Two Higgs doublet model with μ-τ flavor violation

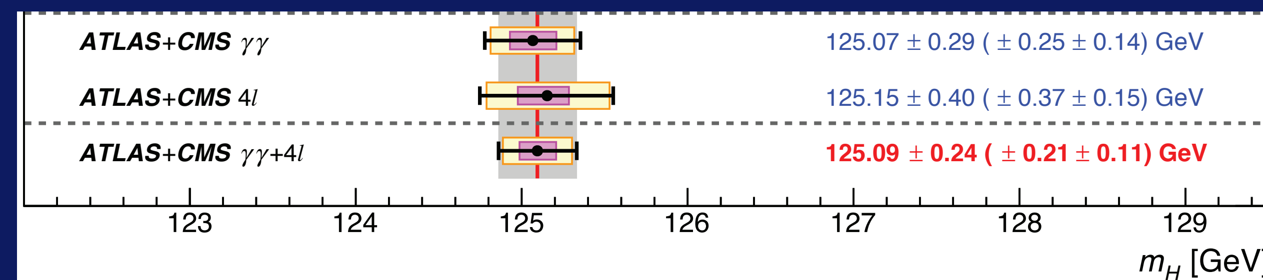
Kazuhiro Tobe

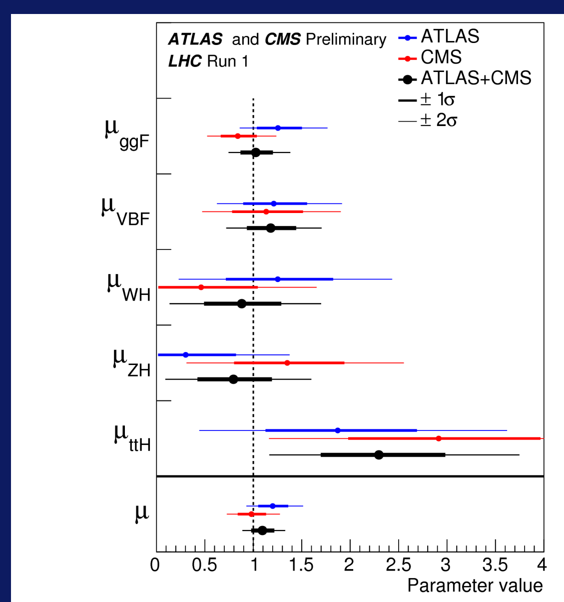
KMI topic, July 13 2016

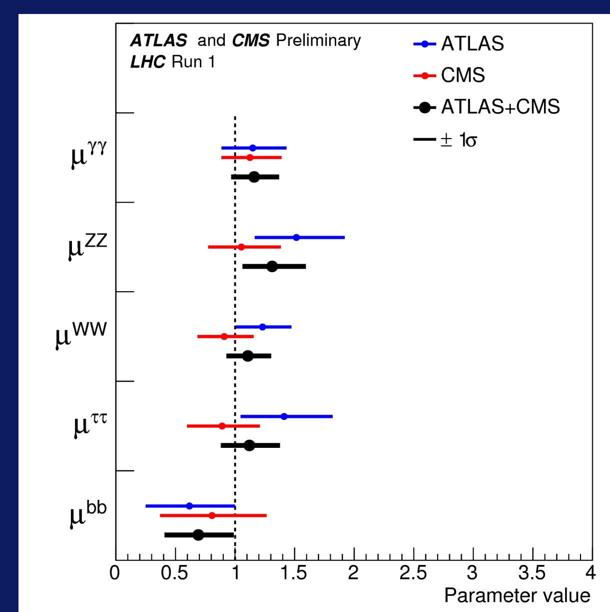
Refs. JHEP 1505, 028 (2015) [1502.07824], [1511.08880], Y. Omura, E. Senaha, K. Tobe +$\cdots$

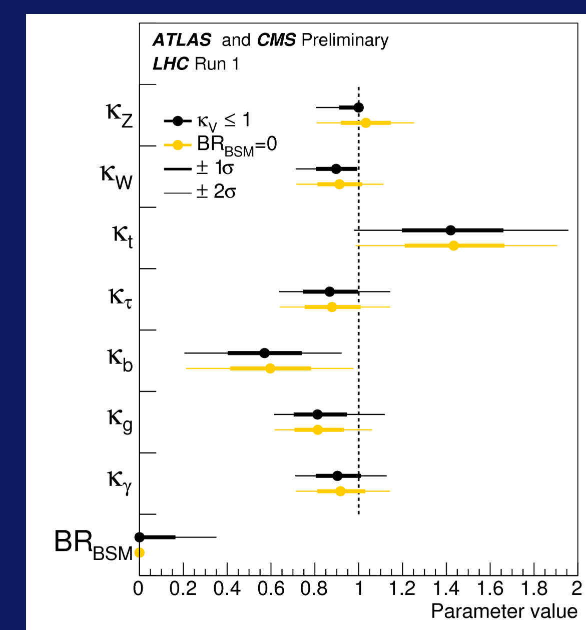
The 4th anniversary of Higgs boson discovery!

The Higgs turns 4!









Higgs production & decay signal strengths in good agreement with SM

Still direct measurement of bottom & top couplings subject to large uncertainties

Sizeable deviations from SM only possible if certain correlations present

HL- LHC : precision on most relevant couplings will be better than/about 10%

Slide from M. Carena @ SUSY 2016, July 4th, 2016

In the standard model,

Higgs sector: One Higgs doublet

minimal structure(?)

Matter sector: Three generations

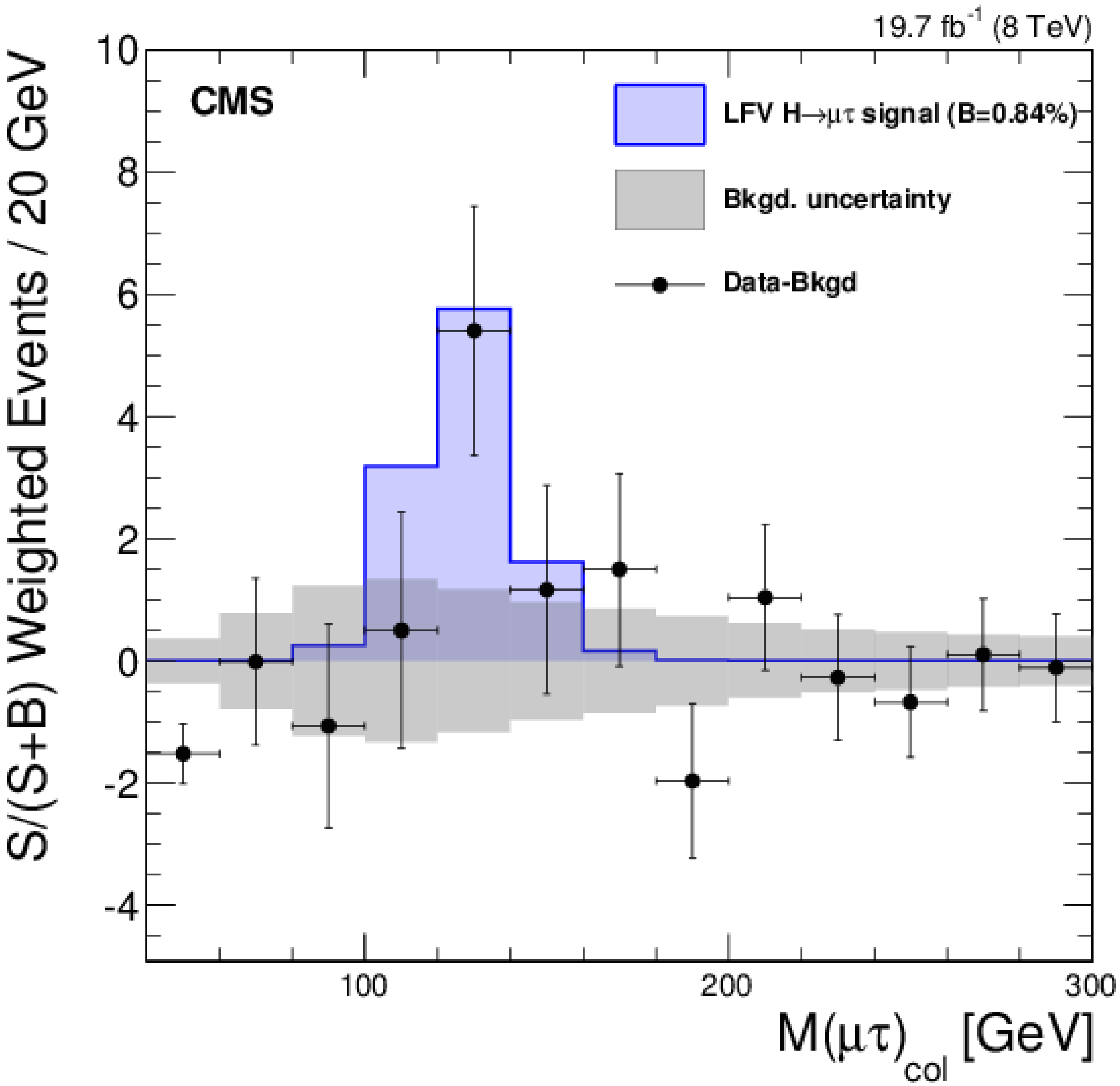
non-minimal structure

Kobayashi-Maskawa:
CP violation in K-system was a hint

Is Higgs sector really minimal?
Any experimental hint for non-minimal Higgs sector?

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

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



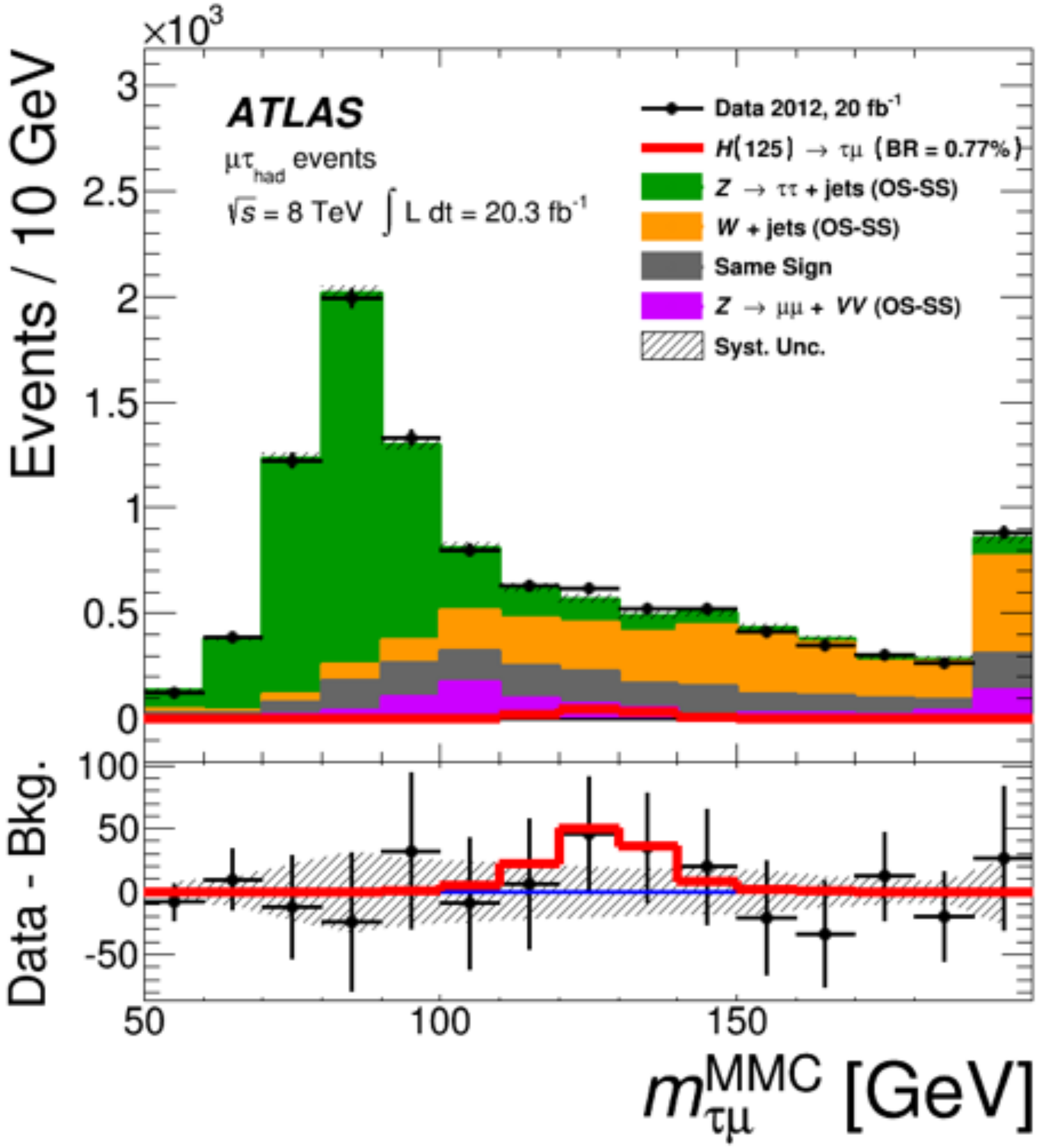
CMS best fit:

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

2.4σ excess

Hint for new physics?

Current status



ATLAS: arXiv: 1508.03372

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

New 13 TeV result from CMS

CMS PAS HIG-16-005

No excess is observed

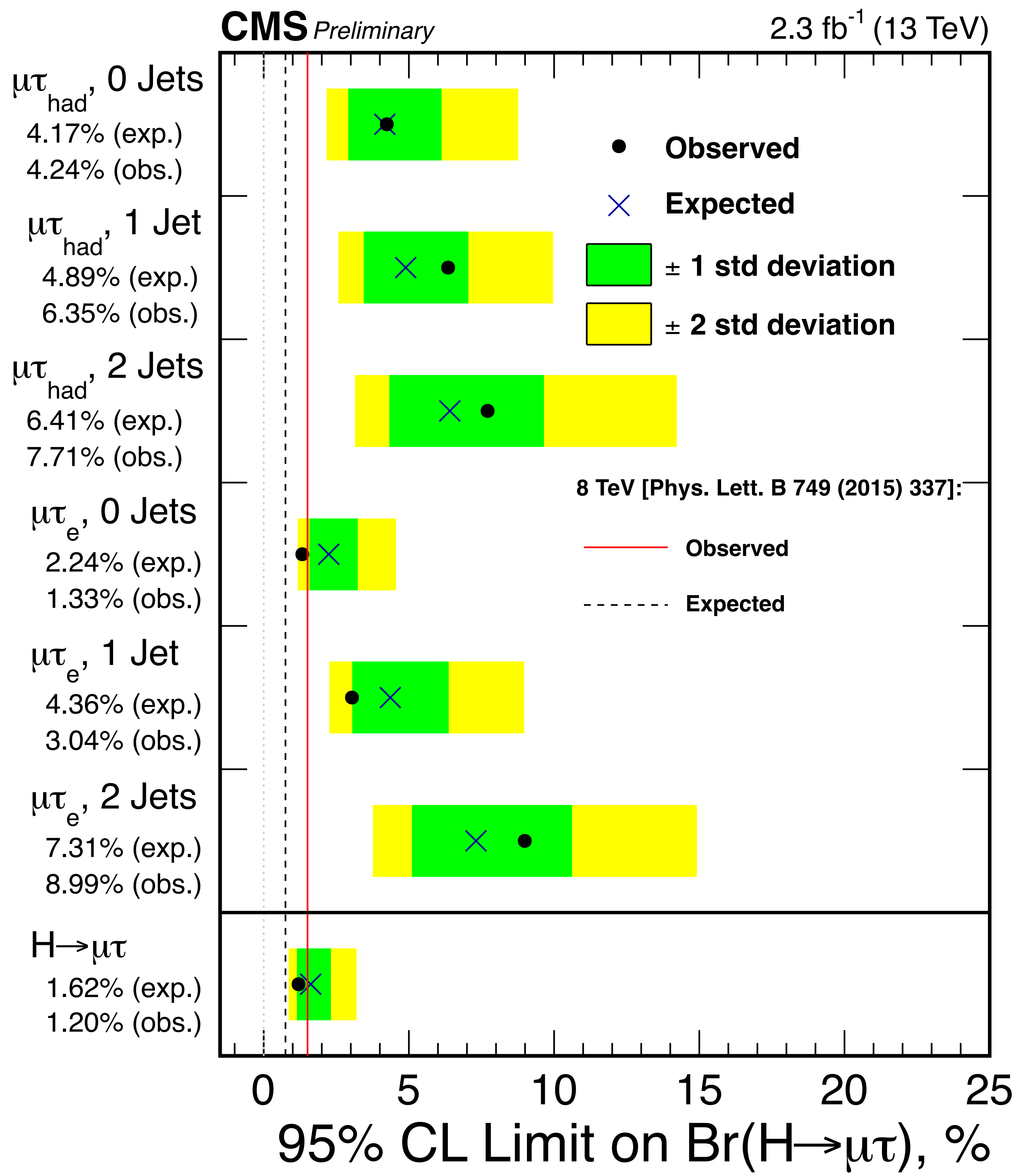


Figure 4: Observed and expected 95% CL upper limits on the $\mathcal{B}(H \to \mu\tau)$ for each individual category and combined. The solid red and dashed black vertical lines correspond, respectively, to the observed and expected 95% CL upper limits obtained at $\sqrt{s} = 8$ TeV [23].

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

If the CMS excess in h→$\mu\tau$ is real, ⋯⋯

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

What we found is ⋯⋯

μ-τ flavor violation in 2HDM can explain muon g-2 anomaly

h→$\mu\tau$

↕ Maybe related?

muon g-2 anomaly

muon g-2

magnetic moment

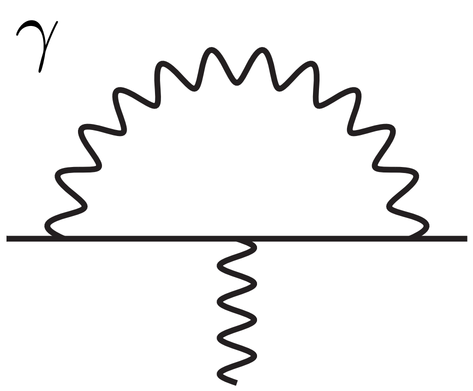
$$\mathcal{H} = -\vec{\mu} \cdot \vec{B}, \qquad \vec{\mu} = g \left(\frac{e}{2m} \right) \vec{S}$$

g-factor

- $g = 2$ at tree level (Dirac fermion)
- $g \neq 2$ by radiative corrections

$$a_\mu = \frac{g-2}{2}$$

anomalous magnetic moment
(muon g-2)



It can be a good test of the standard model
(including the quantum corrections)

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

Contents

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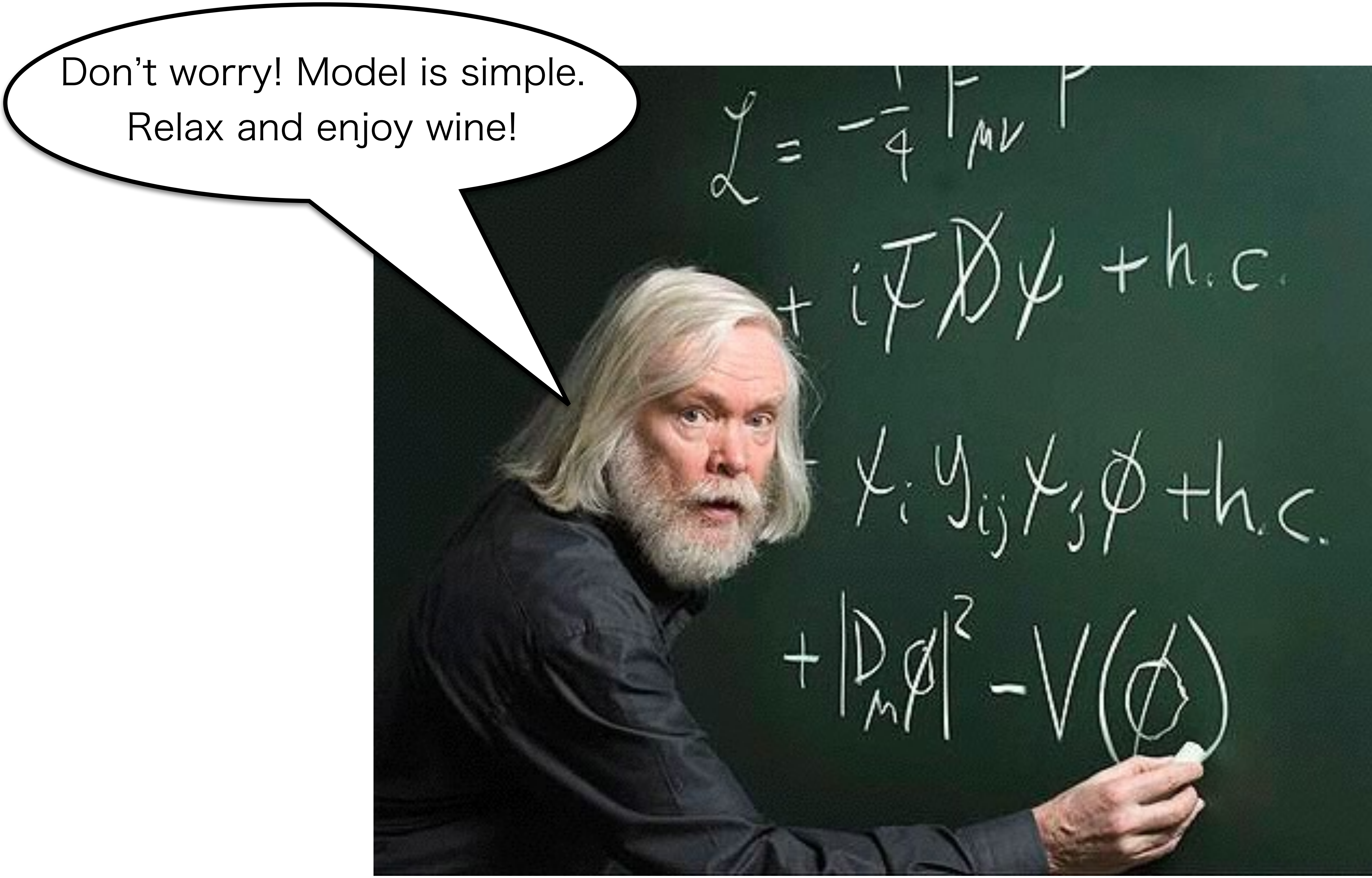
✦Two Higgs double model

✦h→$\mu\tau$ and muon g-2 in 2HDM

✦Any Predictions?

✦Summary

Two Higgs doublet model


Don’t worry! Model is simple.
Relax and enjoy wine!

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)

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

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

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

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

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

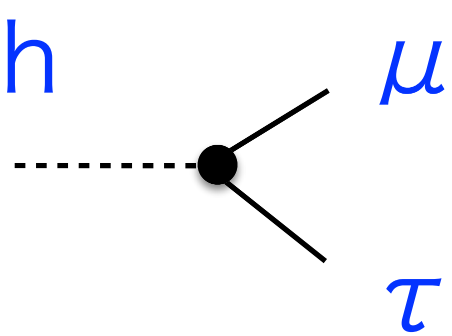
General 2HDM predicts

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....



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

CMS result suggests

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

h→$\mu\tau$ and muon g-2 in 2HDM

$h \to \mu\tau$

Sierra and Vicente, 1409.7690, Crivellin et al., 1501.00993, Lima et al., 1501.06923, $\cdots$
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); $\cdots\cdots$, Blankenburg, Ellis, Isidori, PLB712, 386 (2012),$\cdots\cdots$

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

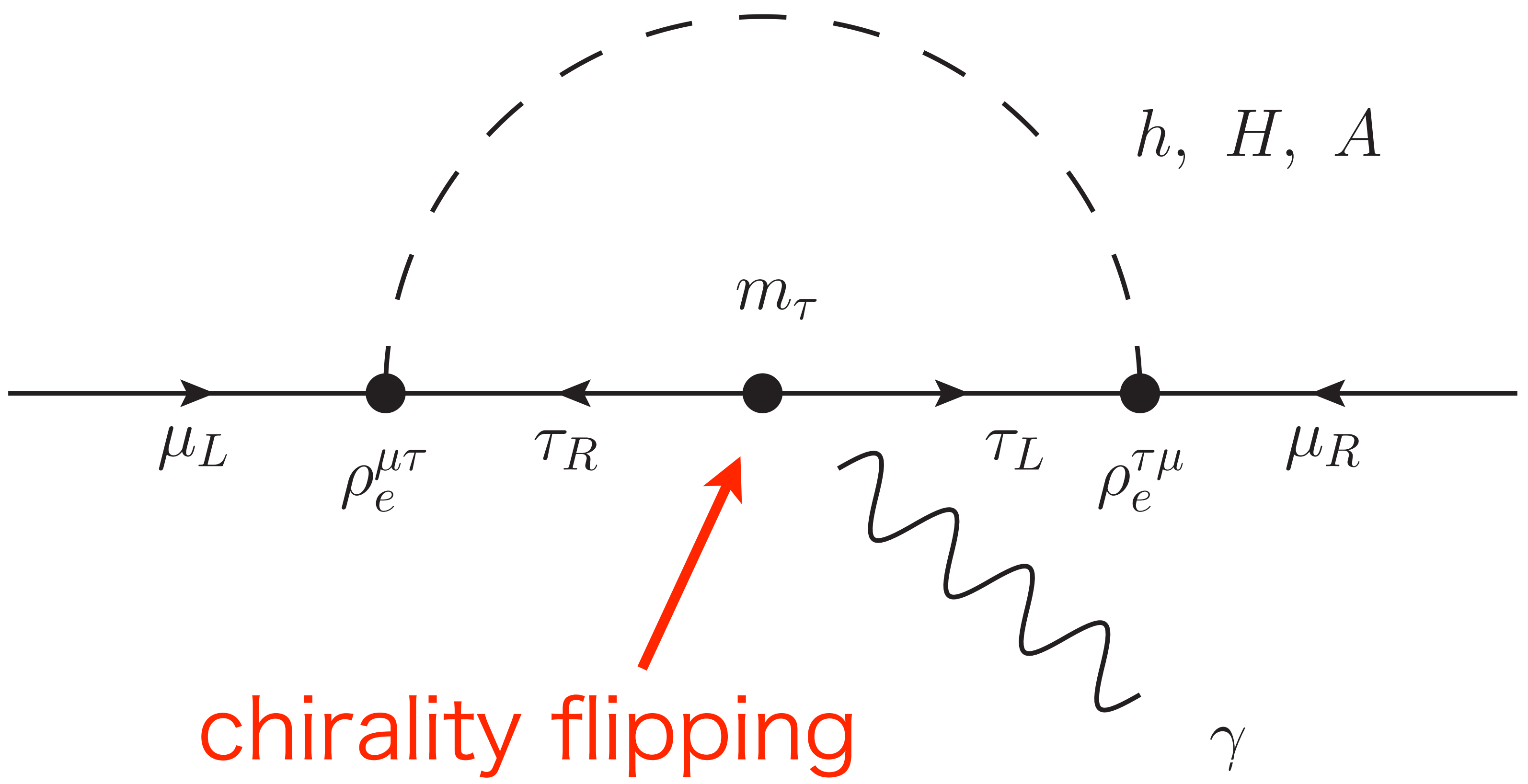
$$\bar{\rho}^{\mu\tau} \equiv \sqrt{\frac{|\rho_e^{\mu\tau}|^2 + |\rho_e^{\tau\mu}|^2}{2}}$$

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

General 2HDM can explain it easily

muon g-2

induced by the μ-τ flavor violating coupling

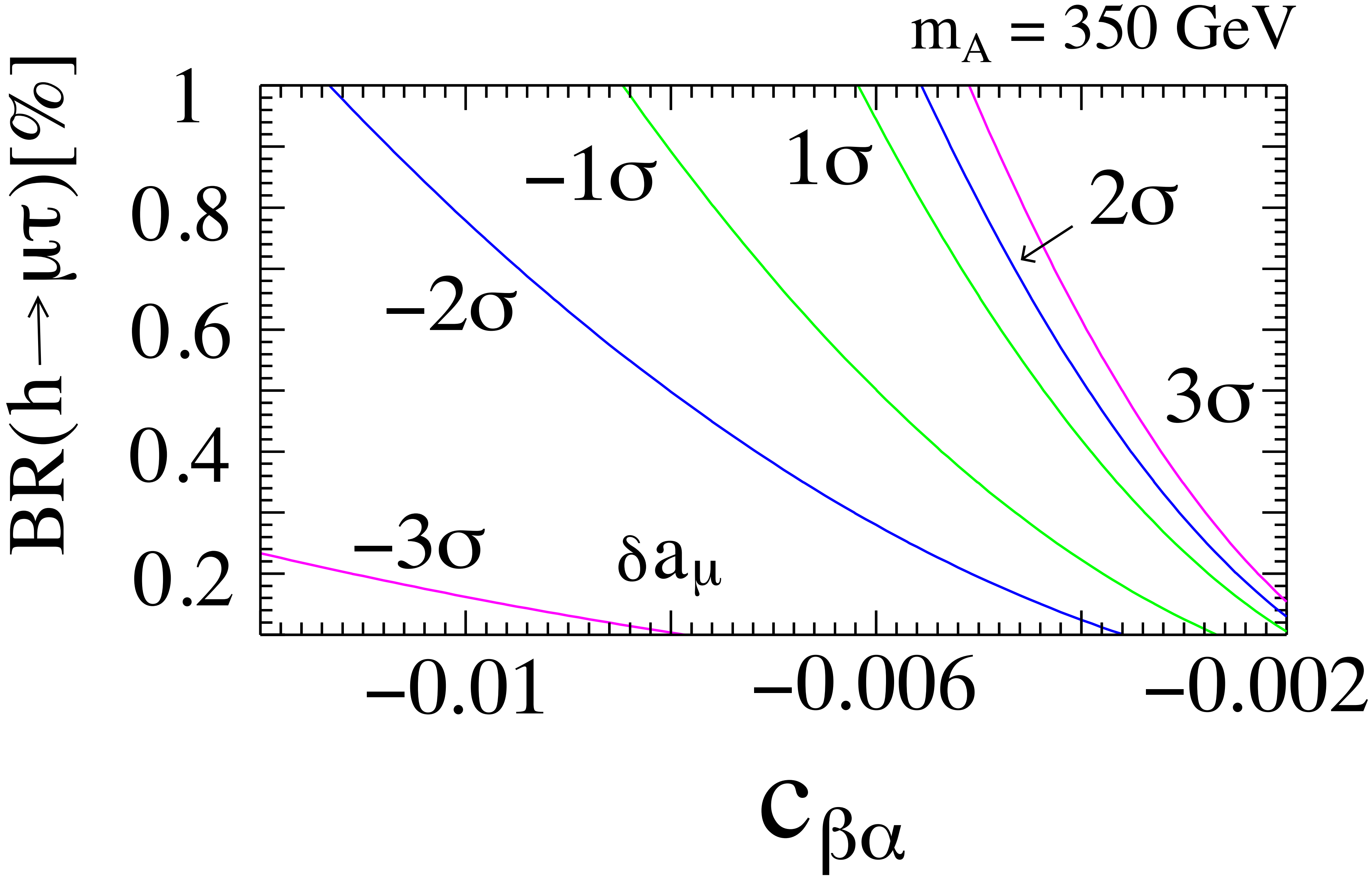


$$O\left(\frac{m_\tau}{m_\mu}\right)$$ enhancement

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

muon g-2

Omura, Senaha, Tobe (2015)

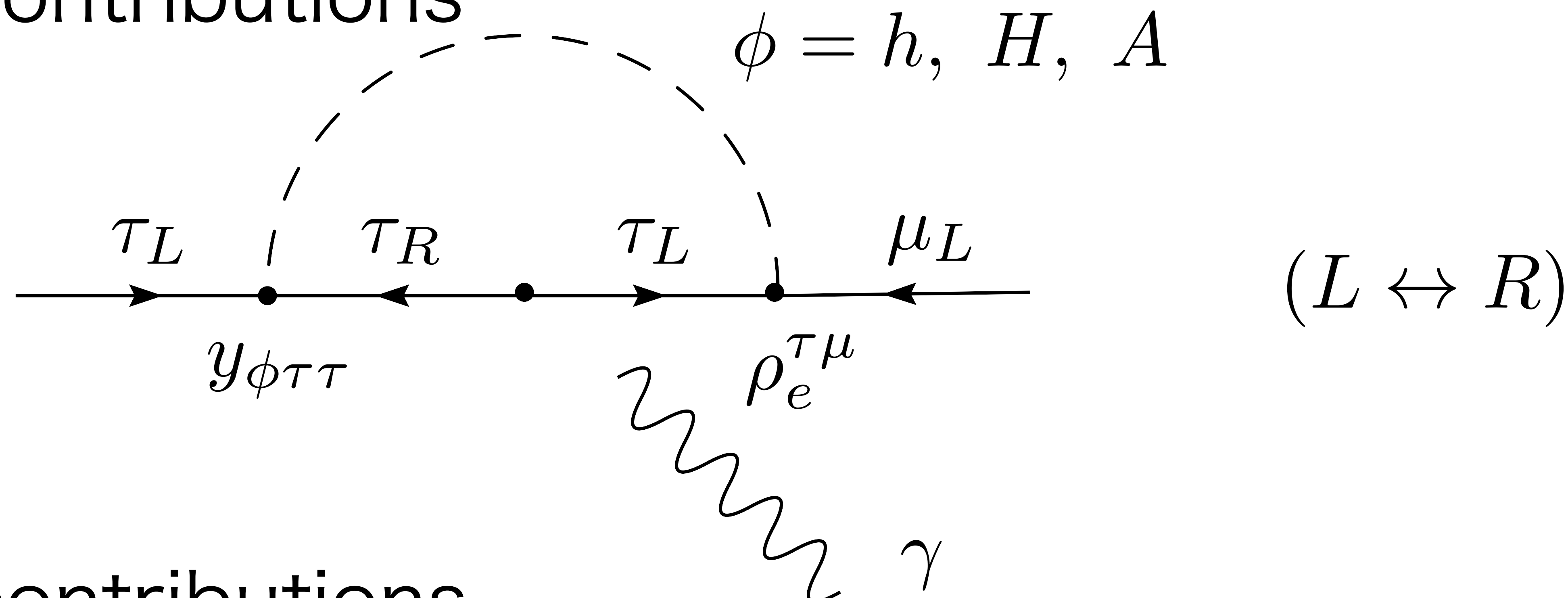


Both anomalies in the muon g-2 and $h \to \mu\tau$ can be accommodated in the general 2HDM

Any Predictions?

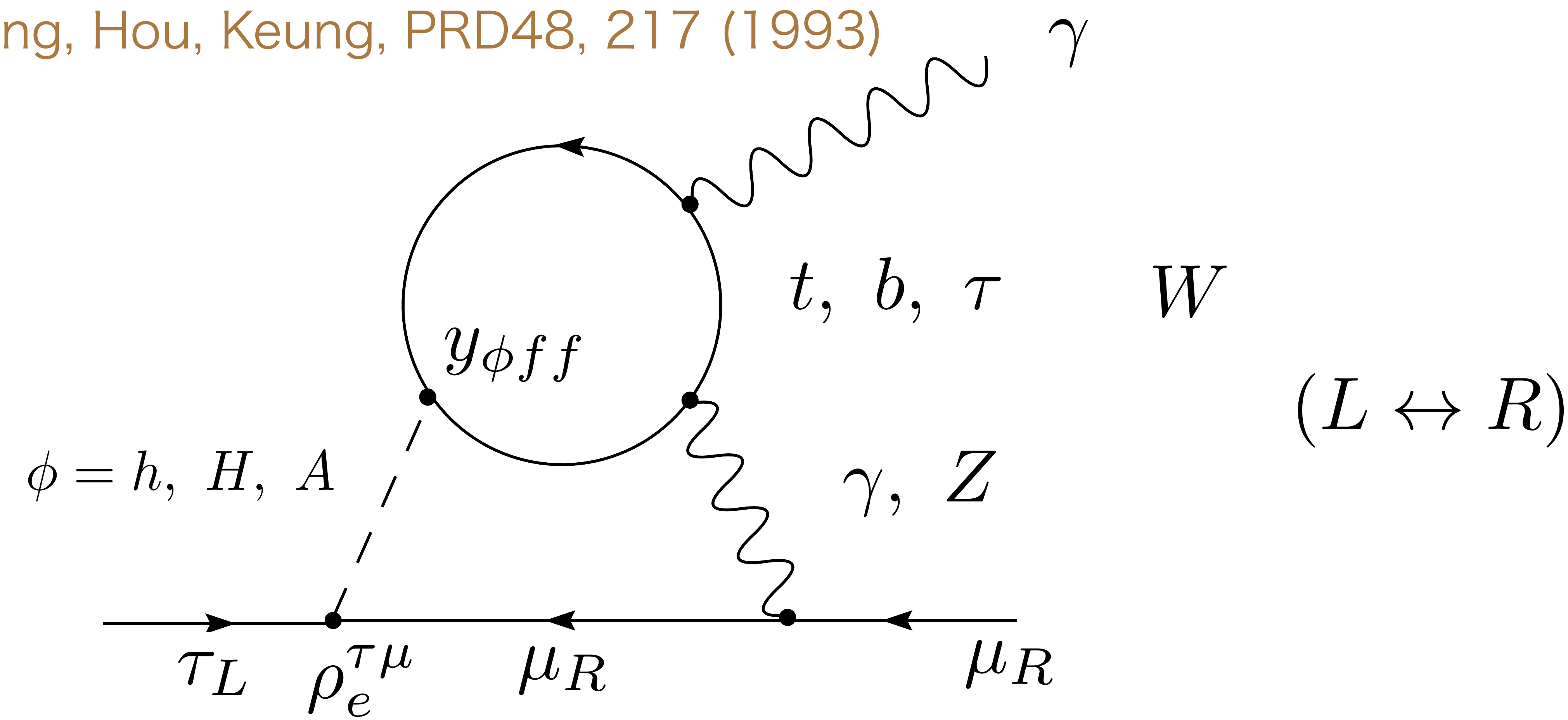
$\tau \to \mu\gamma$

1-loop contributions

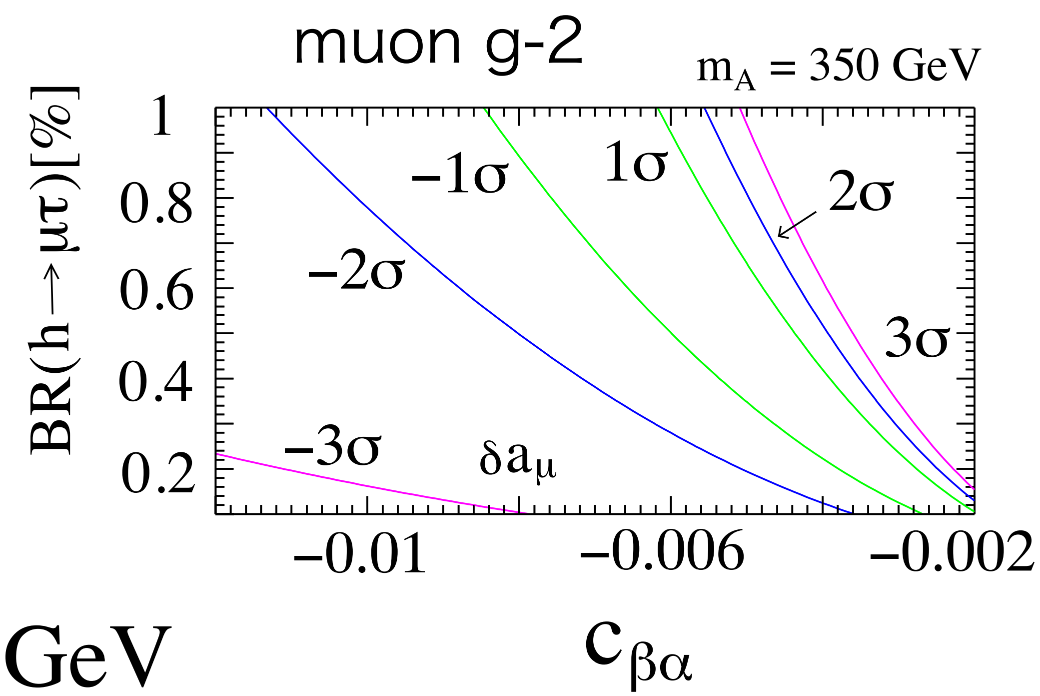


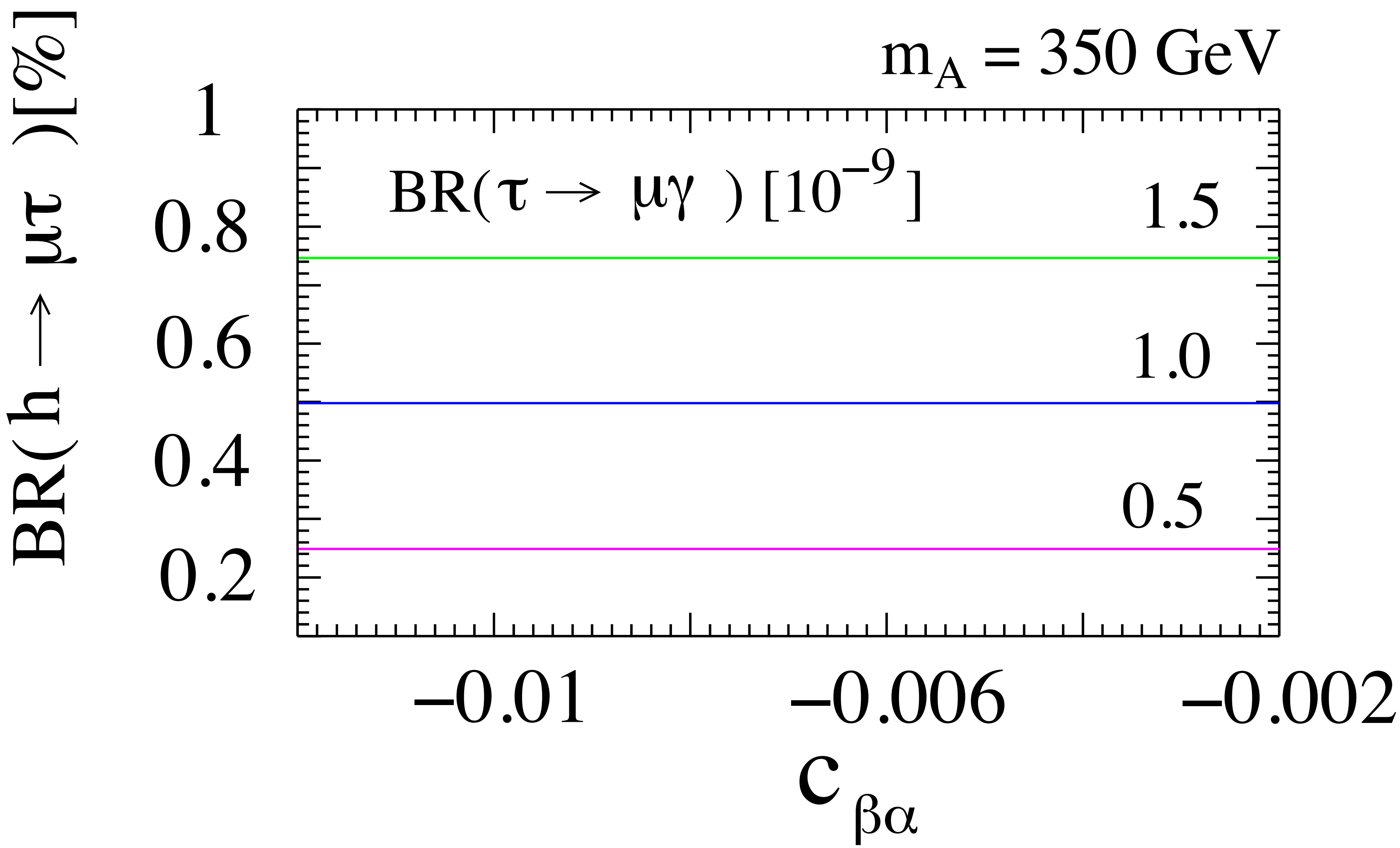
2-loop contributions

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



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





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

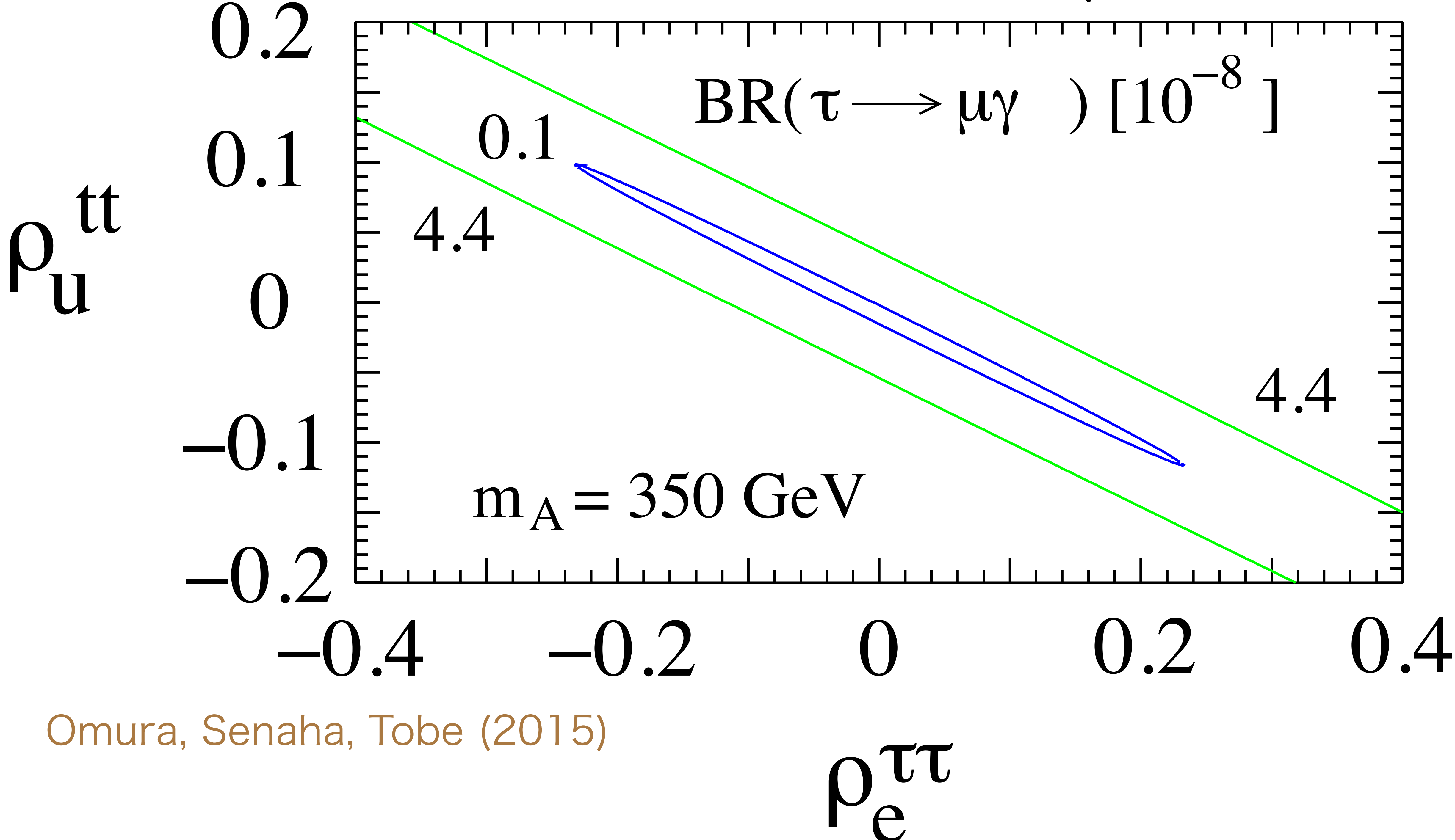
Omura, Senaha, Tobe (2015)

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

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

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

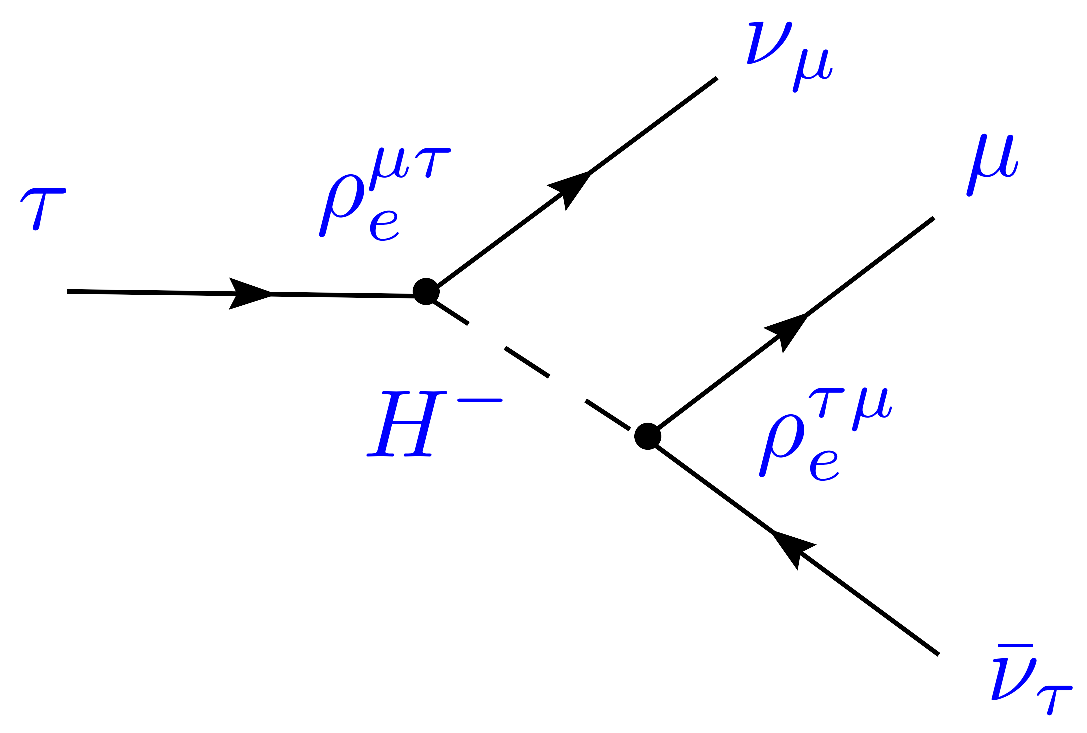
BR(h → μτ) = 0.84%



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



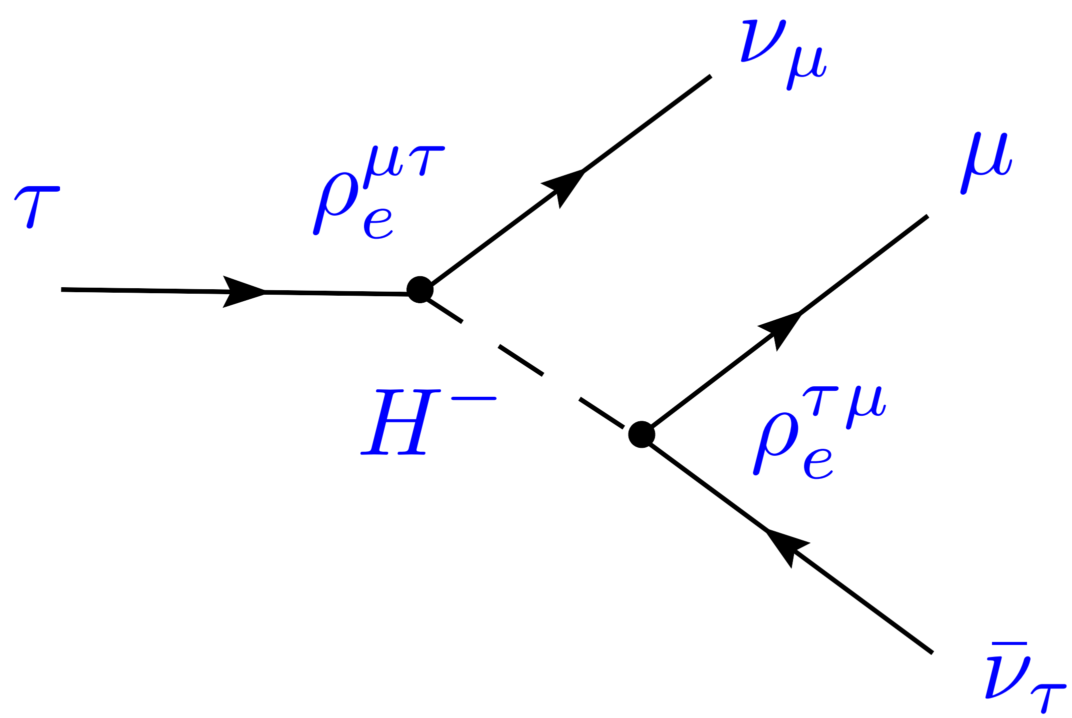
$$\Gamma(\tau \to \mu\nu\bar{\nu}) = \frac{m_\tau^5 G_F^2}{192\pi^3}(1+\delta),$$

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

What about the Michel parameters in τ decay?

(former colleague) Hayasaka-san asked me.

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



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Michel parameters in τ decay

K. Tobe

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

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

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

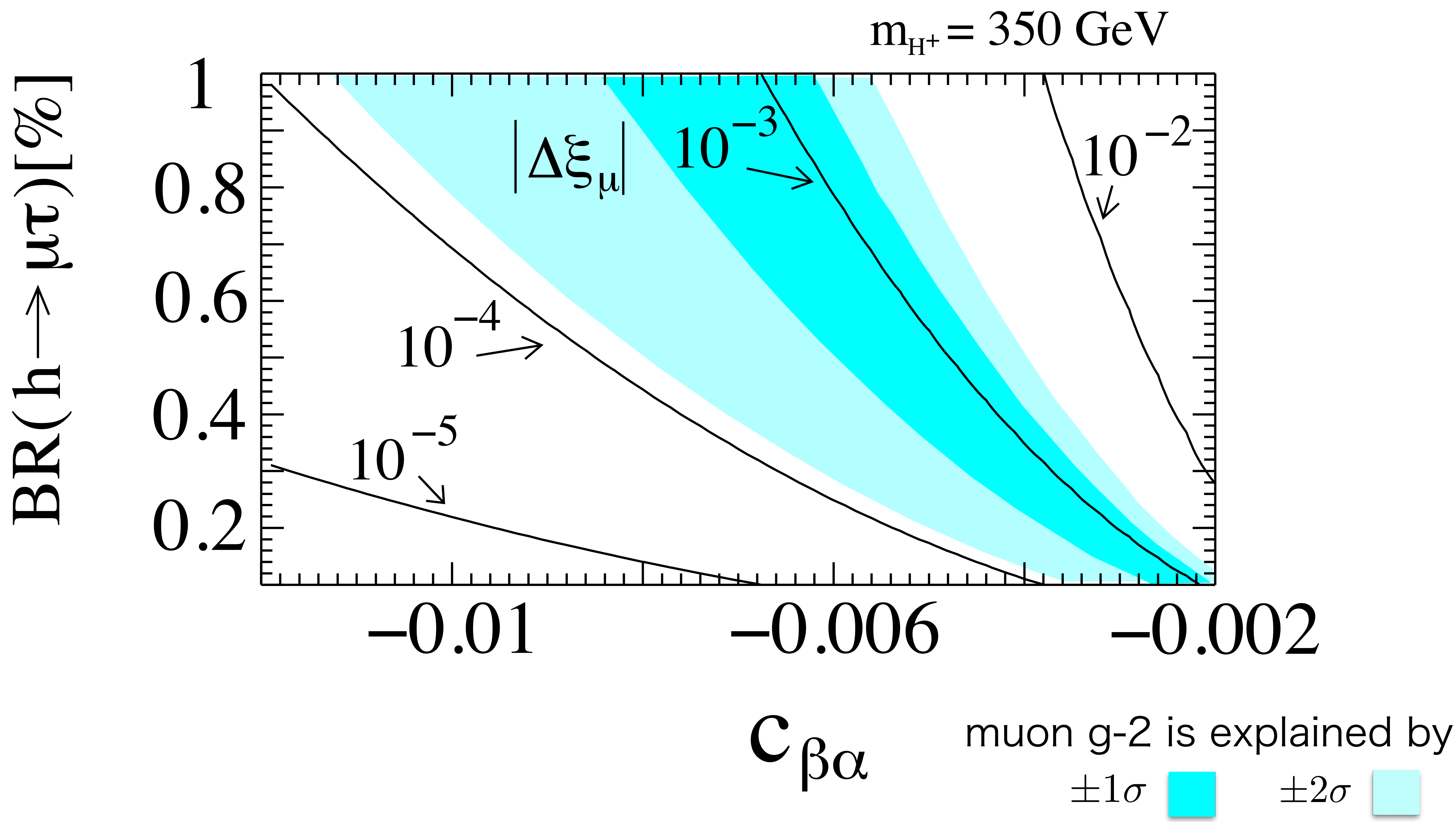
$$w = \frac{m_\tau^2 + m_\mu^2}{2m_\tau} \qquad x = E_\mu/w,\; x_0 = m_\mu/w \qquad \mathcal{P}_\tau :$$ tau polarization

$$\xi \simeq 1 - 2\delta$$

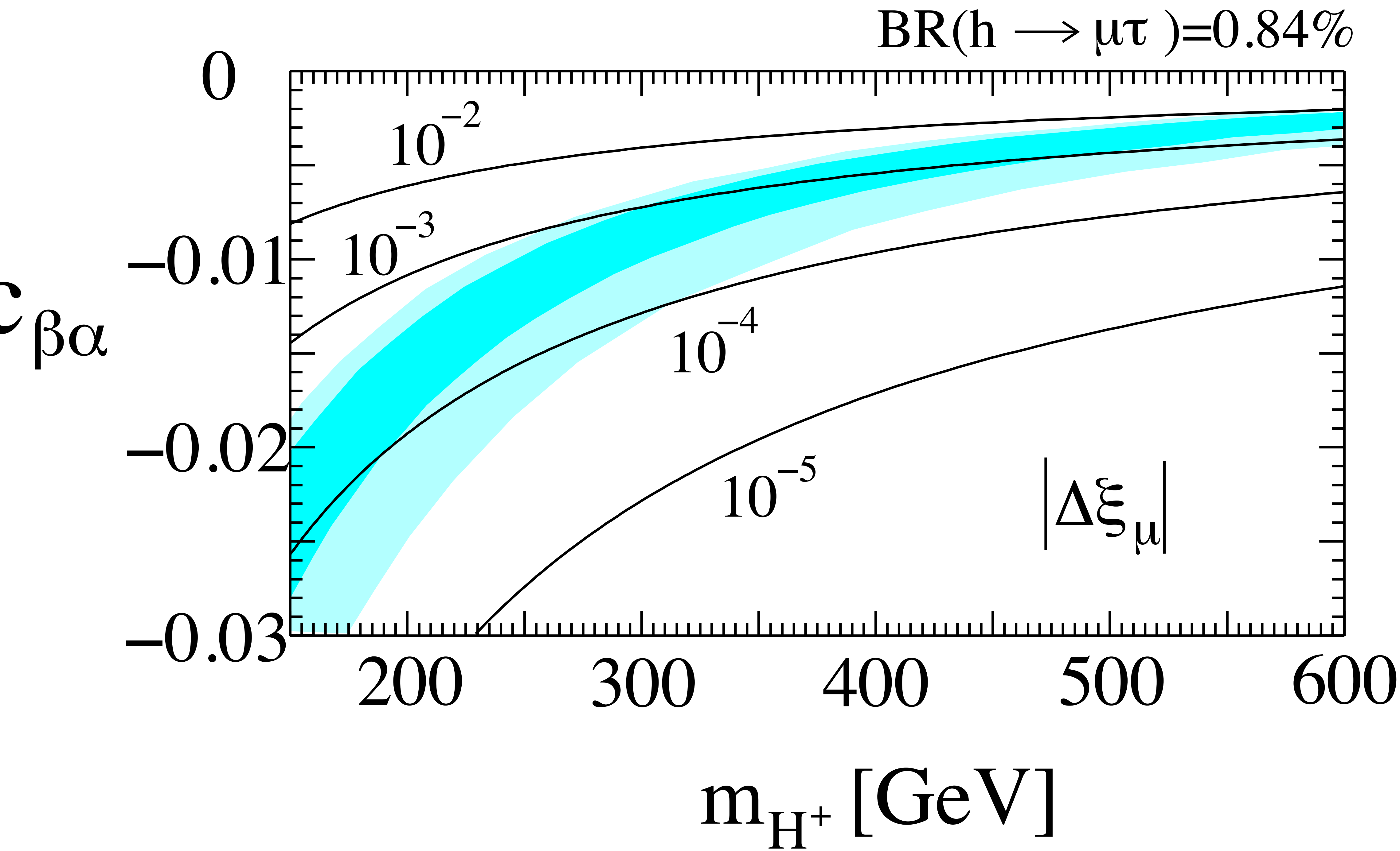
Note: flavor conserving case

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

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



There are 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

Note: BABAR collaboration +others

lepton universality measurement

PRL 105, 051602 (2010)

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

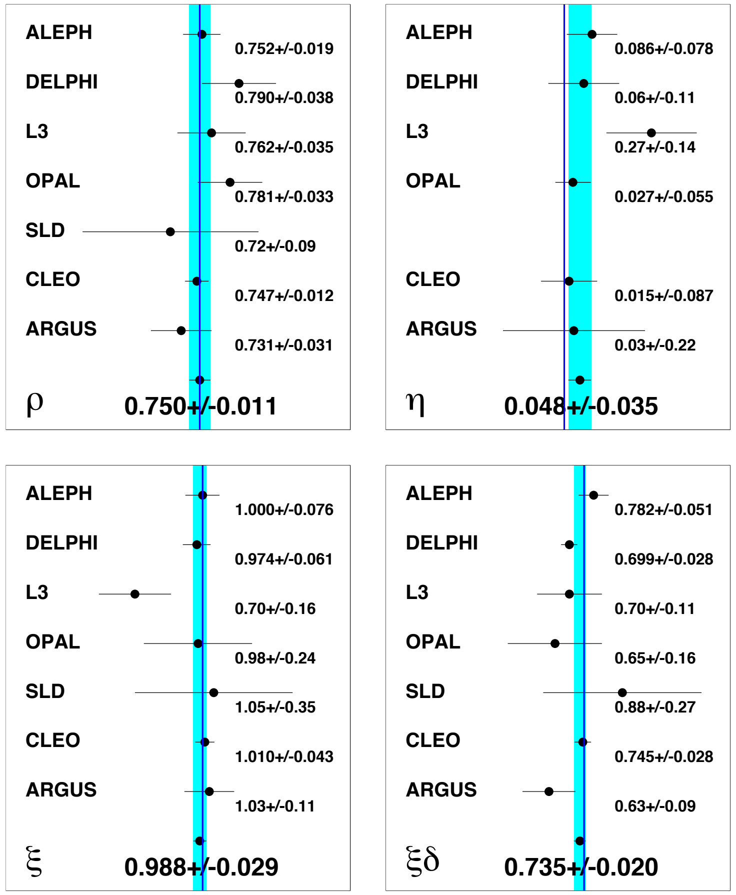
$$\begin{aligned}\left(\frac{g_\mu}{g_e}\right)_\tau &= 1.0036 \pm 0.0020 \text{ (BaBar)} \\ &= 1.0018 \pm 0.0014 \text{ (world average)} \\ &\simeq 1 - \frac{\Delta\xi}{4} \text{ (2HDM)}\end{aligned}$$

The precise measurement will be important.

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

Status of Michel parameters in τ decays

Michel par.	Measured value	Experiment	SM value
ρ (e or μ)	$0.747 \pm 0.010 \pm 0.006$ 1.2%	CLEO-97	3/4
η (e or μ)	$0.012 \pm 0.026 \pm 0.004$ 2.6%	ALEPH-01	0
ξ (e or μ)	$1.007 \pm 0.040 \pm 0.015$ 4.3%	CLEO-97	1
$\xi\delta$ (e or μ)	$0.745 \pm 0.026 \pm 0.009$ 2.8%	CLEO-97	3/4
ξ_h (all hadr.)	$0.992 \pm 0.007 \pm 0.008$ 1.1%	ALEPH-01	1



I learnt from Hayasaka-san …

Nobuhiro Shimizu, D.Epifanov

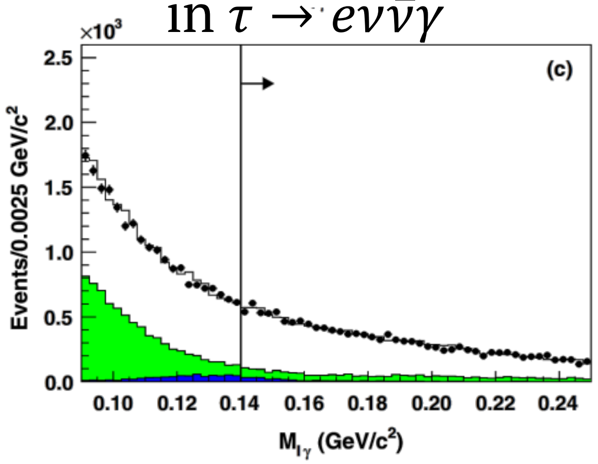
Inconsistency between BR of $\tau \to e\nu\bar{\nu}\gamma$ and theory

- measurement of $\mathcal{B}(\tau \to l\nu\bar{\nu}\gamma)$ was reported in the last summer by BaBar†

Exp.

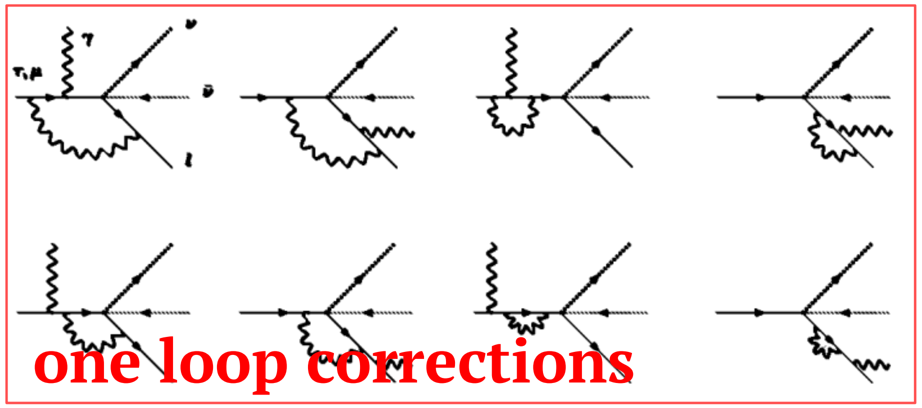
- $\mathcal{B}(\tau \to e\nu\bar{\nu}\gamma)_{E^*_\gamma > 10\mathrm{MeV}} = (1.847 \pm 0.015 \pm 0.052) \times 10^{-2}$
- $\mathcal{B}(\tau \to \mu\nu\bar{\nu}\gamma)_{E^*_\gamma > 10\mathrm{MeV}} = (3.69 \pm 0.03 \pm 0.10) \times 10^{-3}$

$m_{e\gamma}$ distribution in $\tau \to e\nu\bar{\nu}\gamma$



selection cut of $m_{l\gamma}$ well excludes $\tau \to e\nu\bar{\nu}$ + external bremsstrahlung.

- recent theoretical NLO calculation of the branching fraction differs from the BaBar result by 3.5 standard deviations.††
  - $o(\alpha^2)$ QED radiative effect is considered: loop corrections & double γ
  - $\gamma_{soft}\gamma_{vis} \Rightarrow$ *exclusive* mode, $(\gamma_{soft}\gamma_{vis} + \gamma_{vis}\gamma_{vis}) \Rightarrow$ *inclusive* mode



Theory

$\mathcal{B}(\tau \to e\nu\bar{\nu}\gamma)_{E^*_\gamma > 10\mathrm{MeV}} = 1.645(19) \times 10^{-2}$

$\mathcal{B}(\tau \to \mu\nu\bar{\nu}\gamma)_{E^*_\gamma > 10\mathrm{MeV}} = 3.572(3) \times 10^{-3}$

error comes from numerical and NNLO calculation, which is not calculated.

† Phys. Rev. D **91**, 051103

†† JHEP **07**(2015) 153

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

LHC run2 data for h $\to$ μ τ will be crucial

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	$\times$

✦ 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 the sizable rate of $\tau \to \mu\gamma$ and the sizable correction to $\tau \to \mu\nu\bar{\nu}$ and their precise measurements would be important.

Backup

Recognising the First Signs of BSM Physics

From the 2nd Neutrino conference in 1974, in Pennsylvania:

- The Solar Neutrino talk:

> The ^{37}Ar production rates for the standard model and the low Z model are 5.6 ± 1.8 SNU and 1.4 ± 0.35 SNU, respectively. Taking Davis's result[1] without run 27 to be 0.2 ± 0.8 SNU I find that the discrepancy between the experiment and the standard model to be 2.7σ and while the discrepancy with the low Z model is 1.4σ.

(R.K. Ulrik)

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(R.P. Feynman)

Status of muon g-2

.895 (0.008): 5-loop calculation (Aoyama et al '12)

QED contribution	11 658 471.808 (0.015)	Kinoshita & Nio, Aoyama et al
EW contribution	15.4 (0.2)	Czarnecki et al
Hadronic contributions		15.4 (0.1): Higgs mass fixed (Grendiger et al '13)
LO hadronic	**694.9 (4.3)**	HLMNT11
NLO hadronic	−9.8 (0.1)	HLMNT11
light-by-light	10.5 (2.6)	Prades, de Rafael & Vainshtein
Theory TOTAL	**11 659 182.8 (4.9)**	
Experiment	**11 659 208.9 (6.3)**	world avg
Exp − Theory	**26.1 (8.0)**	**3.3 σ discrepancy**

(in units of 10^{-10}. Numbers taken from HLMNT11, arXiv:1105.3149)

n.b.: hadronic contributions: