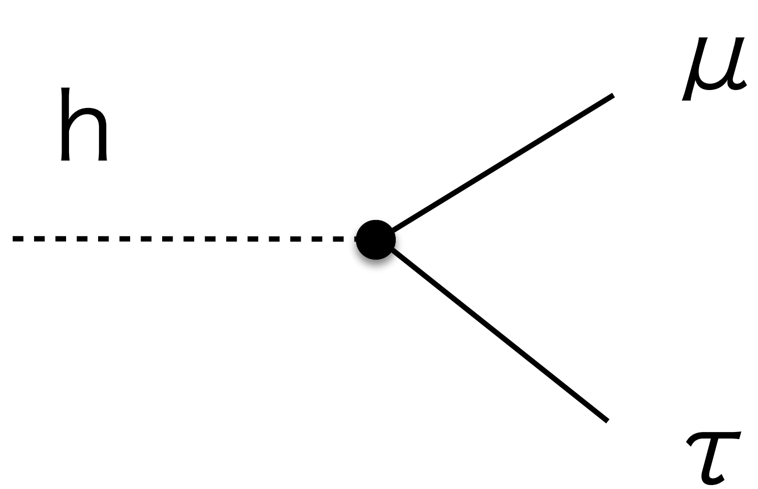
CMS best fit:

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

2.4 σ excess

Hint for new physics!

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



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

$h \to \mu\tau$

Sierra and Vicente, 1409.7690, Crivellin et al., 1501.00993, Lima et al., 1501.06923, ⋯

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

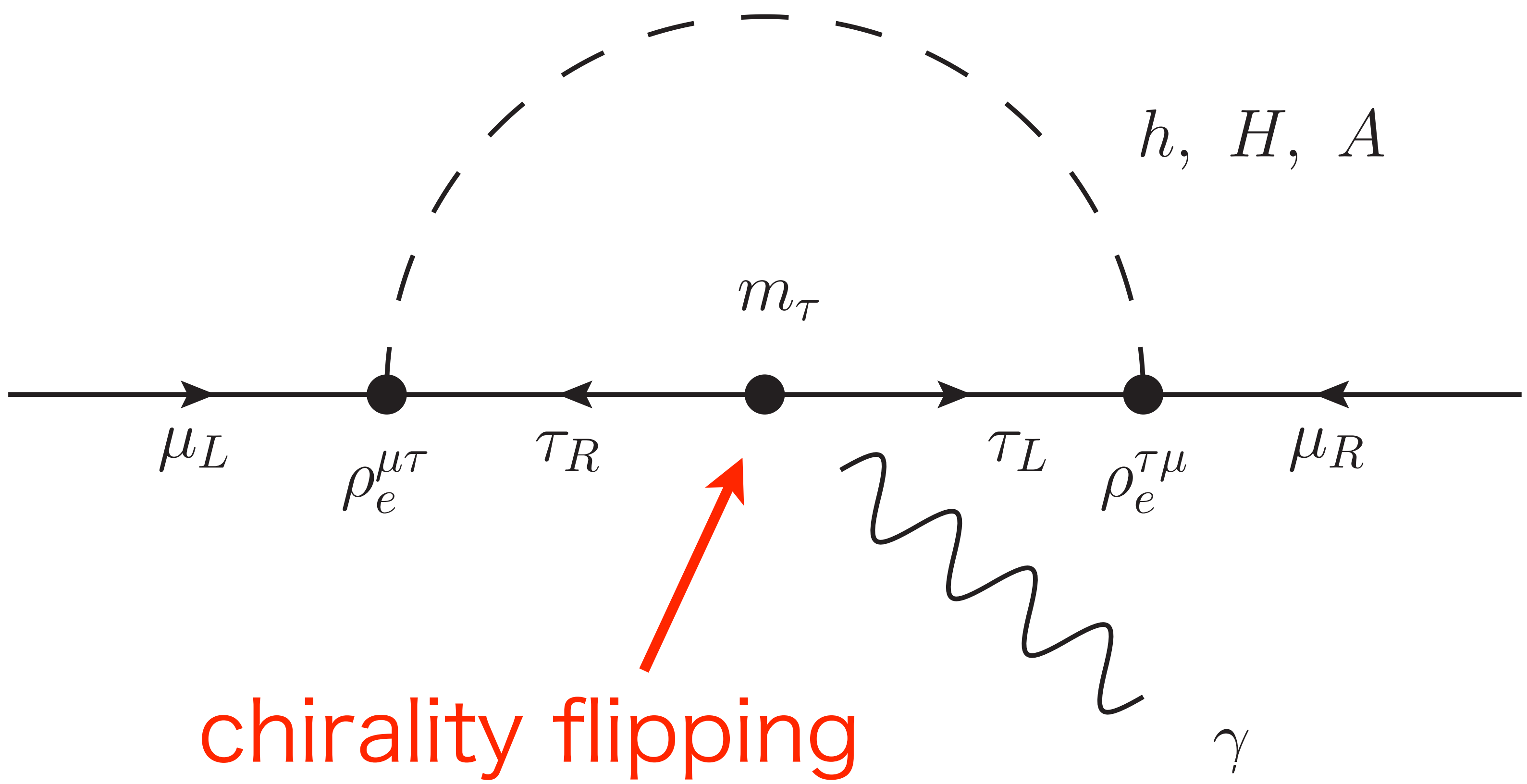
$$\bar{\rho}^{\mu\tau} \equiv \sqrt{\frac{|\rho_e^{\mu\tau}|^2 + |\rho_e^{\tau\mu}|^2}{2}}$$

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

General 2HDM can explain it easily

muon g-2

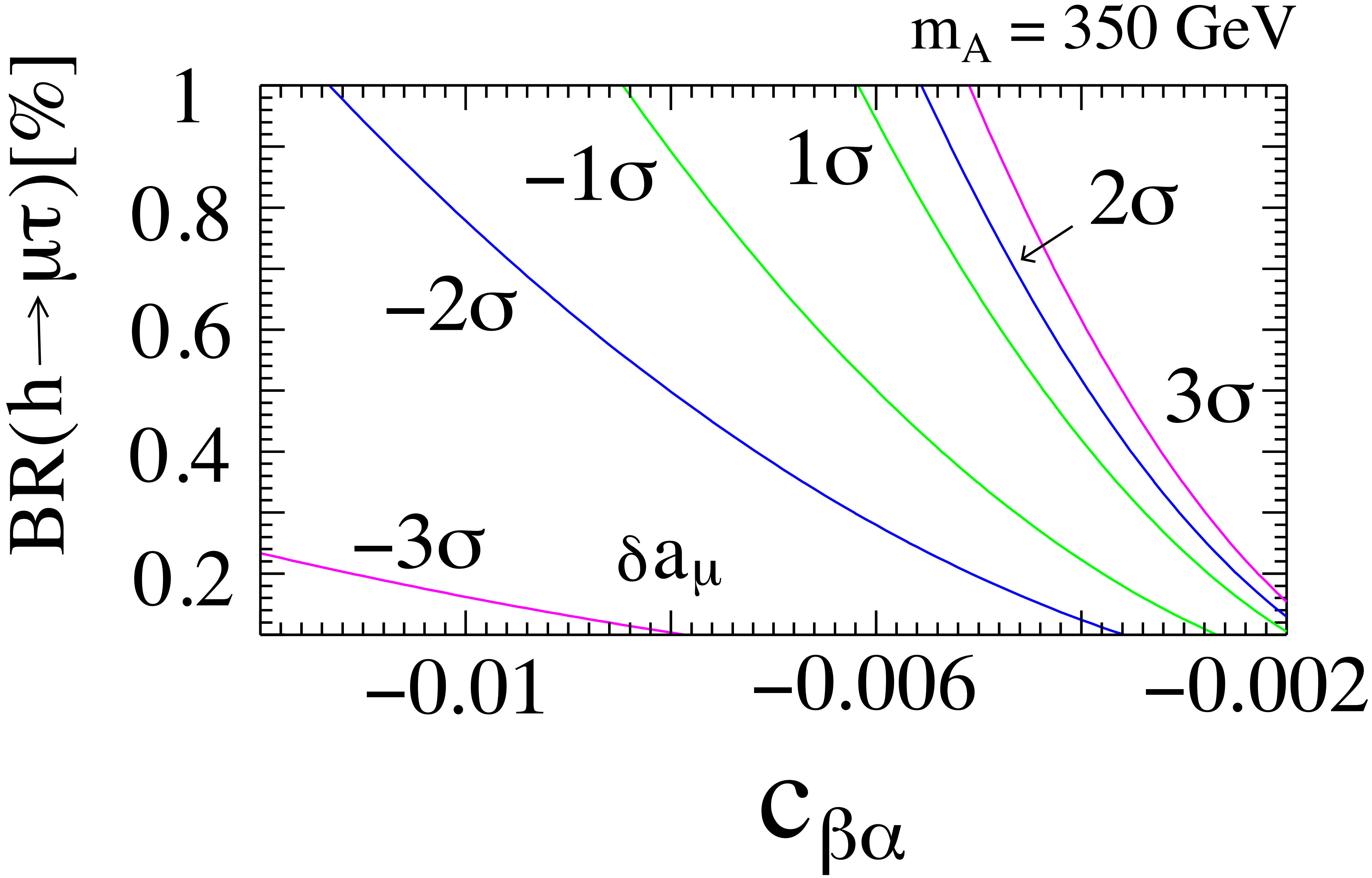
induced by the μ-τ flavor violating coupling



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

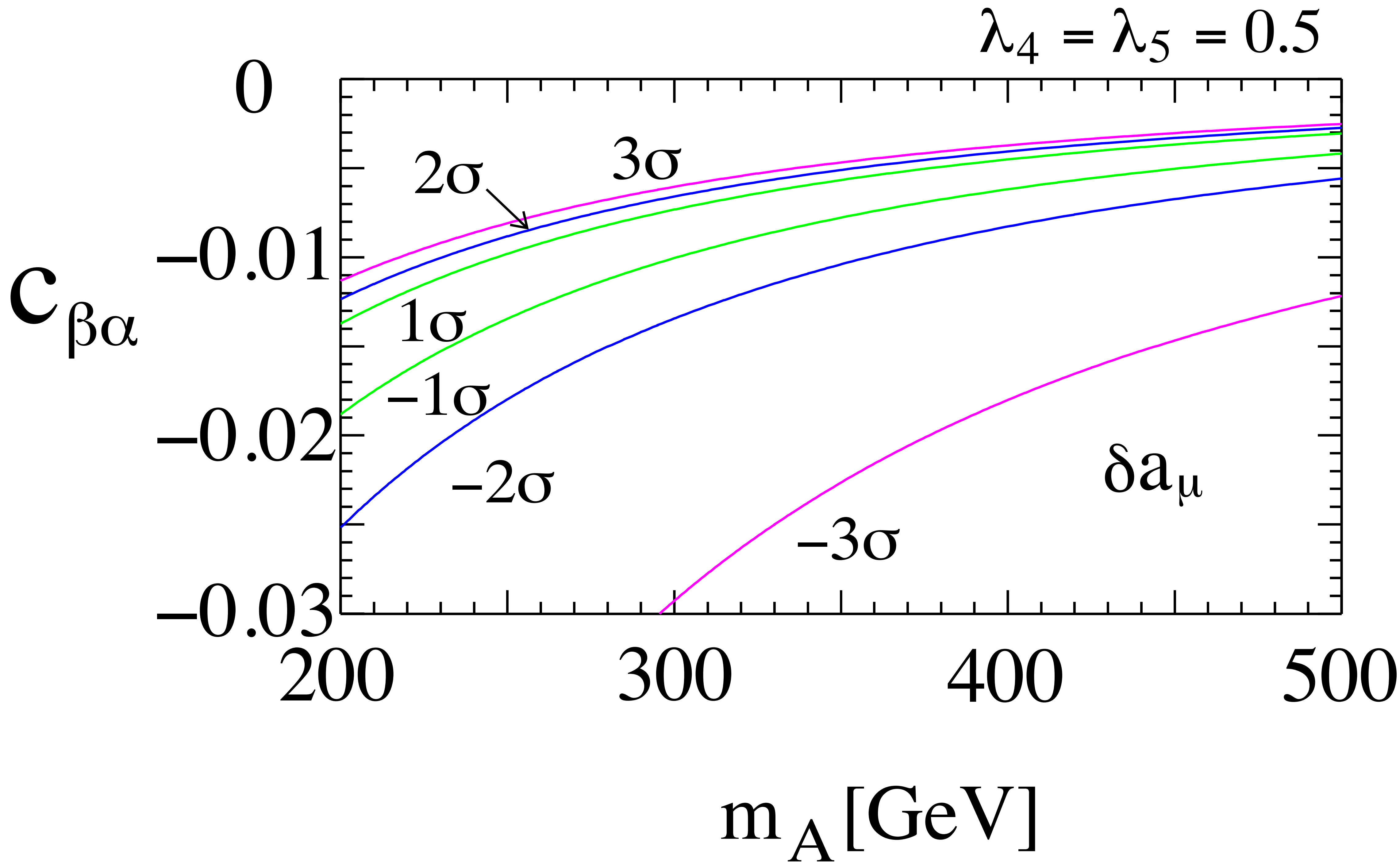
<u>The $\mu - \tau$ flavor-violating coupling can enhance the muon g-2</u>

muon g-2



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

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

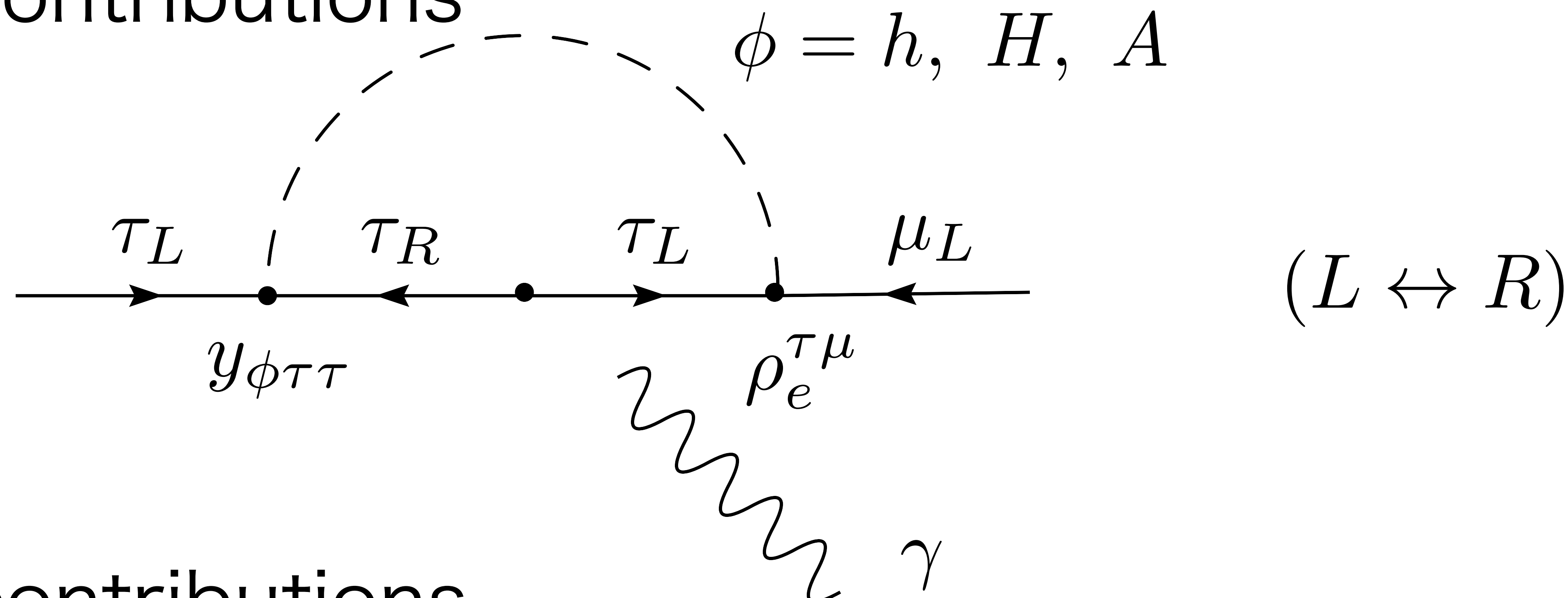


$|\, c_{\beta\alpha} \,|$ should be very small

Predictions (constraints)

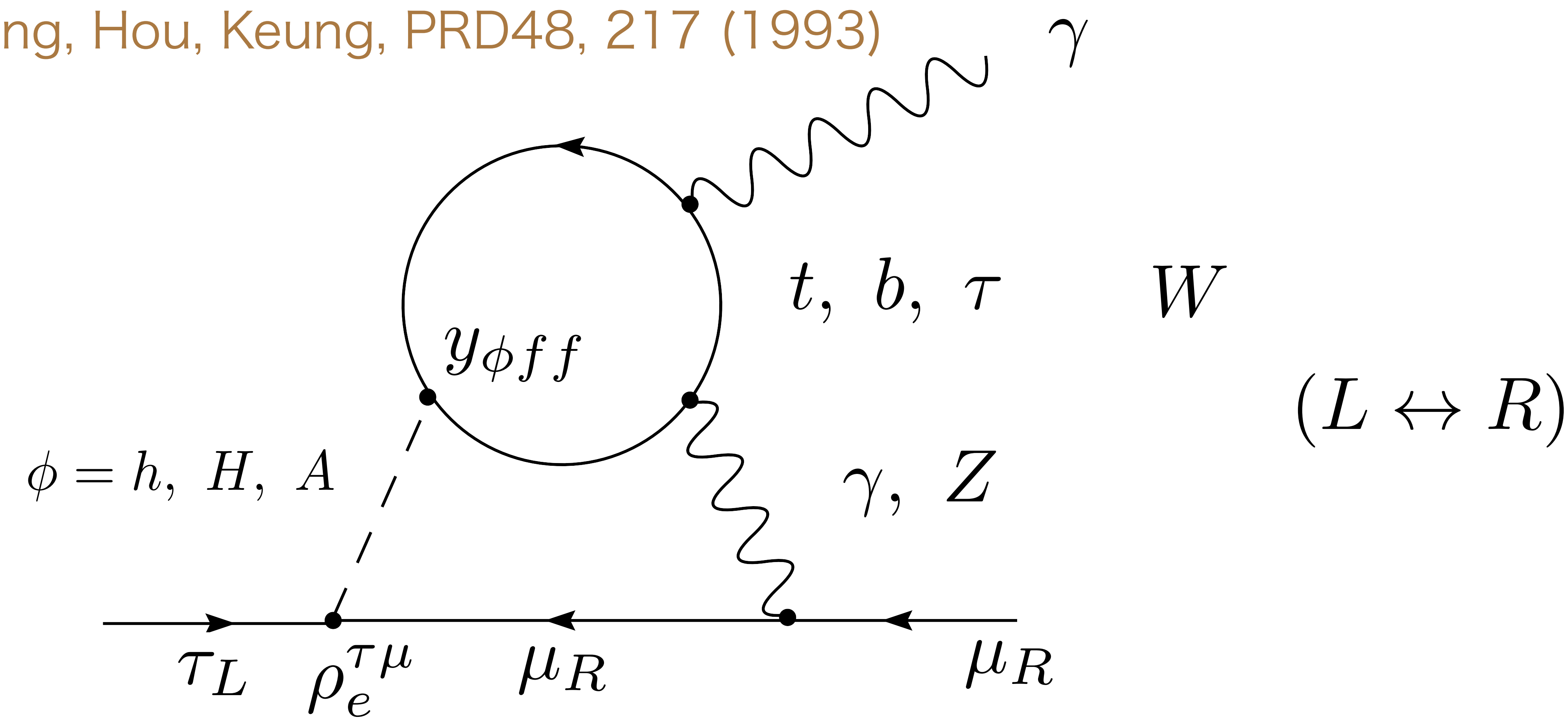
$\tau \to \mu\gamma$

1-loop contributions

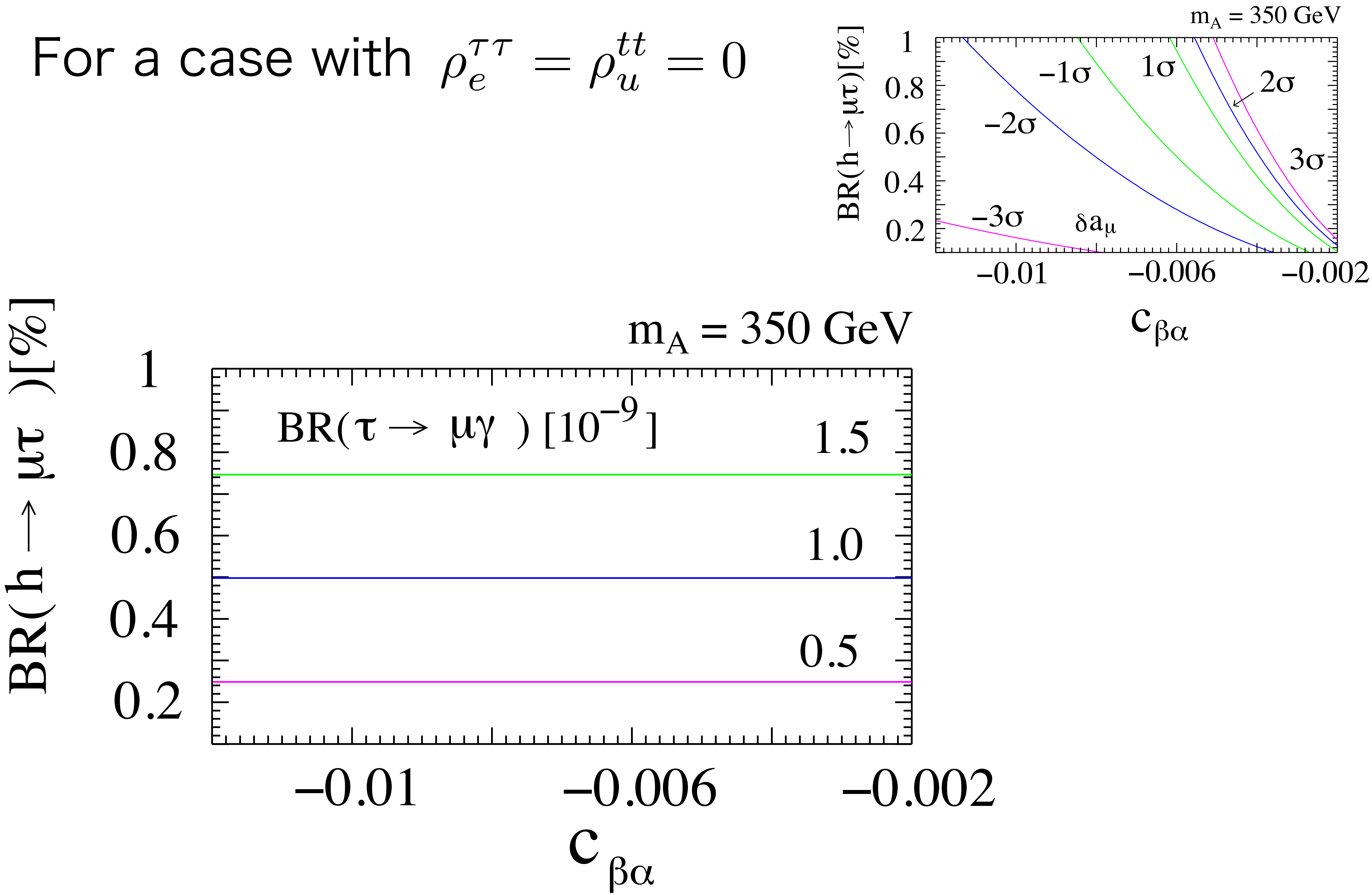


2-loop contributions

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



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

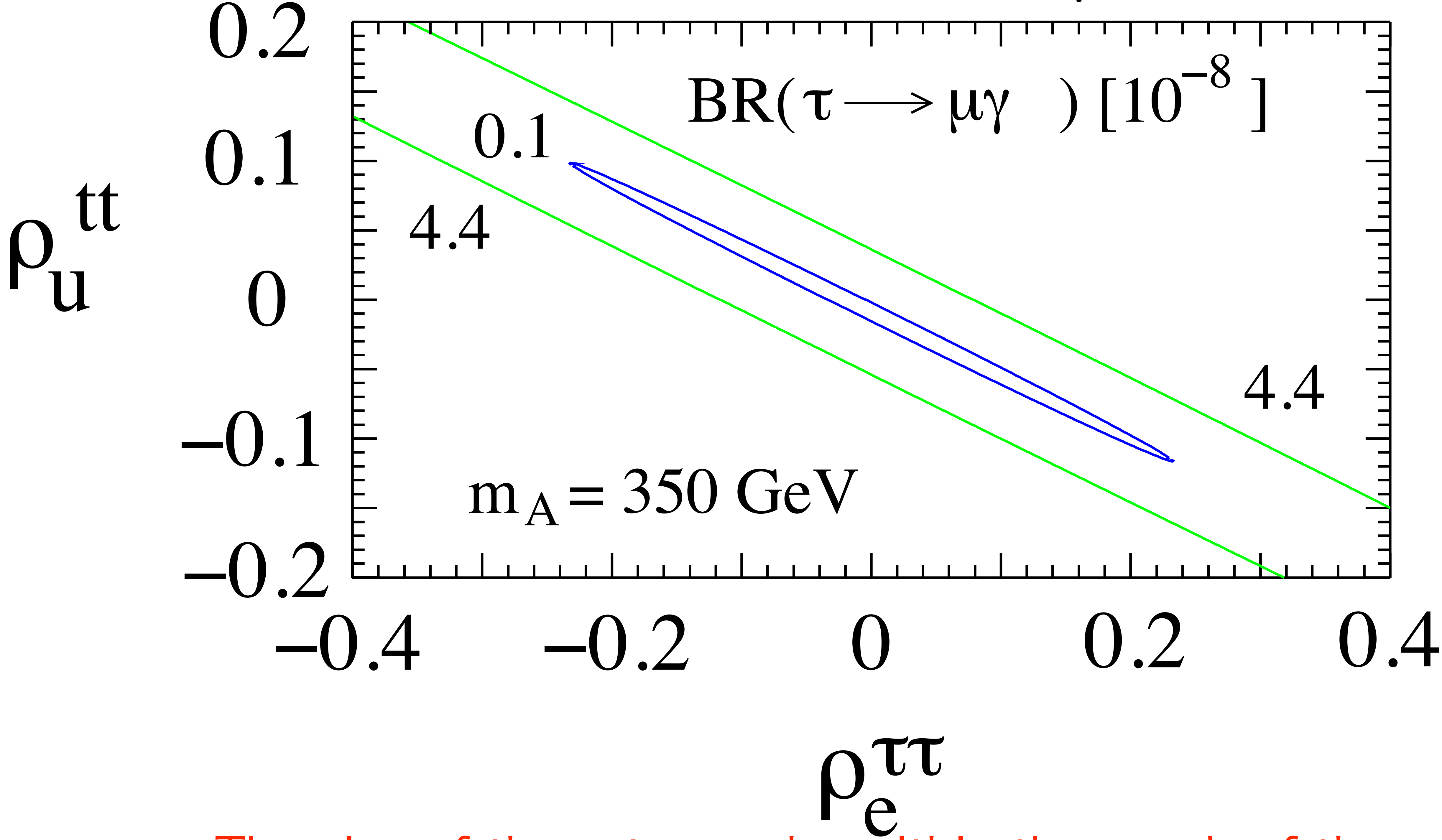


$\mathrm{BR}(\tau \to \mu\gamma)_{\mathrm{exp.}} < 4.4 \times 10^{-8}$

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

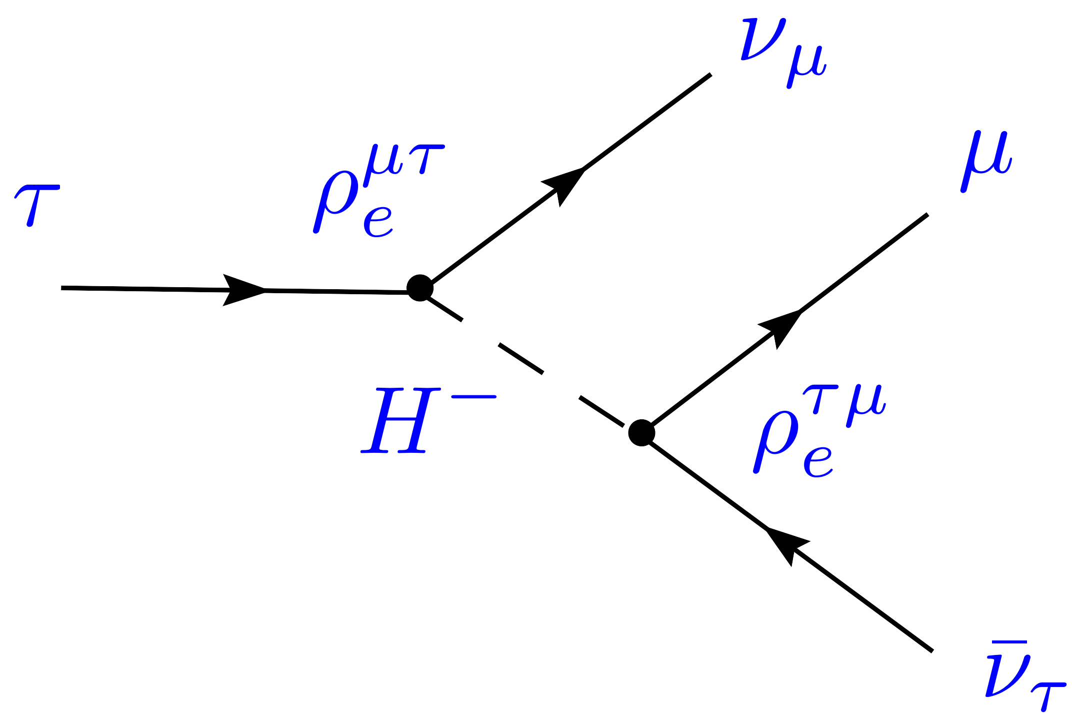
$$c_{\beta\alpha} = -0.007$$
$$\delta a_\mu = 2.2 \times 10^{-9}$$

BR(h → μτ) = 0.84%



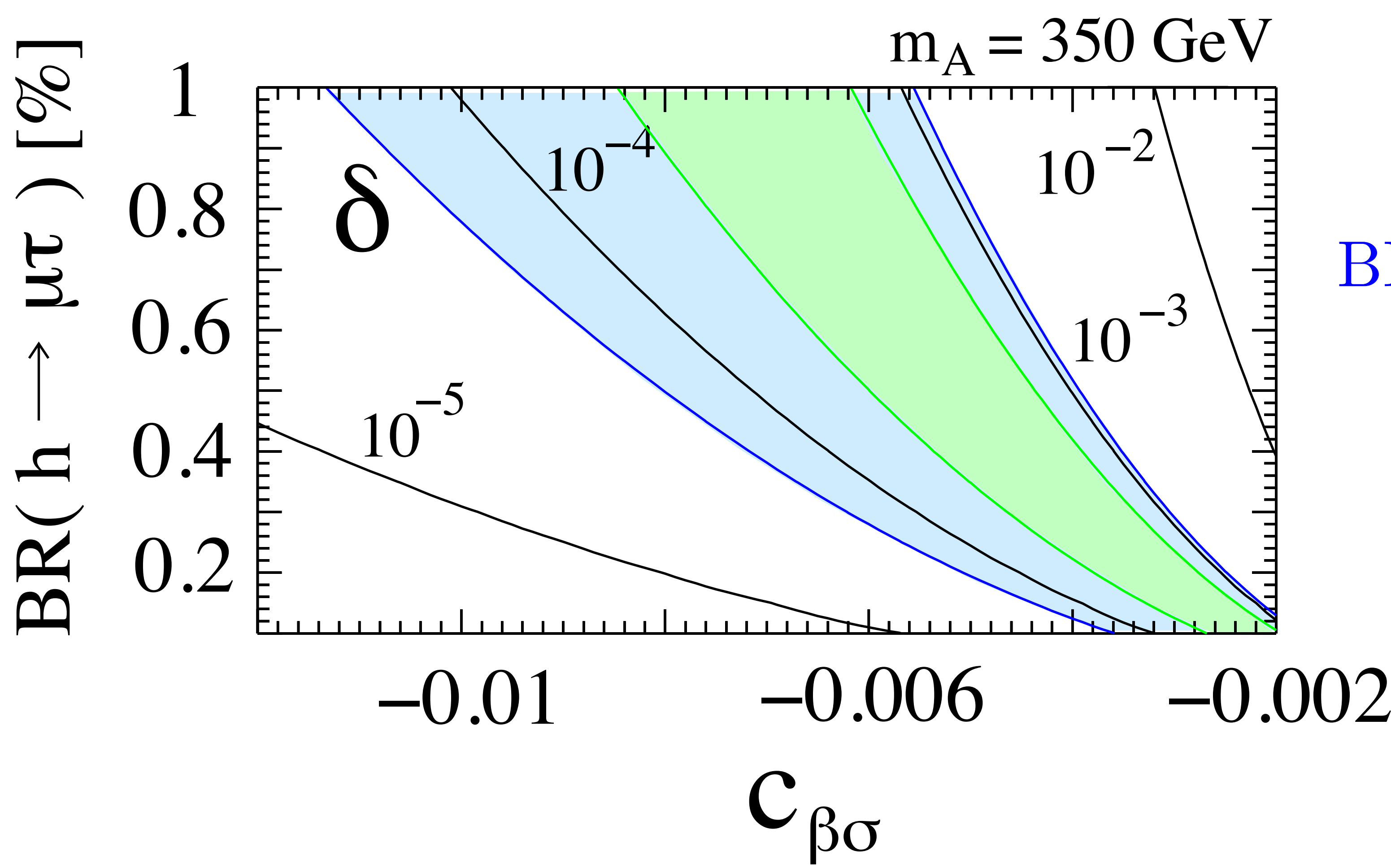
The size of the rate can be within the reach of the future B-factory

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



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

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



$\mathrm{BR}(\tau \to \mu\nu\bar{\nu}) = (17.41 \pm 0.04)\%$

$\delta_{\text{"exp"}} \sim 2 \times 10^{-3}$

Note: BABAR collaboration

lepton universality measurement

PRL 105, 051602 (2010)

$$\left(\frac{g_\mu}{g_e}\right)_\tau^2 = \frac{\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau)} \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)},$$

$$\left(\frac{g_\mu}{g_e}\right) = 1.0036 \pm 0.0020 \;\; (\mathrm{BaBar})$$

$$= 1 + \frac{1}{2}\delta \quad (\mathrm{our\ model})$$

The precise measurement may be important.

Belle’s result will 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.

★ $\tau \to \mu\gamma$ and $\tau \to \mu\nu\bar{\nu}$ are interesting in this scenario

Process	typical value	observability
muon g-2	$\delta a_\mu = (2.6 \pm 0.8) \times 10^{-9}$	(input)
$\tau \to \mu\gamma$	BR $\leq 10^{-9}$	$\circ$
$\tau \to e\gamma$	small	$\times$
$\tau \to \mu l^+ l^-$ $(l = e,\ \mu)$	depends on $\rho_e^{\mu\mu}$ and ρ_e^{ee}	$(\circ)$
$\tau^- \to e^- l^+ l^-,\ e^-\mu^+ e^-,\ \mu^- e^+ \mu^-$	small	$\times$
$\tau \to \mu\eta$	depends on ρ_d^{ss}	$(\circ)$
$\tau \to \mu\nu\bar{\nu}$	$\delta \leq 10^{-3}$, lepton non-universality	$\triangle$
$\tau \to e\nu\bar{\nu}$	small, lepton non-universality	$\triangle$
$\mu \to e\gamma$	depends on $\rho_e^{\tau e(e\tau)}$ and $\rho_e^{\mu e(e\mu)}$	$(\circ)$
$\mu - e$ conversion	depends on $\rho_e^{\mu e(e\mu)}$ and $\rho_{d,u}^{ij}$	$(\circ)$
$\mu \to 3e$	BR $\leq 10^{-13}$	$(\circ)$
muon EDM	$\lvert\delta d_\mu\rvert \leq 10^{-22} e \cdot \mathrm{cm}$	$(\circ)$
electron g-2	small	$\times$

LFV Higgs decay mode	BR	
$h \to \mu\tau$	$\mathrm{BR} = (0.84^{+0.39}_{-0.37})\%$	(input)
$h \to e\tau$	small	$\times$
$h \to e\mu$	small	$\times$

★ Flavor physics in quark sector should be interesting

★ interplay between LHC and flavor physics is important

Backup slides

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

CMS: arXiv: 1502.07400

Table 6: Event yields in the signal region, $100 < M_{col} < 150\,\text{GeV}$ after fitting for signal and background. The expected contributions are normalized to an integrated luminosity of $19.7\,\text{fb}^{-1}$. The LFV Higgs boson signal is the expected yield for $B(\text{H} \to \mu\tau) = 0.84\%$ with the SM Higgs boson cross section.

Sample	$\text{H} \to \mu\tau_h$			$\text{H} \to \mu\tau_e$		
	0-Jet	1-Jet	2-Jets	0-Jet	1-Jet	2-Jets
misidentified leptons	1770 ± 530	377 ± 114	1.8 ± 1.0	42 ± 17	16 ± 7	1.1 ± 0.7
$\text{Z} \to \tau\tau$	187 ± 10	59 ± 4	0.4 ± 0.2	65 ± 3	39 ± 2	1.3 ± 0.2
ZZ, WW	46 ± 8	15 ± 3	0.2 ± 0.2	41 ± 7	22 ± 4	0.7 ± 0.2
$\text{W}\gamma$	—	—	—	2 ± 2	2 ± 2	—
$\text{Z} \to \text{ee or } \mu\mu$	110 ± 23	20 ± 7	0.1 ± 0.1	1.6 ± 0.7	1.8 ± 0.8	—
$\text{t}\bar{\text{t}}$	2.2 ± 0.6	24 ± 3	0.9 ± 0.5	4.8 ± 0.7	30 ± 3	1.8 ± 0.4
$\text{t}\bar{\text{t}}$	2.2 ± 1.1	13 ± 3	0.5 ± 0.5	1.9 ± 0.2	6.8 ± 0.8	0.2 ± 0.1
SM H background	7.1 ± 1.3	5.3 ± 0.8	1.6 ± 0.5	1.9 ± 0.3	1.6 ± 0.2	0.6 ± 0.1
sum of backgrounds	2125 ± 530	513 ± 114	5.4 ± 1.4	160 ± 19	118 ± 9	5.6 ± 0.9
LFV Higgs boson signal	66 ± 18	30 ± 8	2.9 ± 1.1	23 ± 6	13 ± 3	1.2 ± 0.3
data	2147	511	10	180	128	6

a best fit: $\text{BR}(h \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$

2.4 σ excess

neutral Higgs mass spectrum from tree level potential

potential

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

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

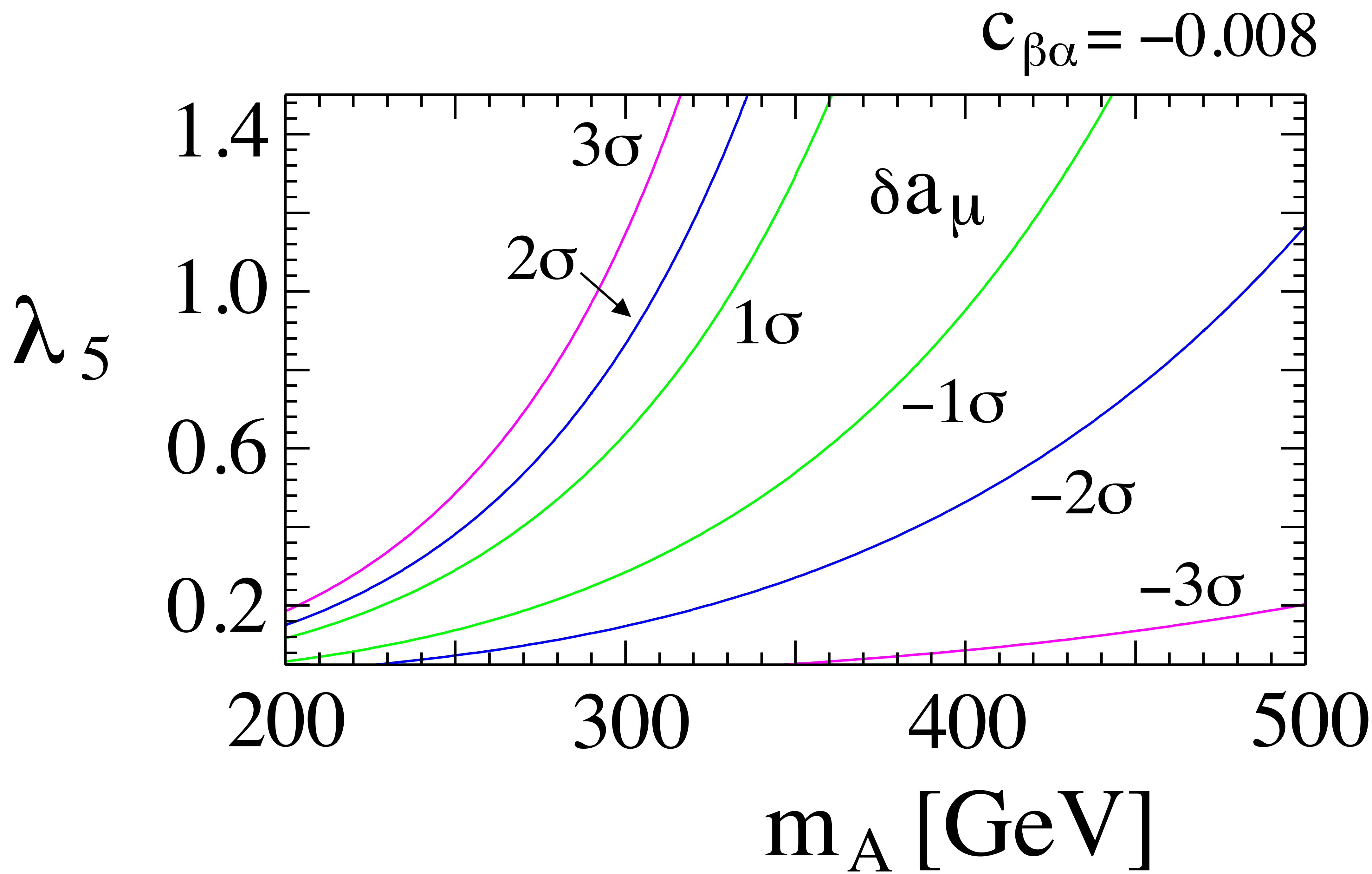
the small $c_{\beta\alpha}$ suppresses the correction

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

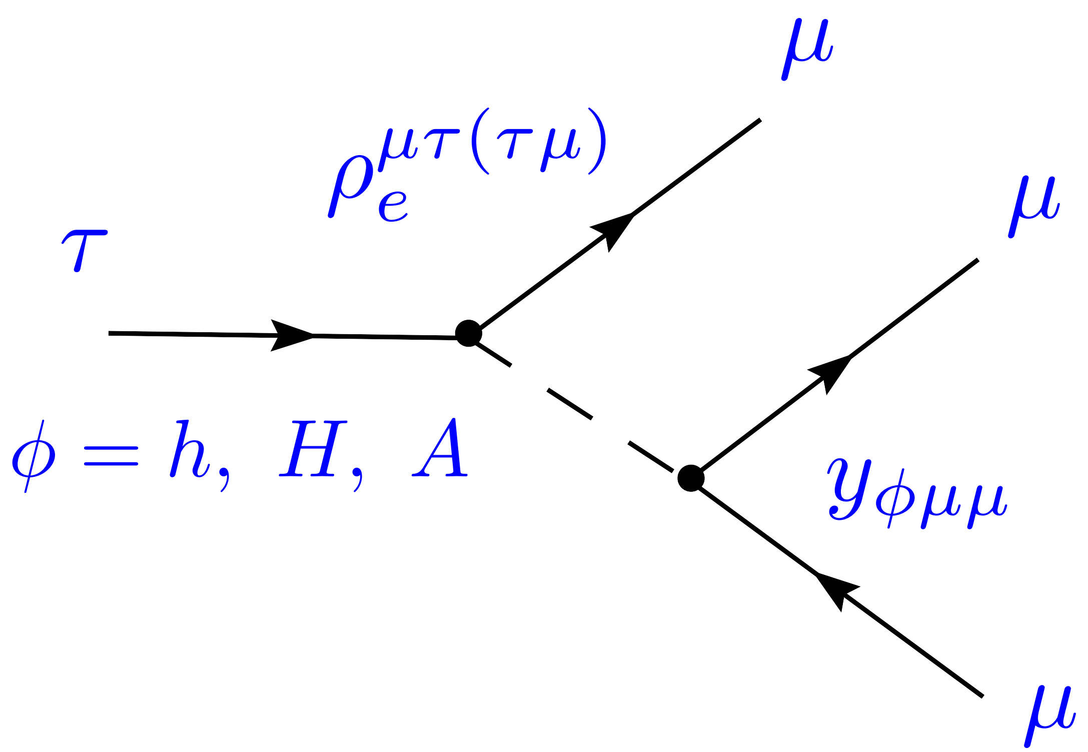
Note:

$$\delta a_\mu \simeq \frac{m_\mu m_\tau \rho_e^{\mu\tau} \rho_e^{\tau\mu}}{16\pi^2} \left[\frac{c_{\beta\alpha}^2 (\log \frac{m_h^2}{m_\tau^2} - \frac{3}{2})}{m_h^2} + \frac{s_{\beta\alpha}^2 (\log \frac{m_H^2}{m_\tau^2} - \frac{3}{2})}{m_H^2} - \frac{\log \frac{m_A^2}{m_\tau^2} - \frac{3}{2}}{m_A^2} \right],$$

If all neutral Higgs bosons are degenerate,
the new contributions are suppressed



$c_{\beta\alpha} = -0.008$
1.4
1.0
0.6
0.2
λ_5
3σ
2σ
1σ
δa_μ
−1σ
−2σ
−3σ
200
300
400
500
m_A [GeV]



Even if other ρ_f (other than $\rho_e^{\mu\tau(\tau\mu)}$) are negligible,

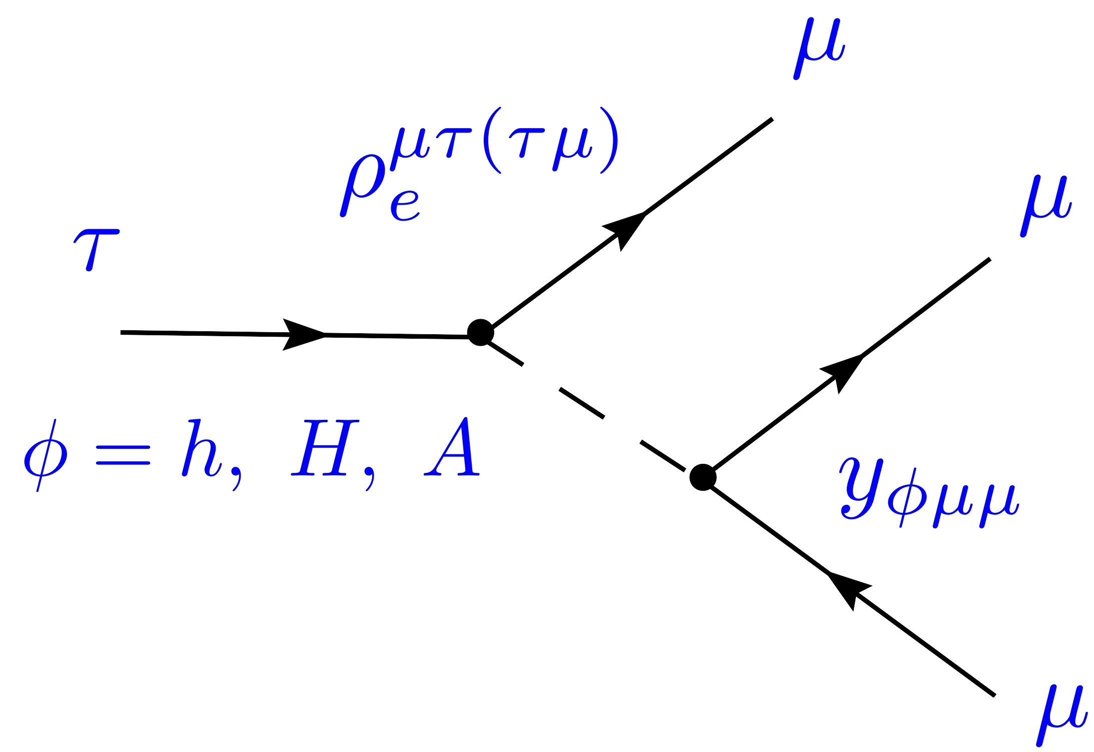
non-zero rate of $\tau \to 3\mu$ is predicted

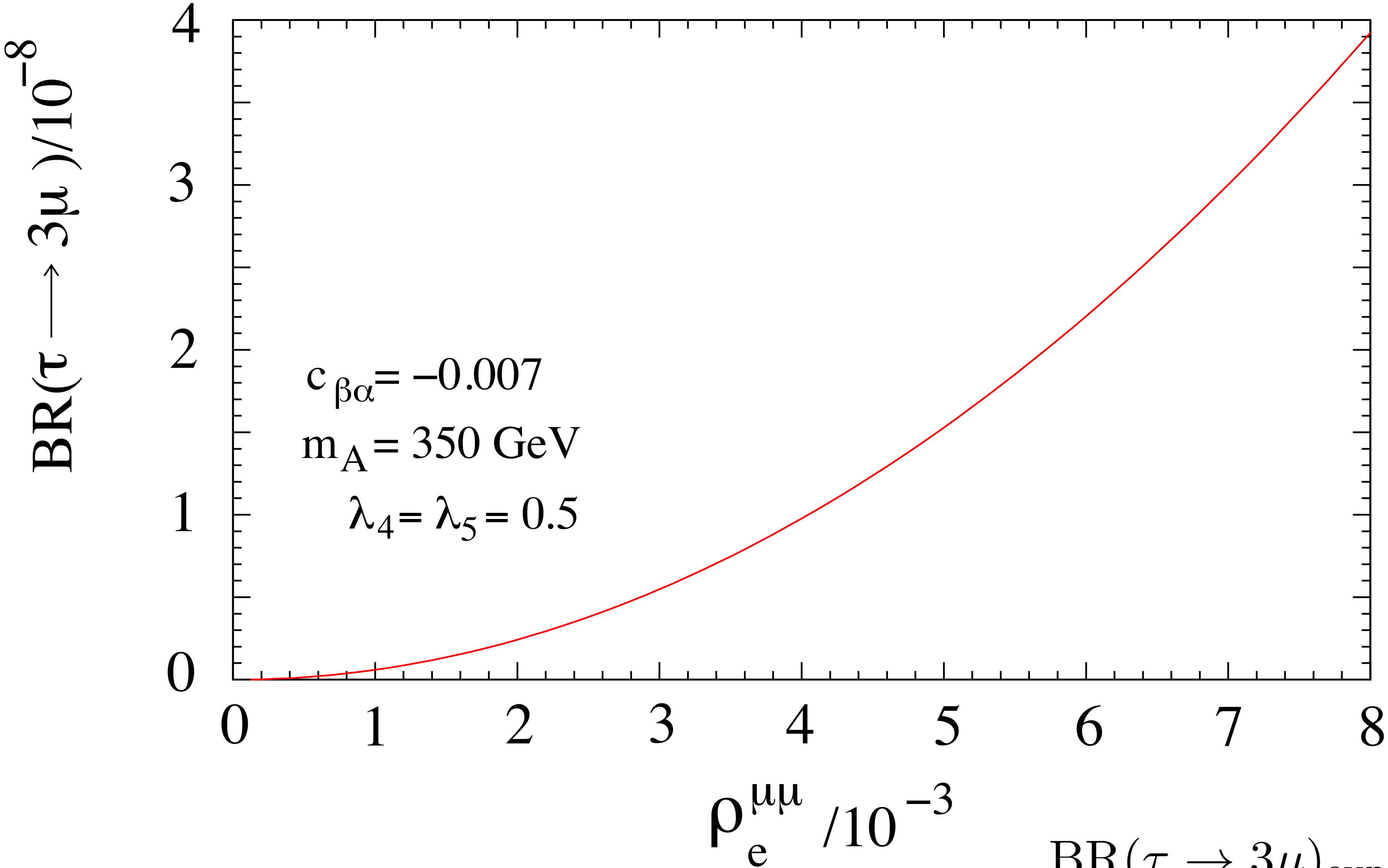
$$\mathrm{BR}(\tau \to 3\mu)_{\mathrm{exp.}} < 2.1 \times 10^{-8}$$

but it is very small $O(10^{-13} - 10^{-12})$

(since muon Yukawa is very small)

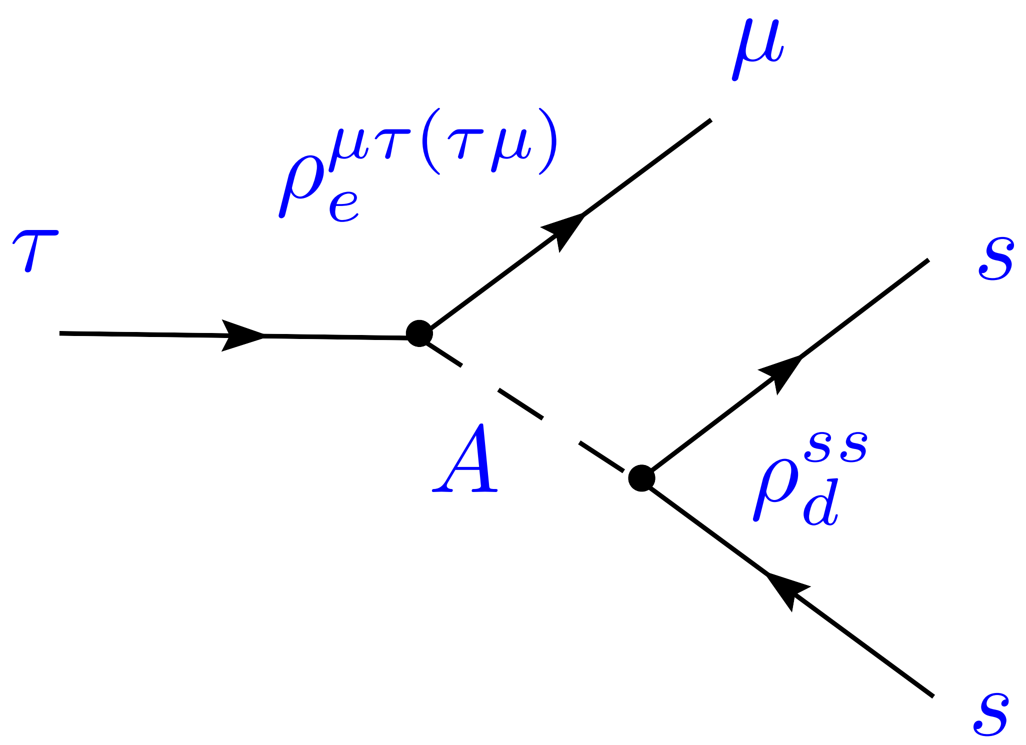
$$y_\mu = \frac{\sqrt{2} m_\mu}{v} \sim 6 \times 10^{-4}$$





$\mathrm{BR}(\tau \to 3\mu)_{\mathrm{exp.}} < 2.1 \times 10^{-8}$

$\tau \to \mu\eta$



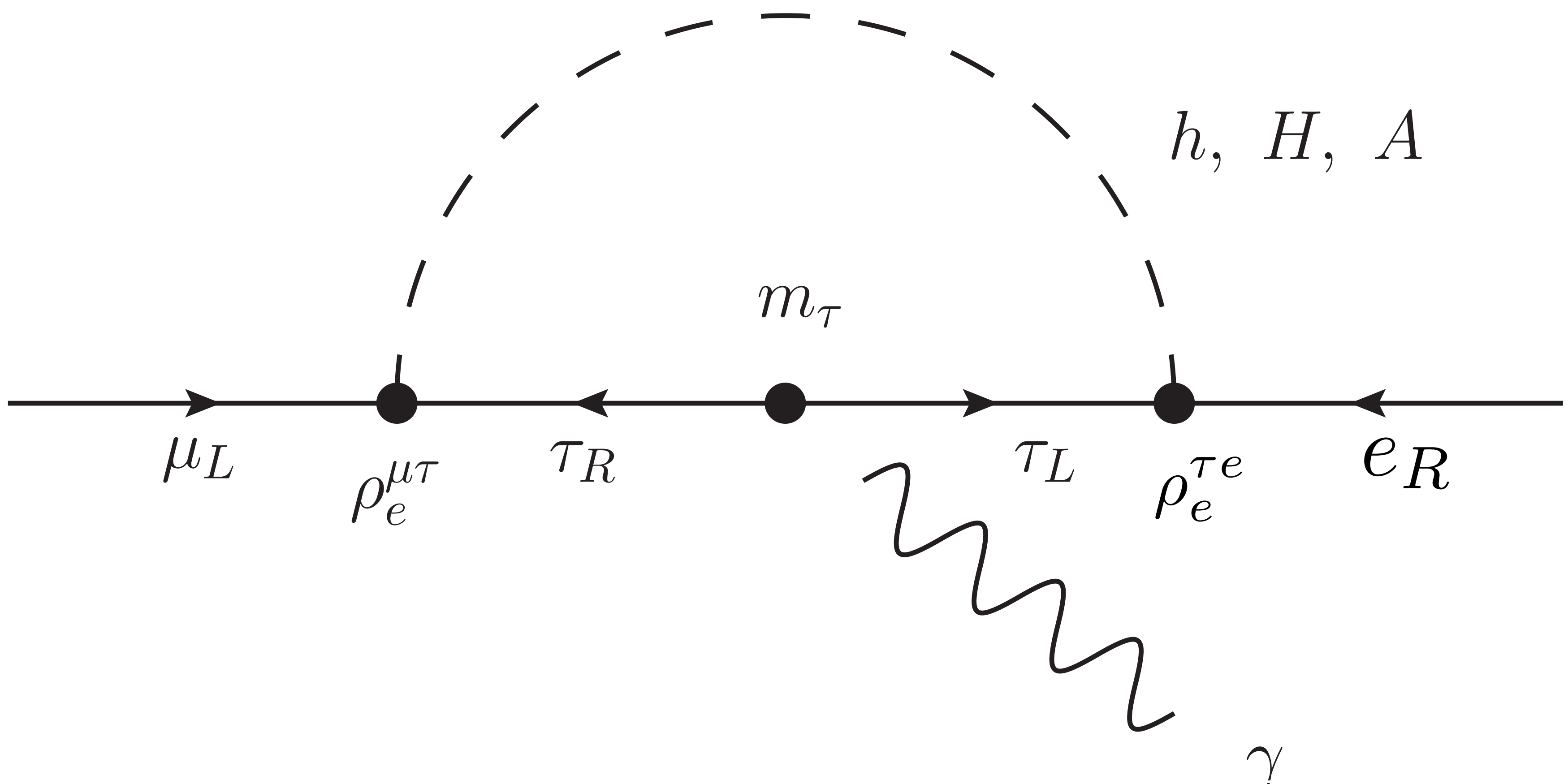
$$\mathrm{BR}(\tau \to \mu\eta)_{\mathrm{exp.}} < 6.5 \times 10^{-8}$$

$$|\rho_d^{ss}| < 0.007 \left(\frac{0.3}{\bar{\rho}^{\mu\tau}}\right)\left(\frac{m_A}{350\ \mathrm{GeV}}\right)^2$$

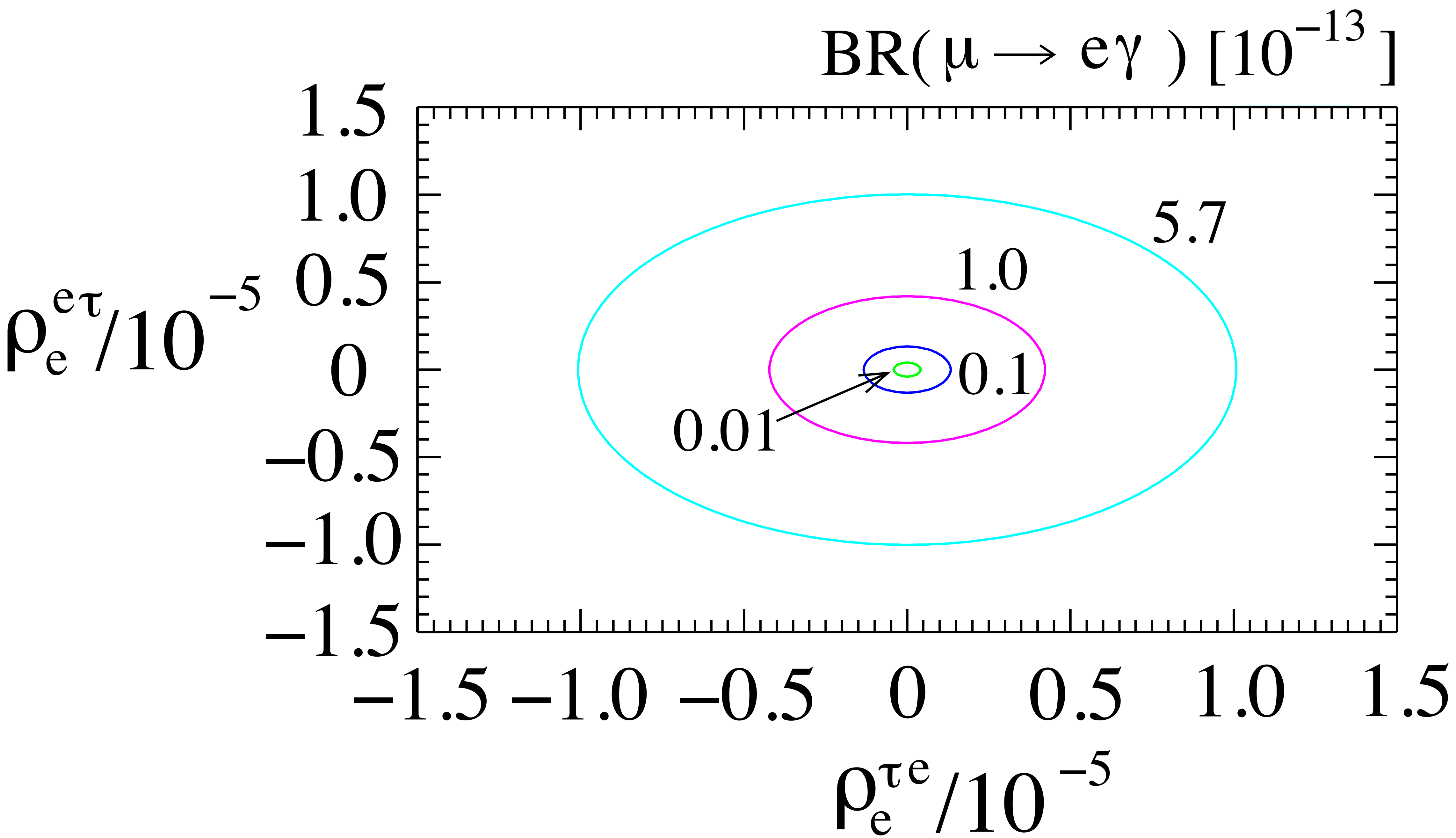
Note: $y_s = \frac{\sqrt{s} m_s}{v} \simeq 5 \times 10^{-4}$

Other lepton flavor violating Yukawa couplings (e-τ, e-μ couplings) are strongly constrained from $\mu \to e\gamma$ process

e-τ flavor violation



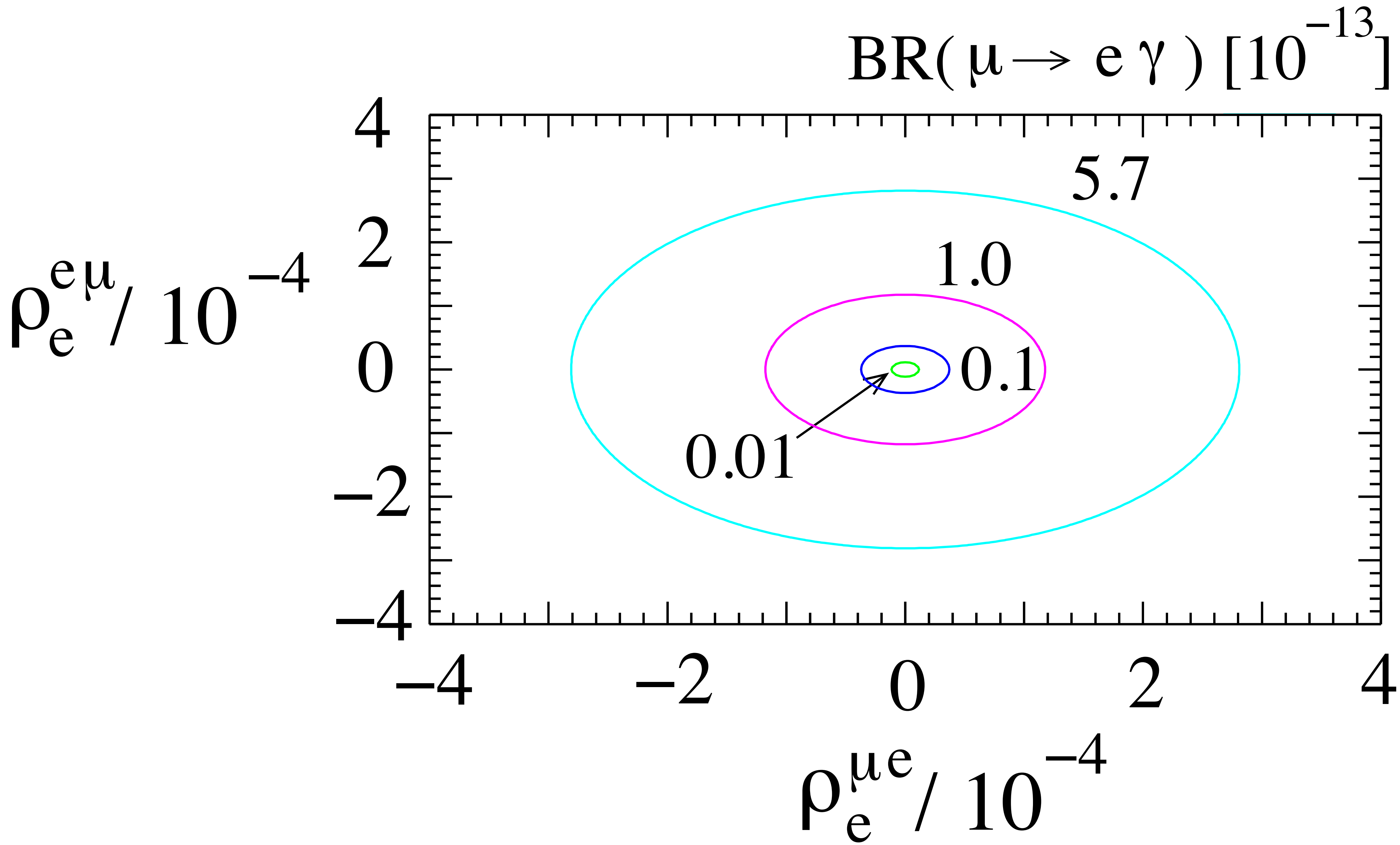
large enhancement



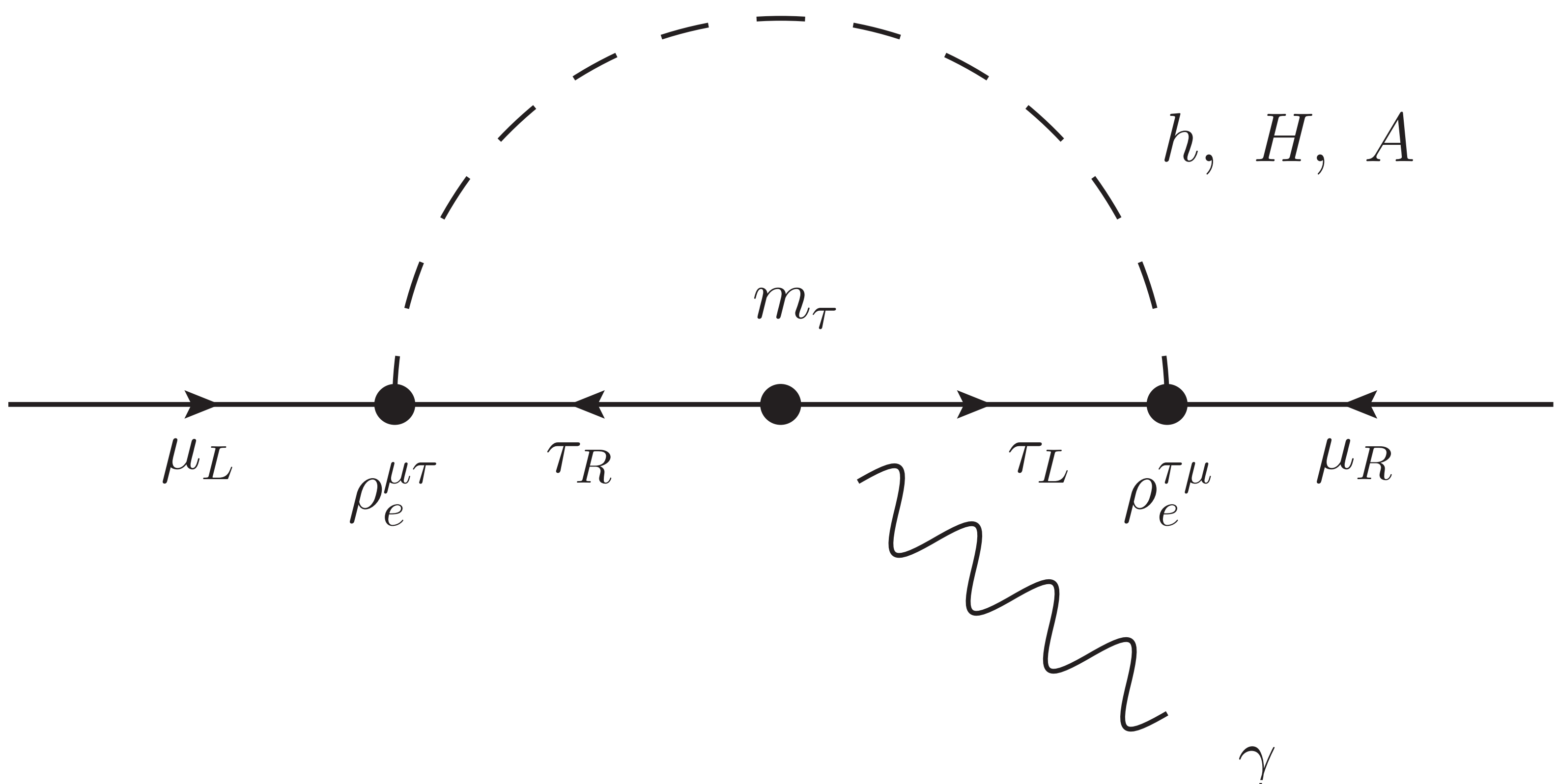
strongly constrained

e-μ flavor violation

similar to $\tau \to \mu \gamma$, 2-loop contributions are important



Muon electric dipole moment (muon EDM)



$$\rho_e^{\mu\tau}\rho_e^{\tau\mu} = |\rho_e^{\mu\tau}\rho_e^{\tau\mu}|e^{i\phi}$$

imaginary parts of the Yukawas induce the muon EDM

$$\mathcal{L} = \bar{\mu}\sigma^{\mu\nu}\left(\frac{e}{4m_\mu}\delta a_\mu - \frac{i}{2}\delta d_\mu \gamma_5\right)\mu F_{\mu\nu}.$$

A relation between δa_μ and δd_μ

$$\frac{\delta d_\mu}{\delta a_\mu} = -\frac{e\tan\phi}{2m_\mu}.$$

$$\frac{\delta d_\mu}{\delta a_\mu} = -\frac{e \tan\phi}{2m_\mu}.$$

Prediction

$$\delta d_\mu = -3 \times 10^{-22}\ e \cdot \mathrm{cm}\ \times \left(\frac{\tan\phi}{1.0}\right)\left(\frac{\delta a_\mu}{3 \times 10^{-9}}\right)$$

Current limit

$$|d_\mu| < 1.9 \times 10^{-19}\ e \cdot \mathrm{cm}\ (95\%\ \mathrm{C.L.})$$

Future (J-PARC)

$$d_\mu \sim 10^{-24}\ e \cdot \mathrm{cm}$$

future J-PARC experiment may have a sensitivity

$$\mu^- \to e^- e^+ e^-$$

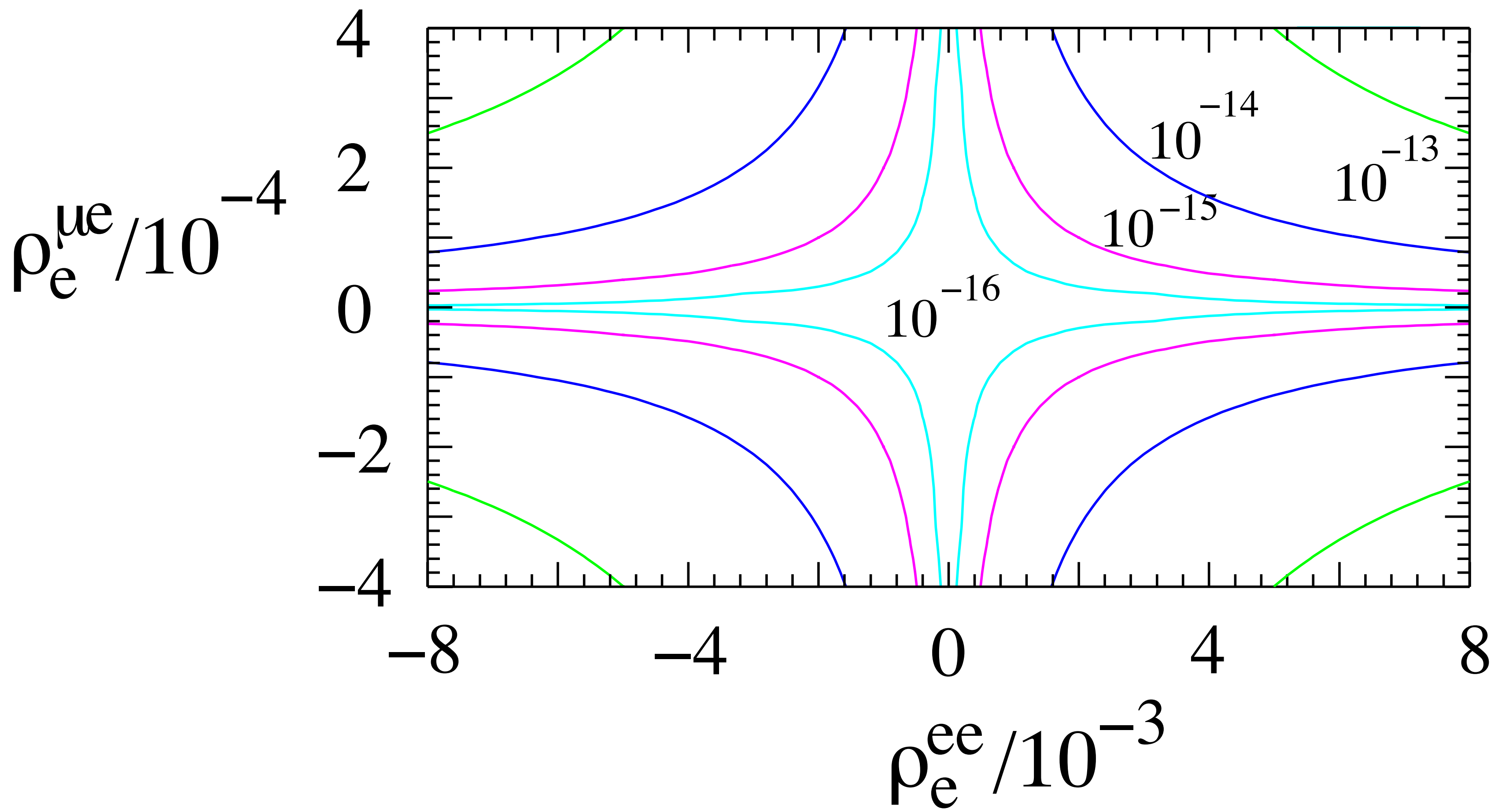


FIG. 12: BR($\mu \to 3e$) as a function of ρ_e^{ee} and $\rho_e^{\mu e}$. Here we have assumed that $\rho_e^{\mu e} = \rho_e^{e\mu}$, $c_{\beta\alpha} = -0.007$ and $m_A = 350$ GeV with $\lambda_4 = \lambda_5 = 0.5$.

Future Mu3e experiment ($\mathrm{BR} \sim 10^{-16}$) may have a sensitivity

Productions via gauge interaction are more predictive

$$q\bar{q}' \to W^{\pm *} \to AH^{\pm *}$$

Q.-H. Cao, S. Kanemura, C.-P. Yuan, PRD 69, 075008 (2004)

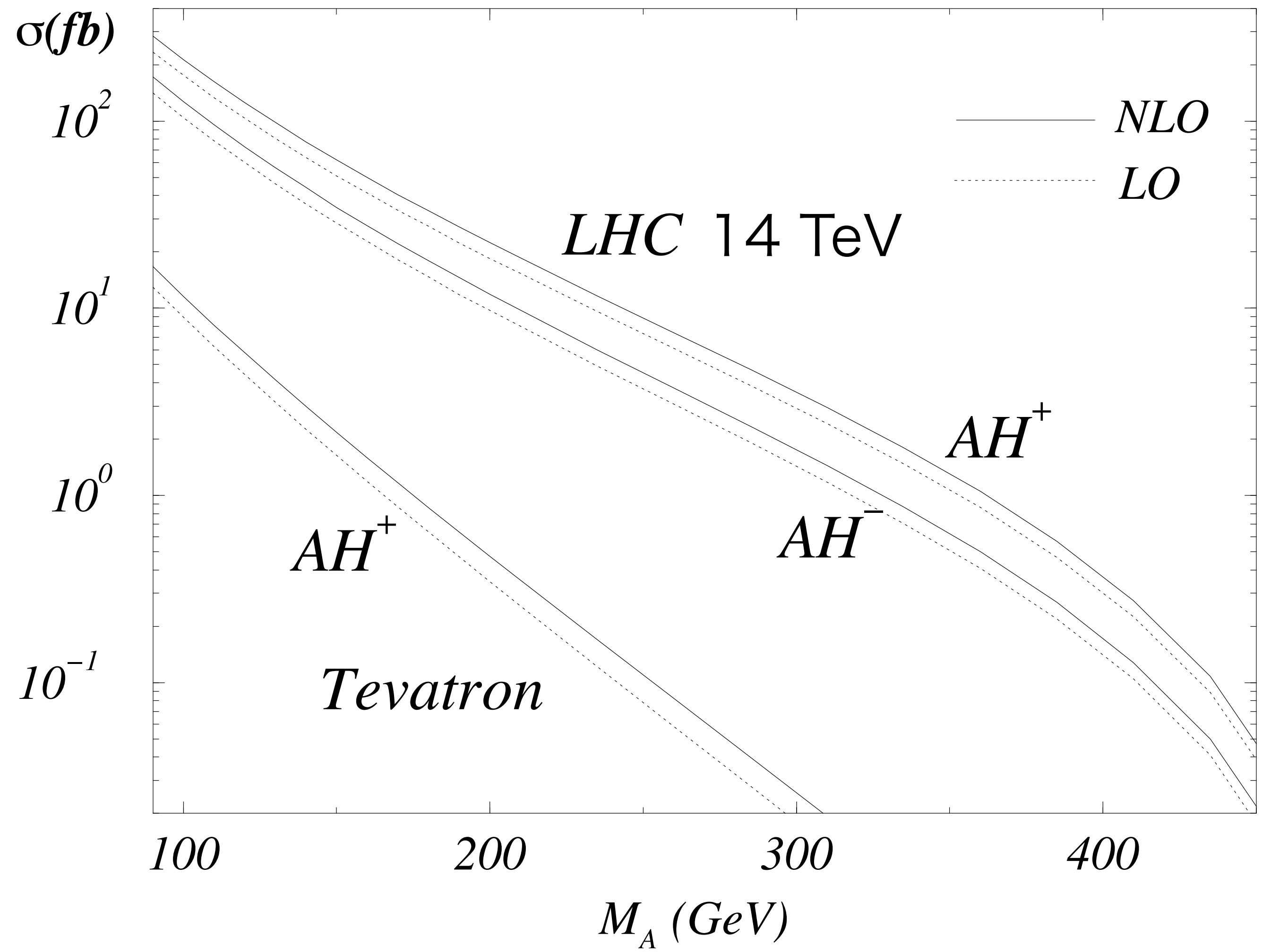
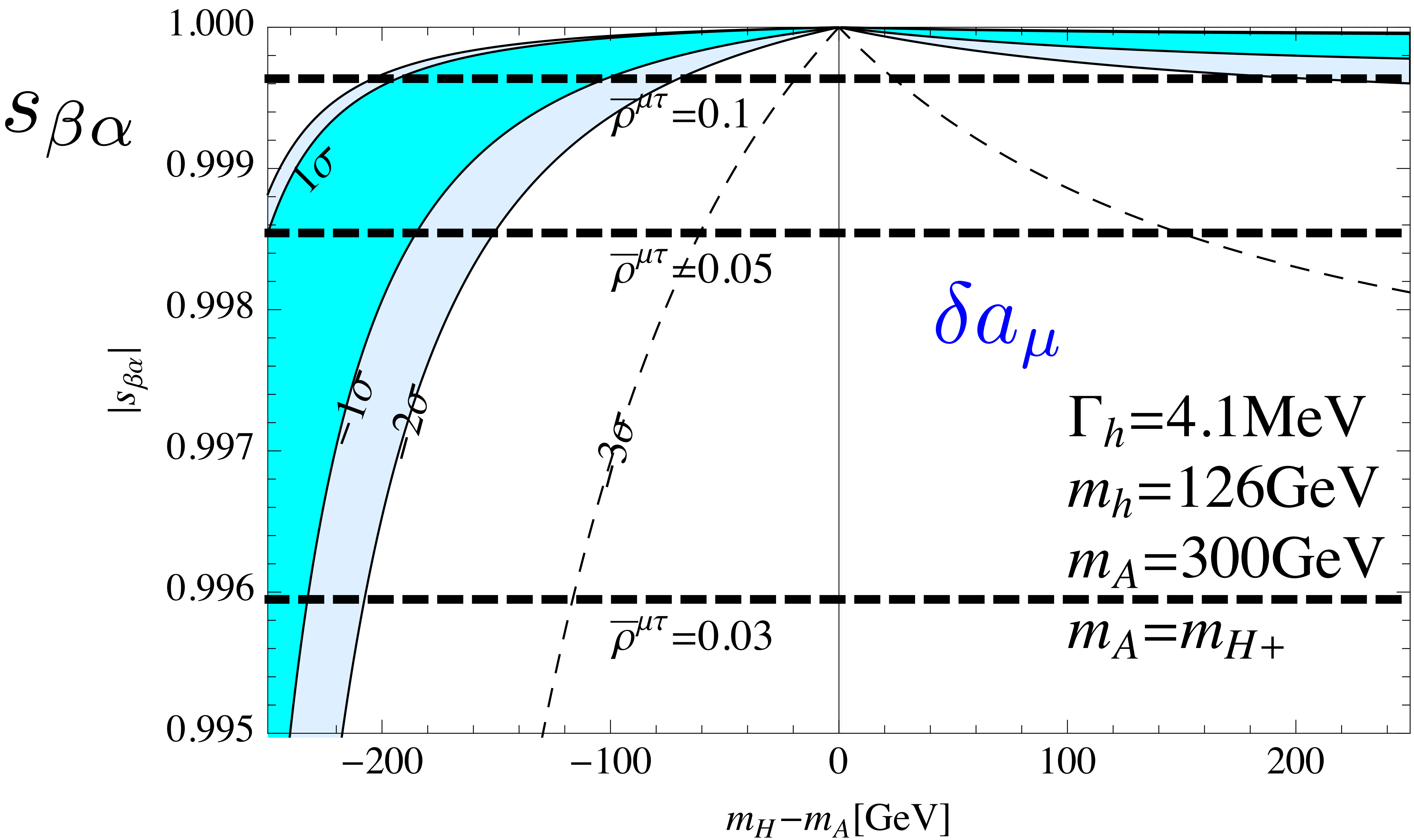


FIG. 1: The LO (dotted lines) and NLO QCD (solid lines) cross sections of the AH^+ and AH^- pairs as a function of M_A at the Tevatron (a 1.96 TeV $p\bar{p}$ collider), and the LHC (a 14 TeV pp collider). The cross sections for AH^+ and AH^- pair productions coincide at the Tevatron for being a $p\bar{p}$ collider.

$$\delta a_\mu = (26.1 \pm 8.0) \times 10^{-10}$$



- $s_{\beta\alpha}$ should be close to 1 ($c_{\beta\alpha}$ is very small)
- non-degeneracy among neutral Higgs bosons increases the muon g-2