Higgs LFV in the general Two-Higgs-Doublet model

Chuan-Hung Chen

National Cheng-Kung University

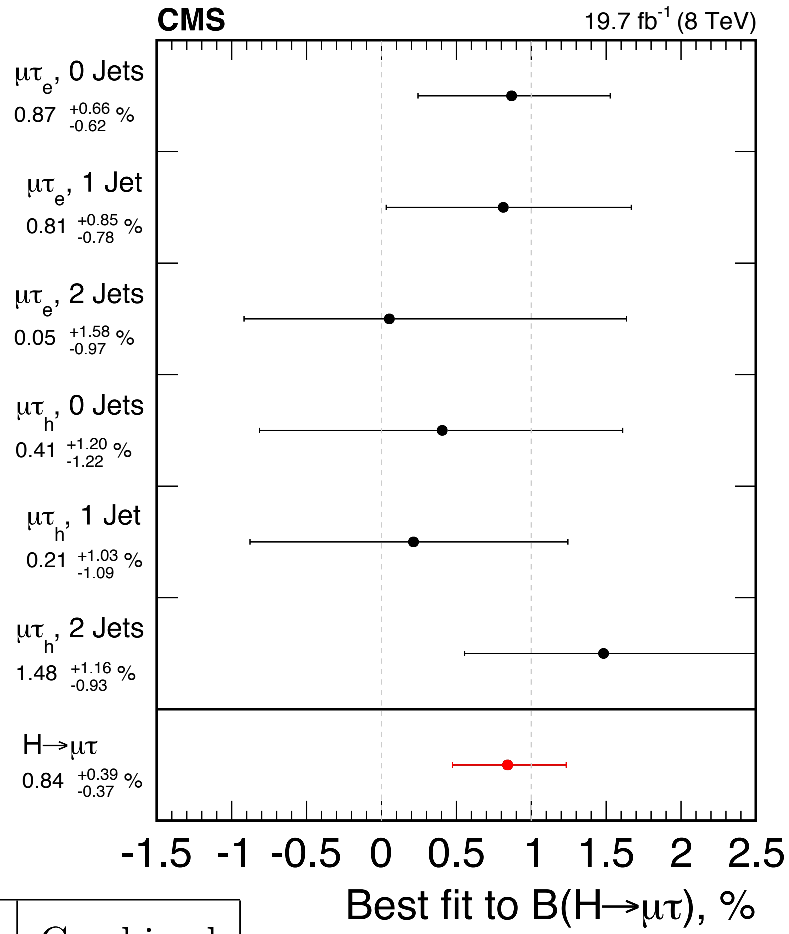
NCTS-KIAS joint workshop, Jan 30- Feb 4, 2016

In collaboration with R. Benbrik & T. Nomura

arXiv:1511.08544

Motivation

Phys.Lett. B749 (15)



- ❑ CMS reported the BR for $h \to \tau\mu$ to be $BR(h \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$ a 2.4 $\boldsymbol{\sigma}$ deviation, PLB749(15)

- ❑ ATLAS did not see the significant excess,

$$BR(h \to \tau\mu) < 1.85\%$$

- ❑ We study the implications on rare tau decays, muon g-2, $Z \to \mu\tau$, etc

	SR1	SR2	Combined
Expected limit on $\mathrm{Br}(H \to \mu\tau)$ [%]	$1.60^{+0.64}_{-0.45}$	$1.75^{+0.71}_{-0.49}$	$1.24^{+0.50}_{-0.35}$
Observed limit on $\mathrm{Br}(H \to \mu\tau)$ [%]	1.55	3.51	1.85
Best fit $\mathrm{Br}(H \to \mu\tau)$ [%]	$-0.07^{+0.81}_{-0.86}$	$1.94^{+0.92}_{-0.89}$	0.77 ± 0.62

JHEP1511(15)

What has been done?

- S_4 flavor symmetry, Campos etal arXiv:1408.1652
- 2HDM type-III, Sierra etal, arXiv:1409.7690
- DM with minimal FV, Lee & Tandean arXiv:1410.6803
- Abelian & non-Abelian FS, Heeck etal, arXiv:1412.3671
- Gauged $L_\mu - L_\tau$ in a 2HDM, Crivellin etal arXiv:1501.00993
- G2HDM, Omura etal, arXiv:1502.07824
- Horizontal gauge symmetries, Crivellin etal arXIv:1503.03477
- Hidden scalars, Das & Kundun, arXiv:1504.01125
- MFV, He etal arXiv:1507.02673
- Axion model, Chiang etal arXiv:1507.04354
- Leptoquark, Cheung etal arXiv:1508.01897
- SUSY inverse seesaw, Arganda etal arXiv:1508.04623
- Leptoquark, Baek etal arXiv:1509.07410
- R-parity, Huang & Tang arXiv:1509.08599
- Lepton-flavored DM, Baek etal arXiv:1510.00100
- SUSY, Arganda arXiv:1510.04685
- MSSM, Aloni arXiv:1511.00979
- More ....

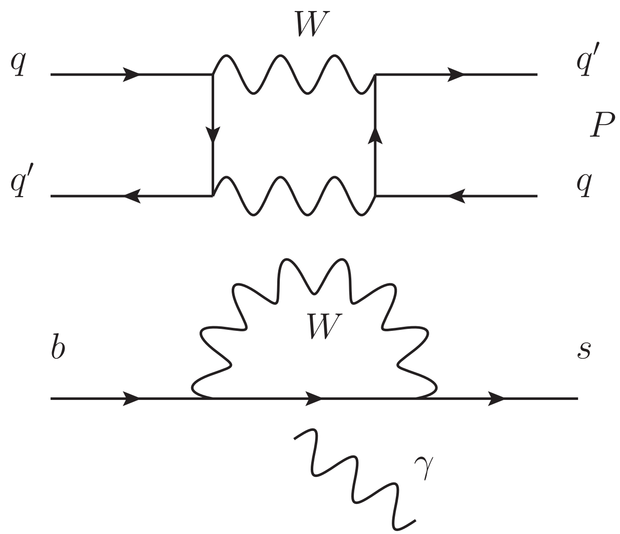
Why is LFV interesting?

- Flavor changing neutral currents (FCNCs) appear in the SM via the charged weak interactions, $D\overline{D}, K\overline{K}, B_q\overline{B_q}, b \to s\gamma, etc$

- Most of these processes involve nonperturbative QCD effects; It is difficult to distinguish the new physics from the SM effects due to the QCD uncertainty

- LFV can be induced in the SM and is irrelevant to QCD; but they are tiny, e.g. $\tau \to \mu\gamma \sim O(10^{-40})$

- Unlike the hadronic cases, if any LFV signal is observed, it is certainly strong evidence for new physics



Higgs LFV in the 2HDM

- Simple extension to the SM by adding a second Higgs doublet; originally proposed for spontaneous CP Violation T.D. Lee PRD8(73); resolution of the strong CP problem Peccei-Quinn PRL38(77)

- Studied well in the literature and classified by several types without FCNCs at tree:

Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

$$\mathcal{L}_Y = y^1_{ij}\bar{\psi}_i\psi_j\Phi_1 + y^2_{ij}\bar{\psi}_i\psi_j\Phi_2,$$

Branco etal Phys.Rept516.(12)

	Type I	Type II	Lepton-specific	Flipped
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^ℓ	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ξ_A^ℓ	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

Higgs LFV in the general 2HDM(Type-III)

- Higgs doublet of SU(2)

$$H_i = \begin{pmatrix} \phi_i^+ \\ (v_i + \phi_i + i\eta_i)/\sqrt{2} \end{pmatrix}$$

- Scalars:

$$\begin{aligned} h &= -s_\alpha \phi_1 + c_\alpha \phi_2 \, , \\ H &= c_\alpha \phi_1 + s_\alpha \phi_2 \, , \\ H^\pm(A) &= -s_\beta \phi_1^\pm(\eta_1) + c_\beta \phi_2^\pm(\eta_2) \end{aligned}$$

$$v = \sqrt{v_1^2 + v_2^2}$$
$$s_\alpha = sin\alpha, c_\alpha = cos\alpha$$
$$s_\beta = sin\beta = \frac{v_1}{v},$$
$$c_\beta = cos\beta = \frac{v_2}{v}$$

2 CP-even; 1 CP-odd; 2 charged Higgs $H^\pm$

Type-III

- Yukawa sector

$$
\begin{aligned}
-\mathcal{L}_Y &= \bar{Q}_L Y_1^u U_R \tilde{H}_1 + \bar{Q}_L Y_2^u U_R \tilde{H}_2 \\
&+ \bar{Q}_L Y_1^d D_R H_1 + \bar{Q}_L Y_2^d D_R H_2 \\
&+ \bar{L} Y_1^\ell \ell_R H_1 + \bar{L} Y_2^\ell \ell_R H_2 + h.c. \,,
\end{aligned}
$$

- Fermion mass matrix

$$
\mathbf{M}_f = \frac{v}{\sqrt{2}} \left(\cos\beta Y_1^f + \sin\beta Y_2^f \right)
$$

- Y_1^f & Y_2^f cannot be diagonalized simultaneously; Unless Y_1^f and Y_2^f are correlated

$Y_1^f \propto Y_2^f$: Aligned case, Pich & Tuzon PRD80(09)

$$
\bar{Y}^F_{2(1)} = \bar{I}^F_{L\rho\sigma} \bar{Y}^F_{1(2)} \tilde{\bar{I}}^F_{R\rho\sigma}
$$

Ahn&Chen, PLB690(10)
Chen&Nomura, PLB749(15)

- Type-III: Y_1^ℓ, Y_2^ℓ are independent in the lepton sector; Y_1^q, Y_2^q are just like type-II

Higgs LFV

$$-\mathcal{L}_{Y\phi} = \bar{\ell}_L \, \epsilon_\phi \mathbf{y}^\ell_\phi \, \ell_R \, \phi + \bar{\nu}_L \, \mathbf{y}^\ell_{H^\pm} \, \ell_R \, H^+ + h.c. \, ,$$

$$(\mathbf{y}^\ell_h)_{ij} = -\frac{s_\alpha}{c_\beta}\frac{m_i}{v}\delta_{ij} + \frac{c_{\beta\alpha}}{c_\beta}X^\ell_{ij} \, ,$$

$$(\mathbf{y}^\ell_H)_{ij} = \frac{c_\alpha}{c_\beta}\frac{m_i}{v}\delta_{ij} - \frac{s_{\beta\alpha}}{c_\beta}X^\ell_{ij} \, ,$$

$$(\mathbf{y}^\ell_A)_{ij} = -\tan\beta\frac{m_i}{v}\delta_{ij} + \frac{X^\ell_{ij}}{c_\beta} \, ,$$

FCNCs

$$\mathbf{X}^\ell = V^\ell_L \frac{Y^\ell_2}{\sqrt{2}} V^{\ell\dagger}_R$$

Cheng&Sher PRD35 (87)

$$Y^\ell_2 = diag(y^\ell_1, y^\ell_2, y^\ell_3)$$

$$c_{\beta\alpha} = \cos(\beta-\alpha)$$
$$s_{\beta\alpha} = \sin(\beta-\alpha)$$

- Flavor conserving parts $\propto m_\ell/v$, H and A couplings have tanβ enhancement
- Decoupling limit $c_{\beta\alpha} \to 0$, FCNCs at tree still exist in H and A couplings
- Besides the flavor changing, X^ℓ_{ii} also affect the flavor conserving couplings

Scalar potential for 2HD

- If we assume the Yukawa matrix to be hermitian, $V_L^\ell = V_R^\ell$

$$\mathbf{X}^\ell = V_L^\ell \frac{Y_2^\ell}{\sqrt{2}} V_R^{\ell\dagger} \quad \Longrightarrow \quad X_{ij}^\ell = X_{ji}^\ell$$

$$\begin{aligned} V(\Phi_1, \Phi_2) \;&=\; m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - (m_{12}^2 \Phi_1^\dagger \Phi_2 + \mathrm{h.c}) + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 \\ &+\; \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ &+\; \left[\frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + \left(\lambda_6 \Phi_1^\dagger \Phi_1 + \lambda_7 \Phi_2^\dagger \Phi_2\right) \Phi_1^\dagger \Phi_2 + \mathrm{h.c.}\right] . \end{aligned}$$

Constraints:

Perturbativity: $\lambda_i < 8\pi$

Vacuum stability:
$$\lambda_1 > 0\,, \qquad \lambda_2 > 0\,, \lambda_3 + \sqrt{\lambda_1\lambda_2} > 0, \quad \sqrt{\lambda_1\lambda_2} + \lambda_3 + \lambda_4 - |\lambda_5| > 0,$$
$$2|\lambda_6 + \lambda_7| \leq \frac{1}{2}(\lambda_1 + \lambda_2) + \lambda_3 + \lambda_4 + \lambda_5\,.$$

Unitarity: $\phi_i\phi_j \rightarrow \phi_i\phi_j$

$\delta\rho = (4.0 \pm 2.4)\times 10^{-4}$

Oblique parameters: $S = 0.05 \pm 0.11, T = 0.09 \pm 0.13, U = 0.01 \pm 0.01$

global fit EPJC72(14)

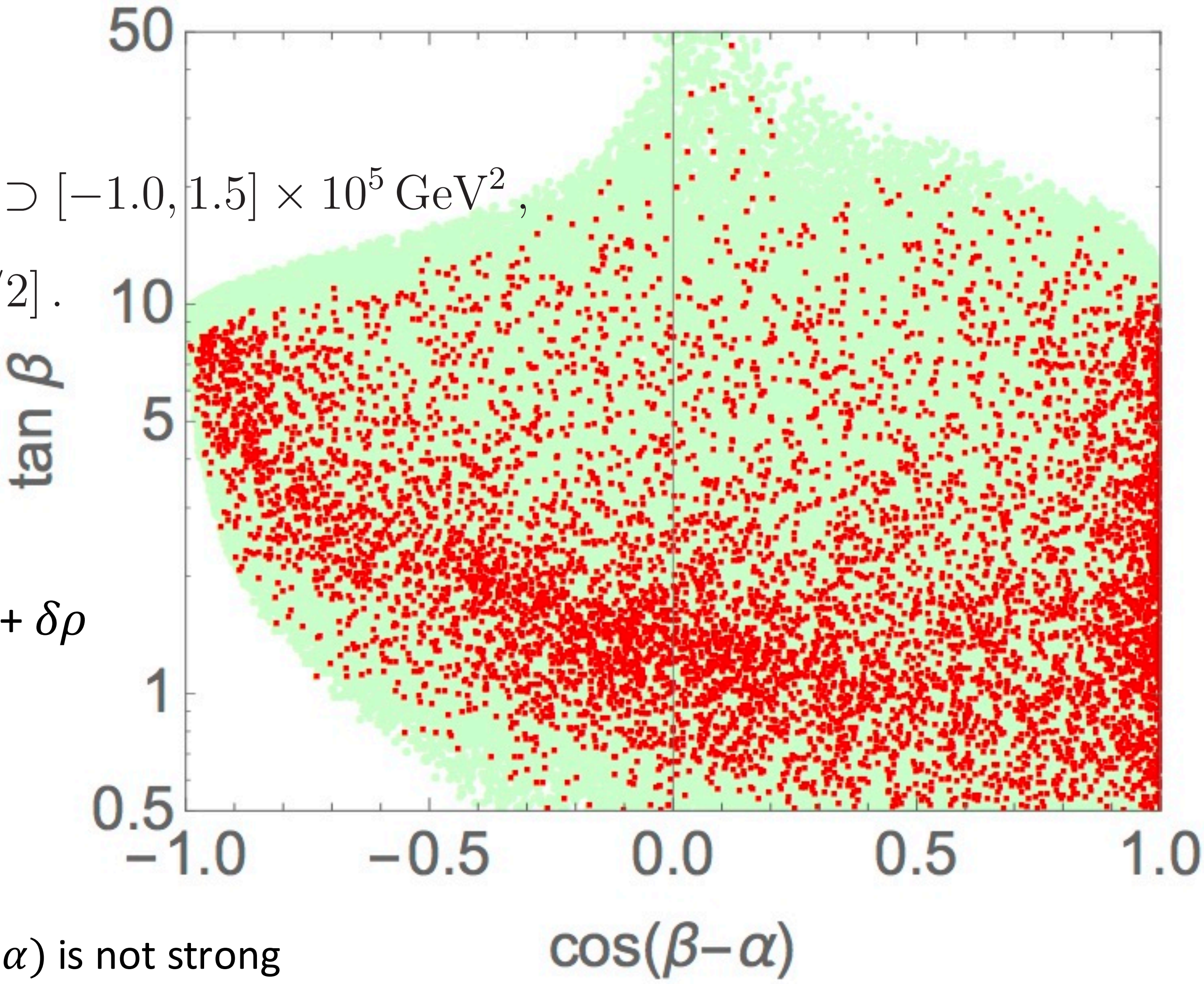
$b \rightarrow s\gamma \rightarrow m_{H^\pm} \geq 480\ GeV$

Parameters used for analysis are

$$\{m_h\,, m_H\,, m_A\,, m_{H^\pm}\,, v\,, \tan\beta\,, \alpha\,, \lambda_6\,, \lambda_7\}$$

$$m_{H,A} \supset [126, 1000]\,\mathrm{GeV}\,, \quad m_{12}^2 \supset [-1.0, 1.5] \times 10^5\,\mathrm{GeV}^2\,,$$

$$\tan\beta \supset [0.5, 50]\,, \quad \alpha = [-\pi/2, \pi/2]\,.$$



Green: theoretical requirements + $\delta\rho$

Red: Green + oblique parameters

Basically, the constraint on $\cos(\beta - \alpha)$ is not strong

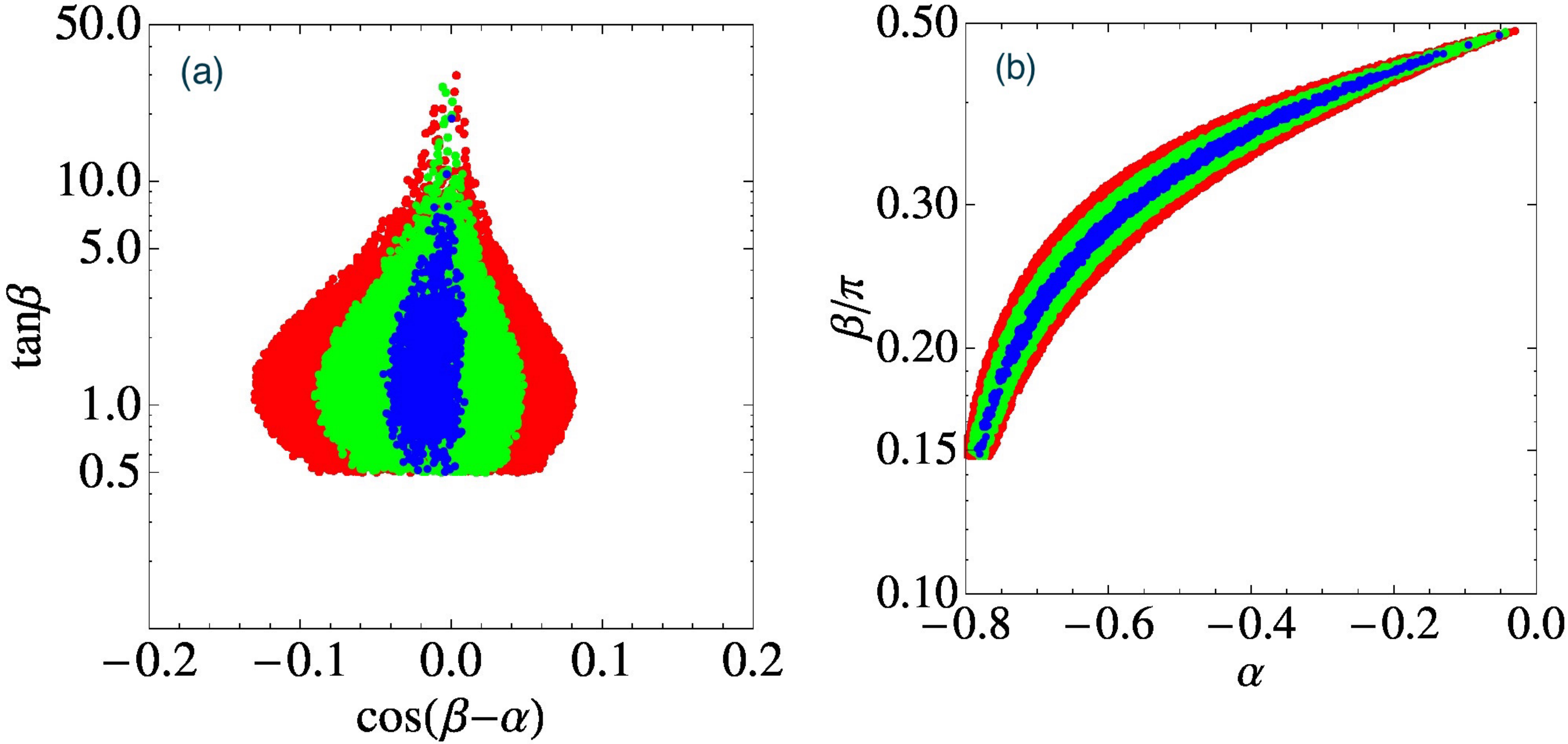
Constraints: from Higgs measurements

TABLE I: Combined best-fit signal strengths $\widehat{\mu}_{\rm ggF+tth}$ and $\widehat{\mu}_{\rm VBF+Vh}$ and the associated correlation coefficient ρ for corresponding Higgs decay mode [61, 62].

f	$\widehat{\mu}^f_{\rm ggF+tth}$	$\widehat{\mu}^f_{\rm VBF+Vh}$	$\pm\, 1\widehat{\sigma}_{\rm ggF+tth}$	$\pm\, 1\widehat{\sigma}_{\rm VBF+Vh}$	ρ
$\gamma\gamma$	1.32	0.8	0.38	0.7	-0.30
ZZ^*	1.70	0.3	0.4	1.20	-0.59
WW^*	0.98	1.28	0.28	0.55	-0.20
$\tau\tau$	2	1.24	1.50	0.59	-0.42
$b\bar{b}$	1.11	0.92	0.65	0.38	0

$$\chi^2_f = \frac{1}{\hat{\sigma}_1^2(1-\rho^2)}(\mu_1^f - \hat{\mu}_1^f)^2 + \frac{1}{\hat{\sigma}_1^2(1-\rho^2)}(\mu_2^f - \hat{\mu}_2^f)^2 - \frac{2\rho}{\hat{\sigma}_1\hat{\sigma}_2(1-\rho^2)}(\mu_1^f - \hat{\mu}_1^f)(\mu_2^f - \hat{\mu}_2^f)\,,$$

$$\chi^2 = \sum_f \chi^2_f + \chi^2_{ST}\,,$$



- Blue: $\Delta\chi^2 = 2.3$; Green: $\Delta\chi^2 = 5.99$; Red: $\Delta\chi^2 = 11.8$

- Higgs data give a strict constraint on $\cos(\beta - \alpha)$, approaching to decoupling limit

Flavor conserving & violating processes

$$(\mathbf{y}_h^\ell)_{ij} = -\frac{s_\alpha}{c_\beta}\frac{m_i}{v}\delta_{ij} + \frac{c_{\beta\alpha}}{c_\beta}X_{ij}^\ell\,,$$

$$(\mathbf{y}_H^\ell)_{ij} = \frac{c_\alpha}{c_\beta}\frac{m_i}{v}\delta_{ij} - \frac{s_{\beta\alpha}}{c_\beta}X_{ij}^\ell\,,$$

$$(\mathbf{y}_A^\ell)_{ij} = -\tan\beta\frac{m_i}{v}\delta_{ij} + \frac{X_{ij}^\ell}{c_\beta}\,,$$

$h \to \tau\mu$:

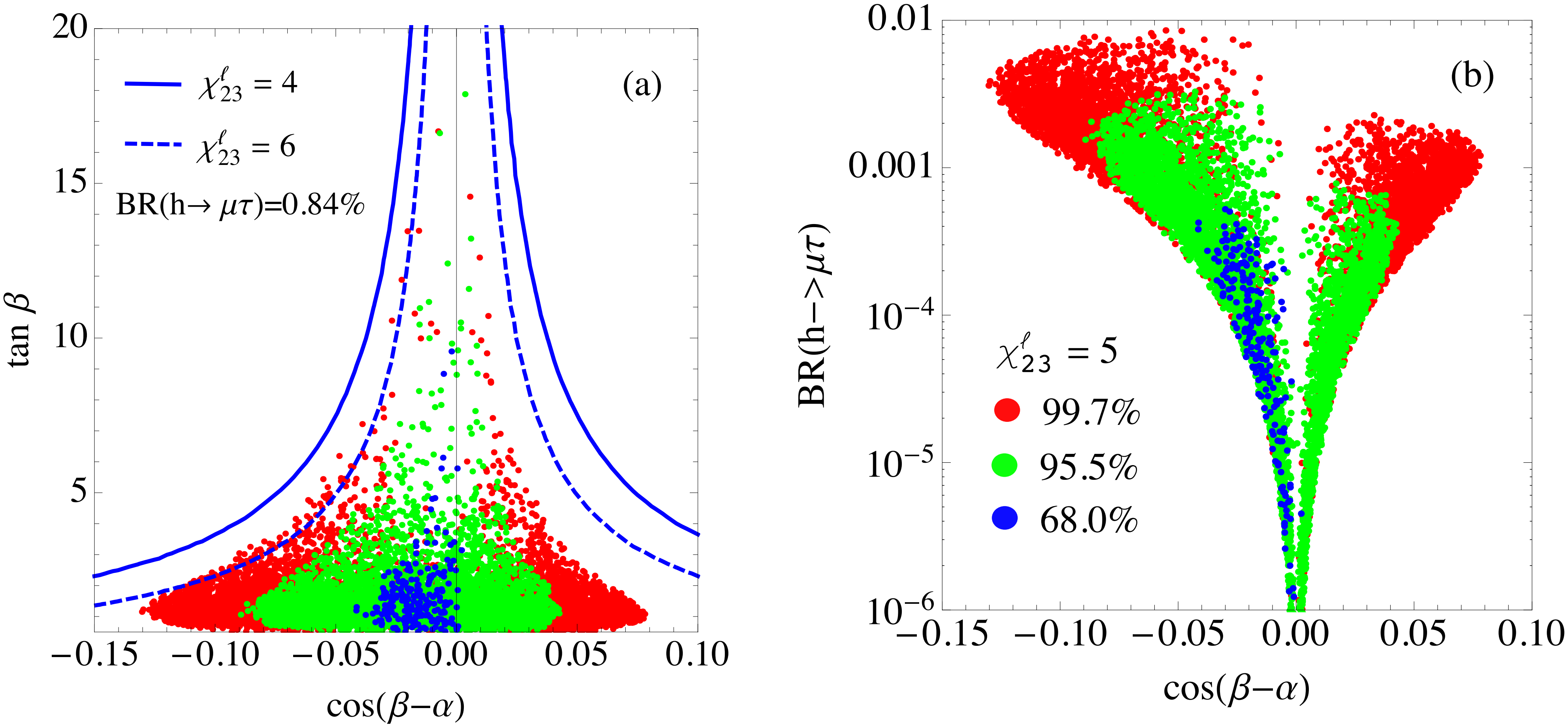
$$BR(h \to \mu\tau) = \frac{c_{\beta\alpha}^2(|X_{23}^\ell|^2 + |X_{32}^\ell|^2)}{16\pi c_\beta^2 \Gamma_h} m_h.$$

With $m_h = 125$ GeV, $\Gamma_h \approx 4.21$ MeV, and $X_{32}^\ell = X_{23}^\ell$, we can express X_{23}^ℓ as

$$X_{23}^\ell = 3.77 \times 10^{-3}\left(\frac{c_\beta}{0.02}\right)\left(\frac{0.01}{c_{\beta\alpha}}\right)\sqrt{\frac{BR(h \to \mu\tau)}{0.84 \times 10^{-2}}}\,,$$

ansatz $X_{\mu\tau}^\ell = \sqrt{\frac{m_\mu m_\tau}{v^2}}\chi_{\mu\tau}^\ell$ $\qquad$ $\chi_{\mu\tau}^\ell \sim 2$ can satisfy the central value of CMS

- In the decoupling limit, $c_{\beta\alpha} = 0 \to BR(h \to \tau\mu) = 0$

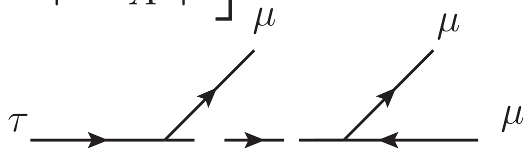

(a)
$\chi^{\ell}_{23} = 4$
$\chi^{\ell}_{23} = 6$
BR(h→ μτ)=0.84%
tan β
cos(β−α)
(b)
BR(h−>μτ)
$\chi^{\ell}_{23} = 5$
99.7%
95.5%
68.0%
cos(β−α)

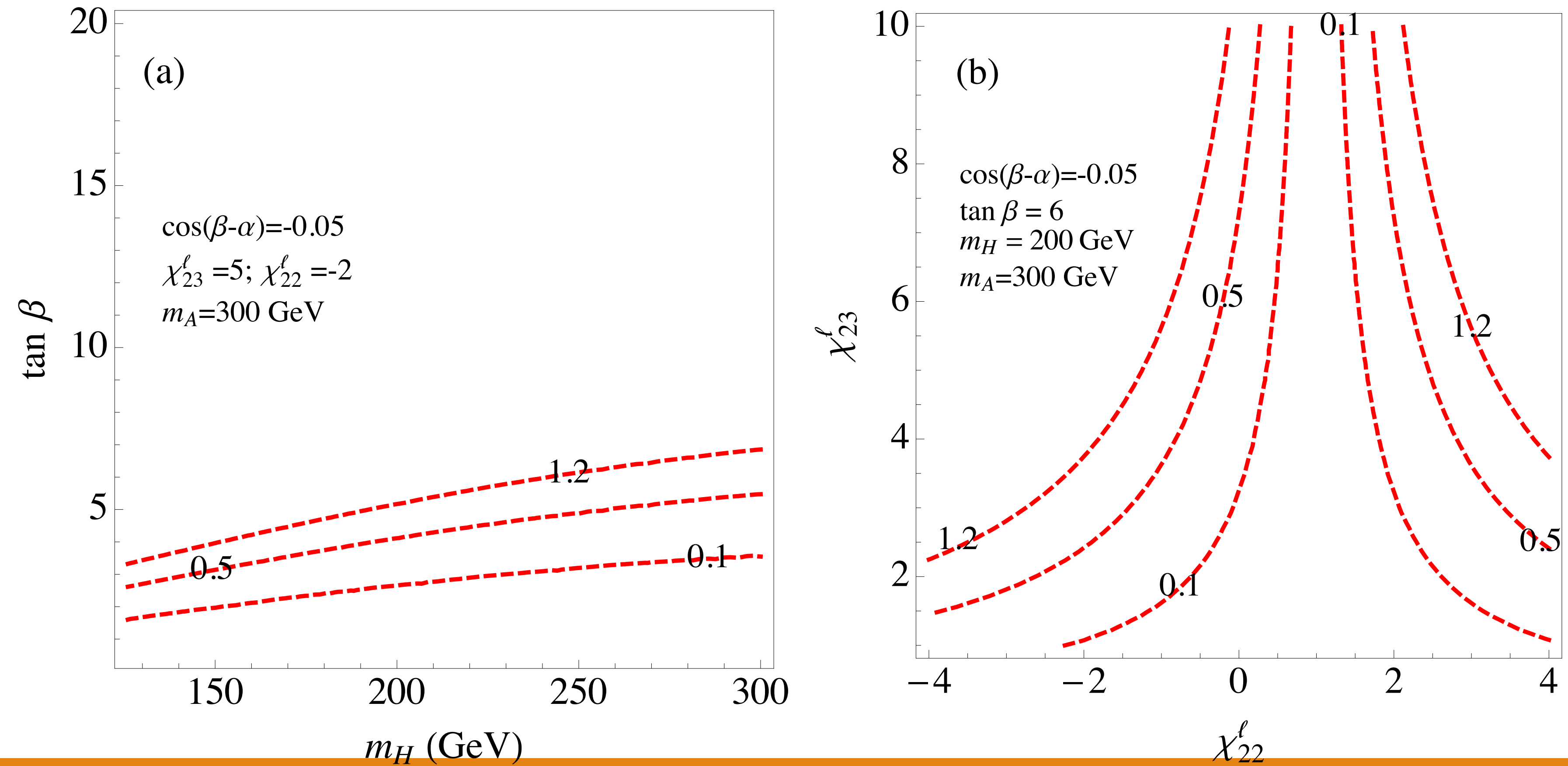
Tree level $\tau \to 3\mu$:

$$BR(\tau \to 3\mu) = \frac{\tau_\tau m_\tau^5}{3 \cdot 2^9 \pi^3} \frac{|X_{23}^\ell|^2}{c_\beta^2} \left[\left| \frac{c_{\beta\alpha} y_{h22}^\ell}{m_h^2} - \frac{s_{\beta\alpha} y_{H22}^\ell}{m_H^2} \right|^2 + \left| \frac{y_{A22}^\ell}{m_A^2} \right|^2 \right]$$

$$X_{ij}^\ell = \sqrt{\frac{m_\mu m_\tau}{v}} \chi_{ij}^\ell$$

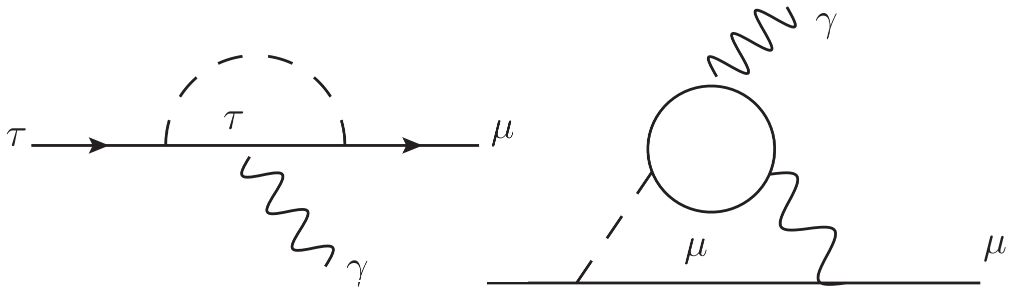
$BR(\tau \to 3\mu)^{exp} < 1.2 \times 10^{-8}$ HFAG

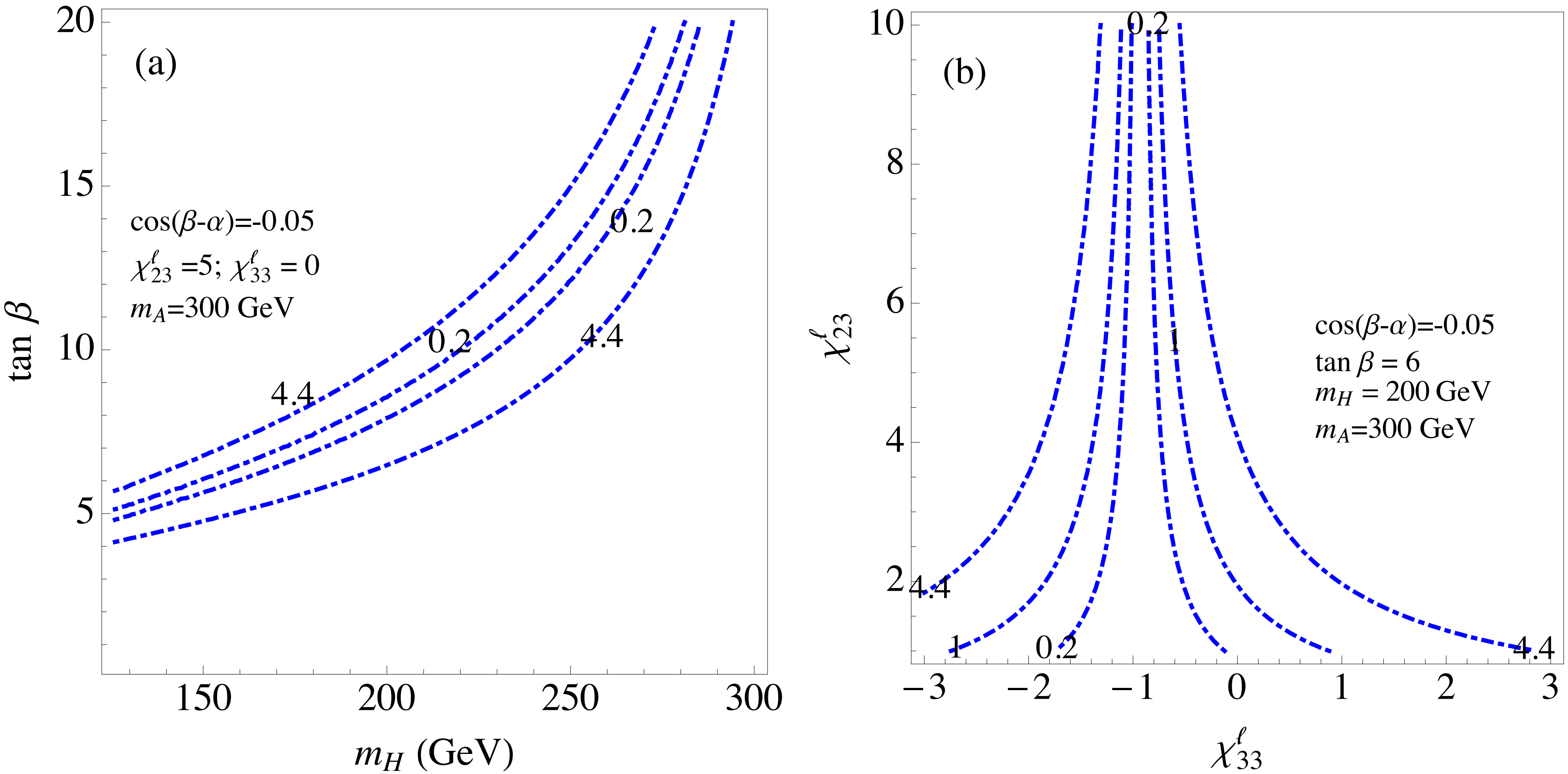




$\tau \to \mu\gamma: one + two$ loops

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

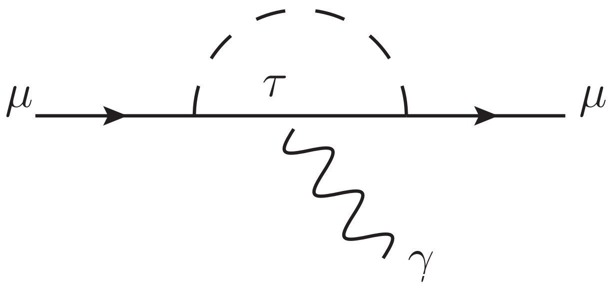




Muon g-2 vs $\mu \to e\gamma$:

$$\Delta a_\mu \simeq \frac{m_\mu m_\tau X^\ell_{23} X^\ell_{32}}{8\pi^2 c_\beta^2} Z_\phi \,,$$

$$Z_\phi = \frac{c^2_{\beta\alpha}\left(\ln(m_h^2/m_\tau^2) - \frac{3}{2}\right)}{m_h^2} + \frac{s^2_{\beta\alpha}\left(\ln(m_H^2/m_\tau^2) - \frac{3}{2}\right)}{m_H^2} - \frac{\ln(m_A^2/m_\tau^2) - \frac{3}{2}}{m_A^2} \,,$$



$$\mathcal{L}_{\mu\to e\gamma} = \frac{e m_\mu}{16\pi^2} \bar{e}\sigma_{\mu\nu}\left(C_L P_L + C_R P_R\right)\mu F^{\mu\nu} \,,$$

$$C_{L(R)} = C^\phi_{L(R)} + C^{H^\pm}_{L(R)} \,,$$

$$C^\phi_L = \frac{X^\ell_{32} X^\ell_{13}}{2c_\beta^2} \frac{m_\tau}{m_\mu} Z_\phi \,,$$

$$C^{H^\pm}_L = -\frac{1}{12 m^2_{H^\pm}} \left(\frac{2X^\ell_{23} X^\ell_{13}}{c_\beta^2}\right) \,,$$

Much smaller than the neutral bosons

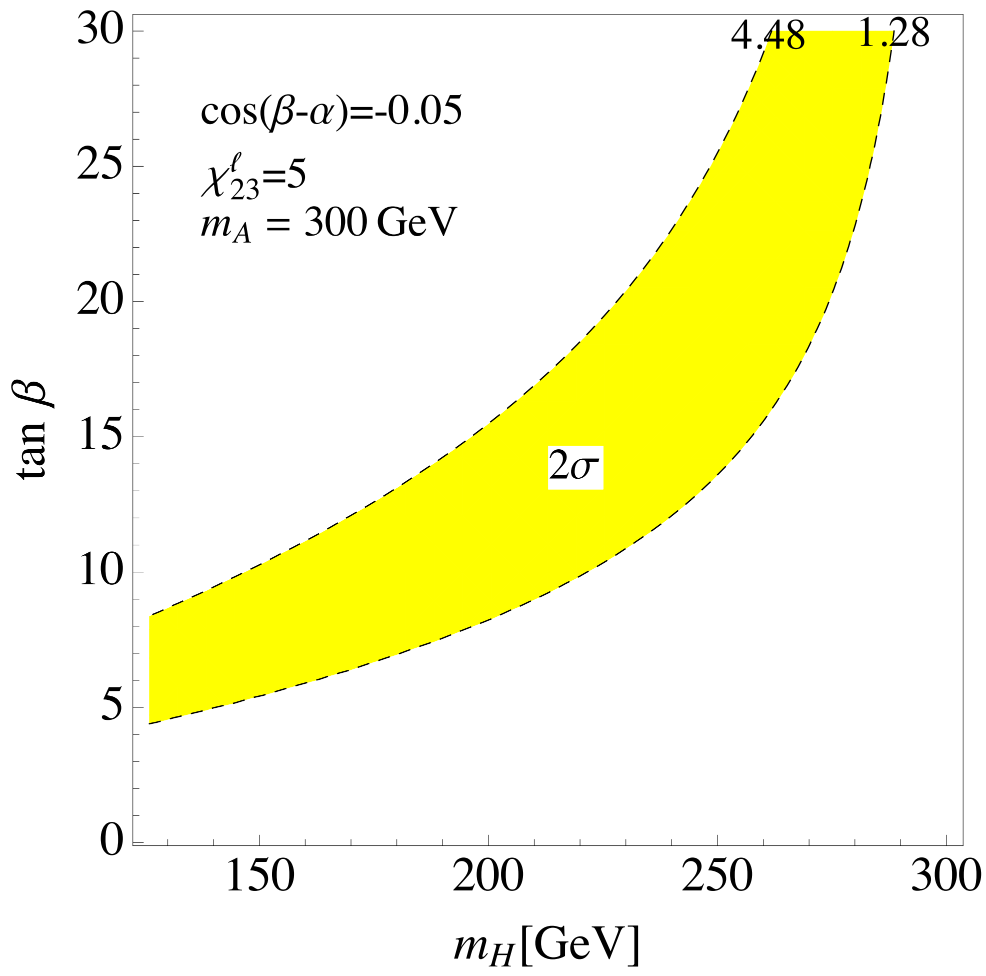
$$C^\phi_{L(R)} = \frac{X^\ell_{13}}{X^\ell_{23}} \frac{4\pi^2 \Delta a_\mu}{m_\mu^2} \,.$$

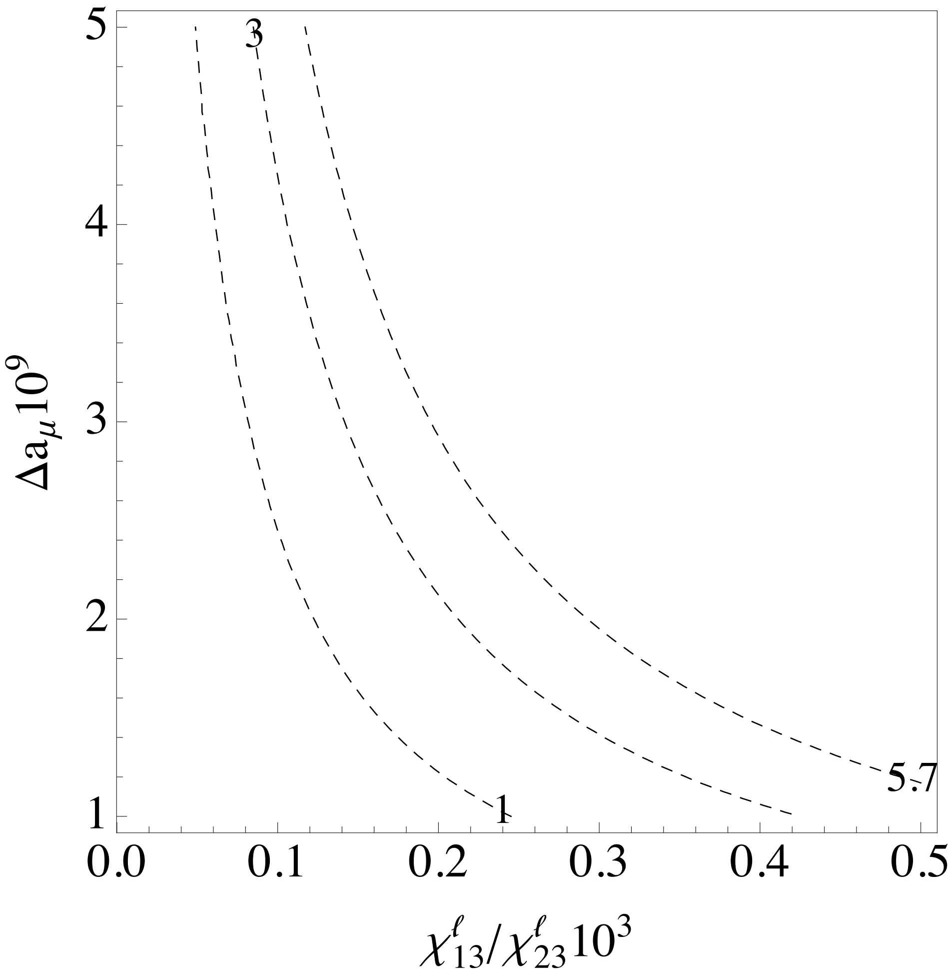
Strongly correlated between Δa_μ and $BR(\mu \to e\,\gamma)$

Muon g-2 vs $\mu \to e\gamma$:

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (28.8 \pm 8.0) \times 10^{-10}$$

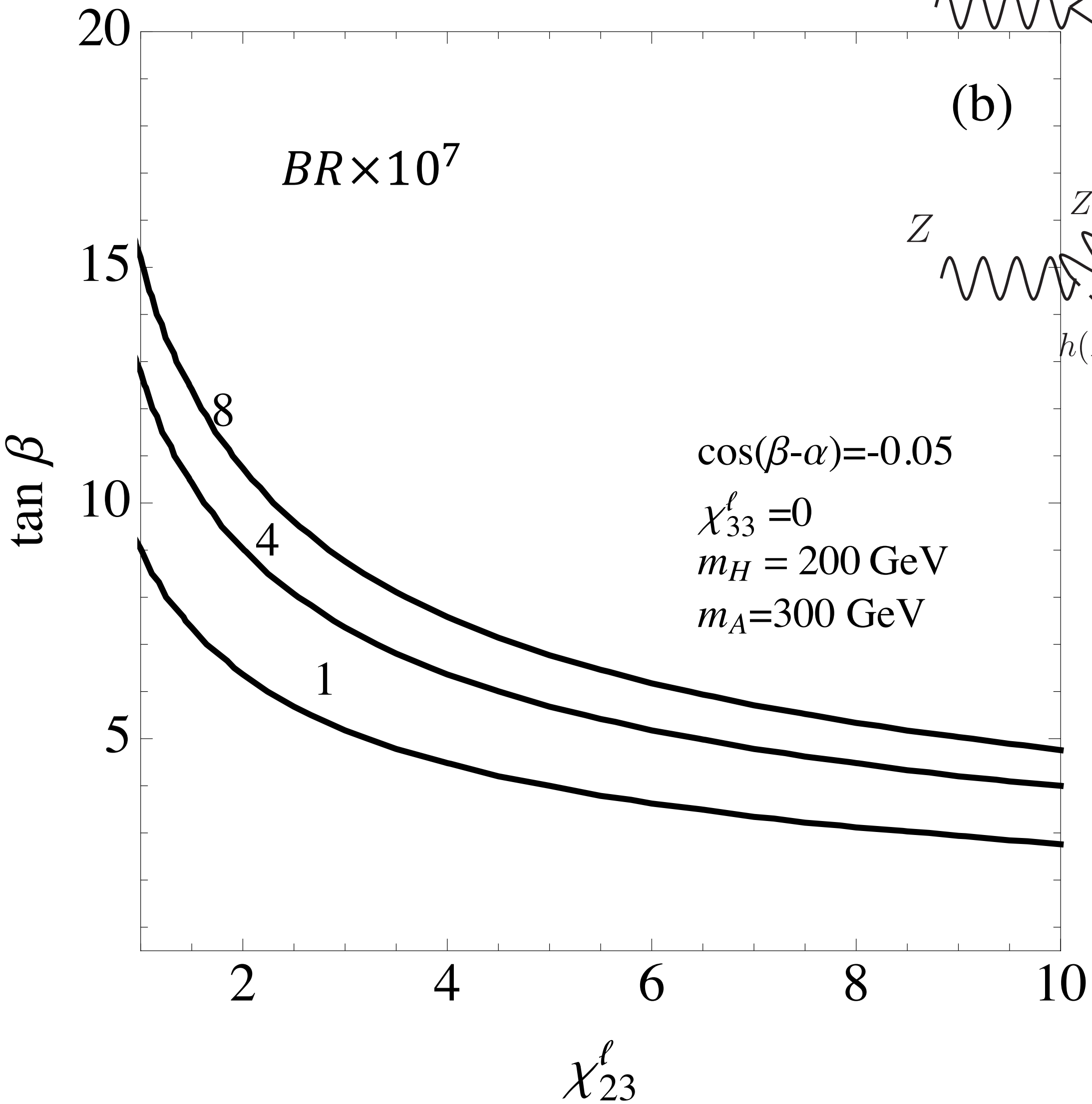
$$BR(\mu \to e\gamma)^{exp} < 5.7 \times 10^{-13}$$

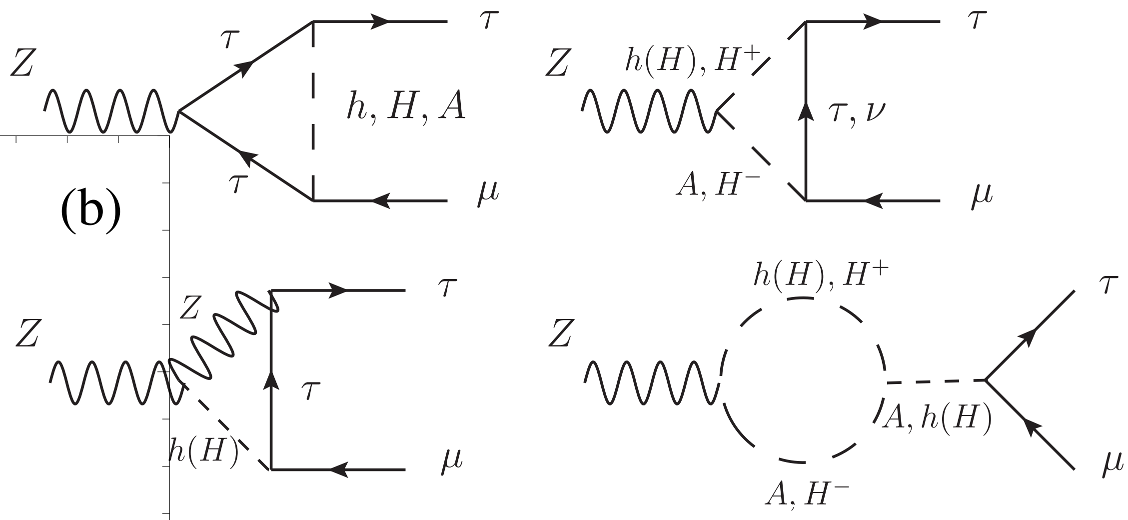




- $\chi^\ell_{13} \ll \chi^\ell_{23}$ $\quad BR(h \to e\tau) < 2 \times 10^{-4} \left(\frac{\chi^\ell_{13}/\chi^\ell_{23}}{10^{-3}} \right)^2 BR(h \to \mu\tau).$

$Z \to \mu\tau$:





$BR(Z \to \mu\tau)^{exp} < 2.1 \times 10^{-5}$

Conclusions:

- We revisit the constraints on the 2HDM by using the theoretical requirements + $\delta\rho$ + oblique parameters + Higgs measurements

- Higgs data give strict constraints on $\cos(\beta - \alpha)$ and $tan\beta$

- With the values of parameters that satisfy CMS $BR(h \to \tau\mu) \sim 0.84\%$,

  - $\tau \to 3\mu, \tau \to \mu\gamma$ can fit the upper limits of current data
  - Δa_μ can be explained
  - Δa_μ has a strong correlation with $\mu \to e\gamma$
  - $\frac{BR(h\to e\tau)}{BR(h\to \mu\tau)} \sim 10^{-4}$
  - $BR(Z \to \mu\tau) < 10^{-6}$