Muon g-2 in 2HDMs (g2HDM, Variant Axion Models)

Michihisa Takeuchi (KMI, Nagoya)

based on arXiv:1907.09845 (with S. Iguro, Y. Omura)
arxiv:1807.00593 (with C.-W. Chiang, P.-Y. Tseng, T. T. Yanagida)
(and JHEP11(2015)057 [arXiv:1507.04354],PhysRevD.97.035015 [arXiv:1711.02993])

KMI
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at the 1st AEI workshop for BSM, Jeju, on 6th Nov. 2019

Muon g-2 : signature of BSM?

magnetic moment (potential term in a magnetic field)

$$\mathcal{H} = -\vec{\mu}\cdot\vec{B} \qquad \vec{\mu} = -g\frac{e}{2m}\vec{S}$$

$g = 2$ tree level, Dirac equation

$g = 2.002\ 331$ QED, $\frac{\alpha}{\pi} = 0.00232\ldots$

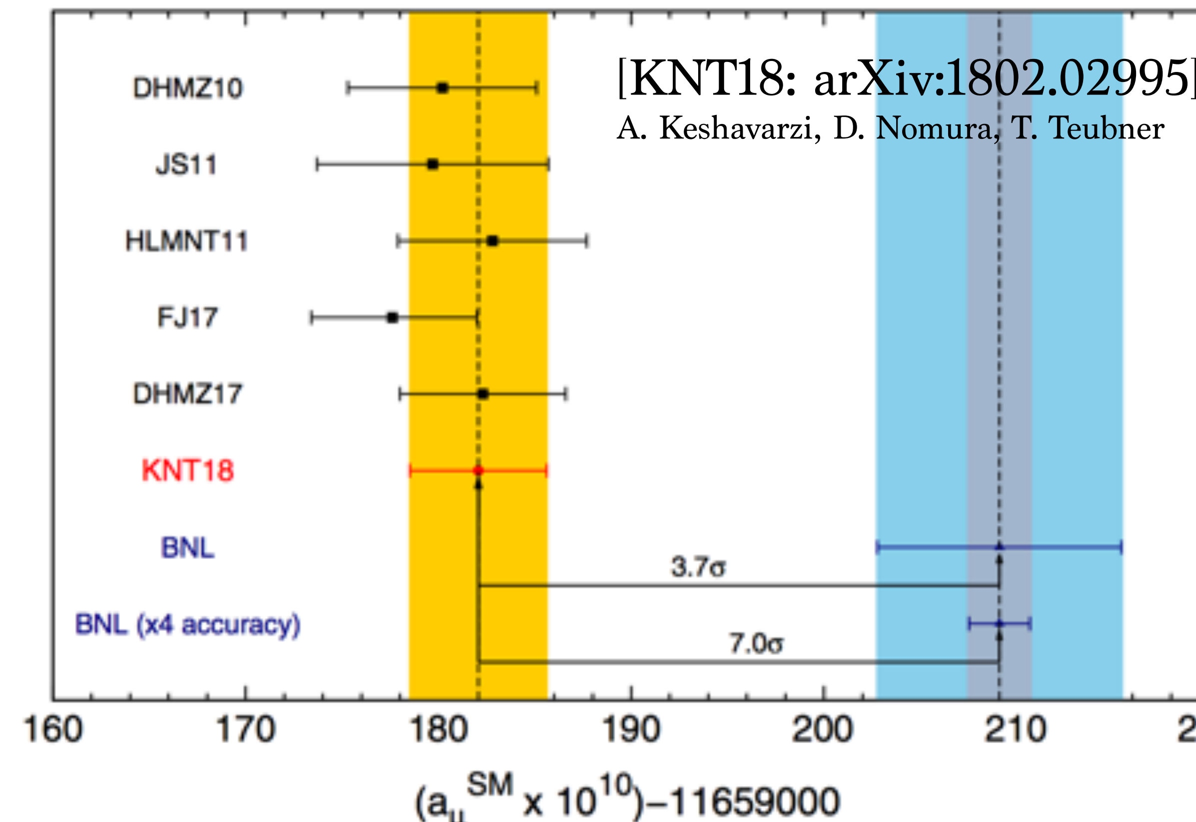
$g = 2.002\ 331\ 83$ hadronic

$g = 2.\underbrace{002\ 331\ 836\ 6}$ EW

anomalous magnetic moment

$$a_\mu = (g_\mu - 2)/2$$

currently computed including 5-loop QED,
up to 9th digit reliable



$\times 10^{-10}$

Theory total	11659182.80 (4.94)	⟶	11659182.05 (3.56)
Experiment			11659209.10 (6.33)
Exp - Theory	26.1 (8.0)	⟶	27.1 (7.3)
Δa_μ	3.3σ	⟶	3.7σ

last year, estimate of the uncertainty reduced
the resulting significance increased

For long time, the 3σ level discrepancy observed

$$\Delta a_\mu = a_\mu^{\rm Exp} - a_\mu^{\rm SM} \sim \Delta a_\mu^{\rm EW} \sim \mathcal{O}(10^{-9})$$

$$\Delta a_\mu^{\rm NP} \sim \frac{g_{\rm NP}^2}{16\pi^2}\frac{m_\mu^2}{m_{\rm NP}^2}$$

Hint for BSM?
New physics at O(100GeV) ?

Two Higgs Doublet Models (2HDM)

one additional Higgs doublet to the SM : new states $H, A, H^{\pm}$

$$\Phi_1 = \begin{pmatrix} H_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + h_1 + ia_1) \end{pmatrix}, \Phi_2 = \begin{pmatrix} H_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + h_2 + ia_2) \end{pmatrix}$$

$$v_1^2 + v_2^2 = v_{\rm SM}^2 = (246{\rm GeV})^2$$

$$\tan\beta = v_2/v_1$$

appear as a low energy EFT in many well-motivated models (MSSM, Axion Models (PQ sym))

Yukawa interactions in general for both higgs doublets

$$\mathcal{L} = -\bar{Q}_L^i H_1 y_d^i d_R^i - \bar{Q}_L^i H_2 \rho_d^{ij} d_R^j - \bar{Q}_L^i (V^\dagger)^{ij} \tilde{H}_1 y_u^j u_R^j - \bar{Q}_L^i (V^\dagger)^{ij} \tilde{H}_2 \rho_u^{jk} u_R^k$$
$$- \bar{L}_L^i H_1 y_e^i e_R^i - \bar{L}_L^i H_2 \rho_e^{ij} e_R^j + \text{h.c.}.$$

$$\tilde{H} = (i\sigma_2) H^*$$

to avoid tree-level FCNC, certain parity structure is often introduced (otherwise simultaneously not diagonalized)
each type of fermions can couple to one higgs doublet

model	u_R	d_R	e_R	ζ_u	ζ_d	ζ_e
Type I	Φ_2	Φ_2	Φ_2	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type II (MSSM-like)	Φ_2	Φ_1	Φ_1	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type X (Lepton-specific)	Φ_2	Φ_2	Φ_1	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type Y (Flipped)	Φ_2	Φ_1	Φ_2	$\cot\beta$	$-\tan\beta$	$\cot\beta$

$$\xi_f^h = s_{\beta-\alpha} + c_{\beta-\alpha}\zeta_f$$
$$\xi_f^H = c_{\beta-\alpha} - s_{\beta-\alpha}\zeta_f$$
$$\xi_f^A = (2T_f^3)\zeta_f$$

* tan beta enhancement always with the minus sign, the pseudo-scaler couplings depends on isospin

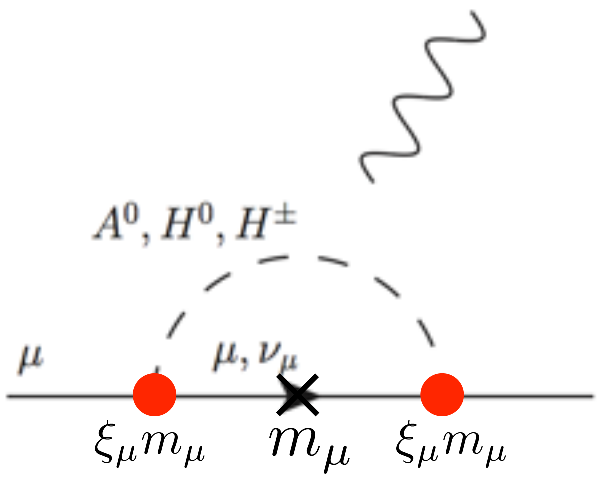
g-2 in 2HDM

$r_f^i = m_f^2/m_i^2$

$f_{h,H}(r) = \int_0^1 dx \frac{x^2(2-x)}{1-x+rx^2}, \quad f_A(r) = \int_0^1 dx \frac{-x^3}{1-x+rx^2}$

$f_{H^\pm}(r) = \int_0^1 dx \frac{-x(1-x)}{1-r(1-x)}.$

1-loop in 2HDM



suppressed by $\frac{m_\mu}{v} \sim 10^{-3}$

$$\Delta a_\mu^{1-\mathrm{loop}} = \frac{G_F m_\mu^2}{4\sqrt{2}\pi^2} \sum_i^{h,H,A,H^\pm} (\xi_\mu^i)^2 \frac{m_\mu^2}{m_i^2} f_i(r_f^i)$$

$\sim 10^{-9}$ $\quad\quad$ $\sim 10^{-7}$ $(m_H = 1\mathrm{TeV})$

$\mathcal{O}(10^{-9})$ contribution required

cf.) muon-specific 2HDM [T. Abe, R. Sato, K. Yagyu, arXiv:1705.01469]

$\xi_\mu \sim 3000 \quad m_H = 1\mathrm{TeV}$

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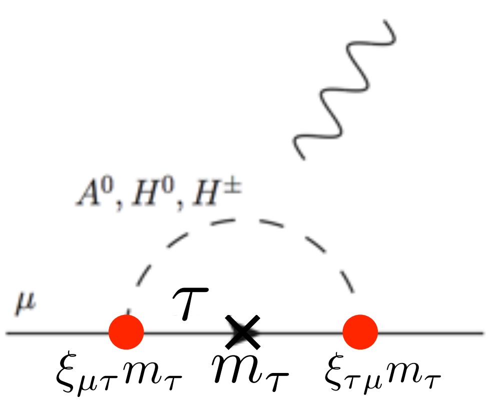
introducing LFV coupling has an advantage



➡ LFV enhance with $m_\tau^3/m_\mu^3 \sim 5000$, $\xi_{\mu\tau} \sim \xi_{\tau\mu} \sim 50$ required $\quad m_H = 1\mathrm{TeV}$

consider the case only LFV couplings $\rho^{\mu\tau}, \rho^{\tau\mu}$ introduced for heavy higgses

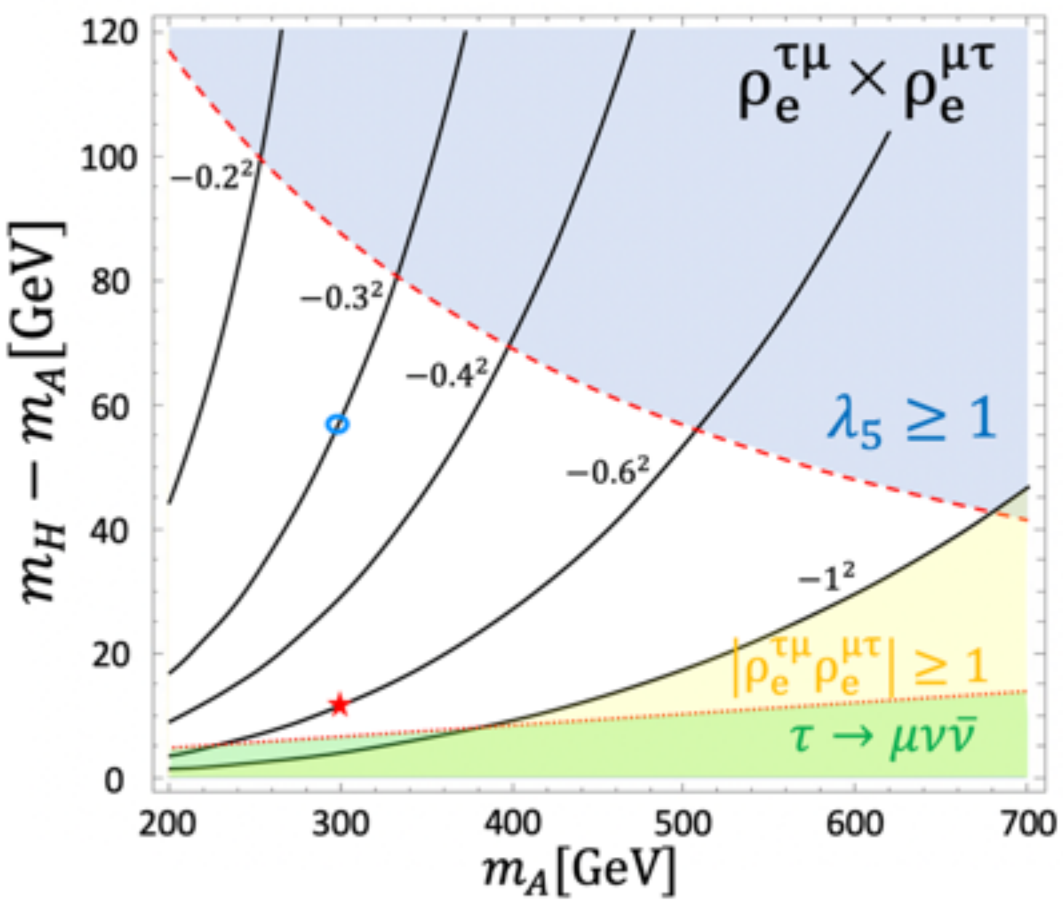
g-2 via lepton flavor violation

[S.Iguro, Y. Omura, MT arXiv:1907.09845]

g2HDM (new Yukawa matrices : free parameters, phenomenological analysis)

we consider only $\rho^{\mu\tau}, \rho^{\tau\mu}$ cf) [Y. Abe, T. Toma and K. Tsumura, arXiv:1904.10908]

$$H_1 = \begin{pmatrix} G^+ \\ \frac{v+\phi_1+iG}{\sqrt{2}} \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ \frac{\phi_2+iA}{\sqrt{2}} \end{pmatrix} \qquad \mathcal{L} = -\bar{\ell}_{Li} H_2 \rho^{ij} e_{Rj} + h.c.$$



$$\Delta a_\mu \simeq -\frac{m_\mu m_\tau \rho_e^{\mu\tau}\rho_e^{\tau\mu}}{8\pi^2}\frac{\Delta_{H-A}}{m_A^3}\left(\ln\frac{m_A^2}{m_\tau^2}-\frac{5}{2}\right)$$
$$\simeq -3\times 10^{-9}\left(\frac{\rho_e^{\mu\tau}\rho_e^{\tau\mu}}{0.3^2}\right)\left(\frac{\Delta_{H-A}}{60[\mathrm{GeV}]}\right)\left(\frac{300[\mathrm{GeV}]}{m_A}\right)^3$$

H, A contributions cancel each other, total contributions $\propto \Delta_{H-A} = m_H - m_A$

controlled by Higgs potential, $V(H_i) = \lambda_4(H_1^\dagger H_2)(H_2^\dagger H_1) + \{\frac{\lambda_5}{2}(H_1^\dagger H_2)^2 + \mathrm{h.c.}\} + \cdots$

$$m_H^2 \simeq m_A^2 + \lambda_5 v^2, \qquad m_{H^\pm}^2 \simeq m_A^2 - \frac{\lambda_4 - \lambda_5}{2}v^2,$$

we assume $m_A \leq m_H = m_{H^\pm}$ and require perturbativity, stability

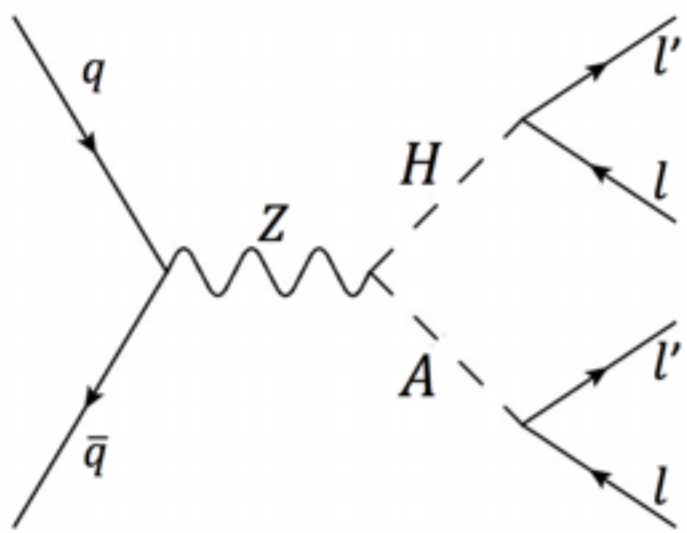
$$0 < \lambda_5 < 1 \qquad |\rho^{\mu\tau}|, |\rho^{\tau\mu}| < 1$$

the parameter region available to explain g-2 is finite

$$m_A \lesssim 700\mathrm{GeV} \quad \text{and} \quad 10\mathrm{GeV} \lesssim \Delta_{H-A} \lesssim 100\mathrm{GeV}$$

g-2 via lepton flavor violation — LHC signatures

[S.Iguro, Y. Omura, MT arXiv:1907.09845]

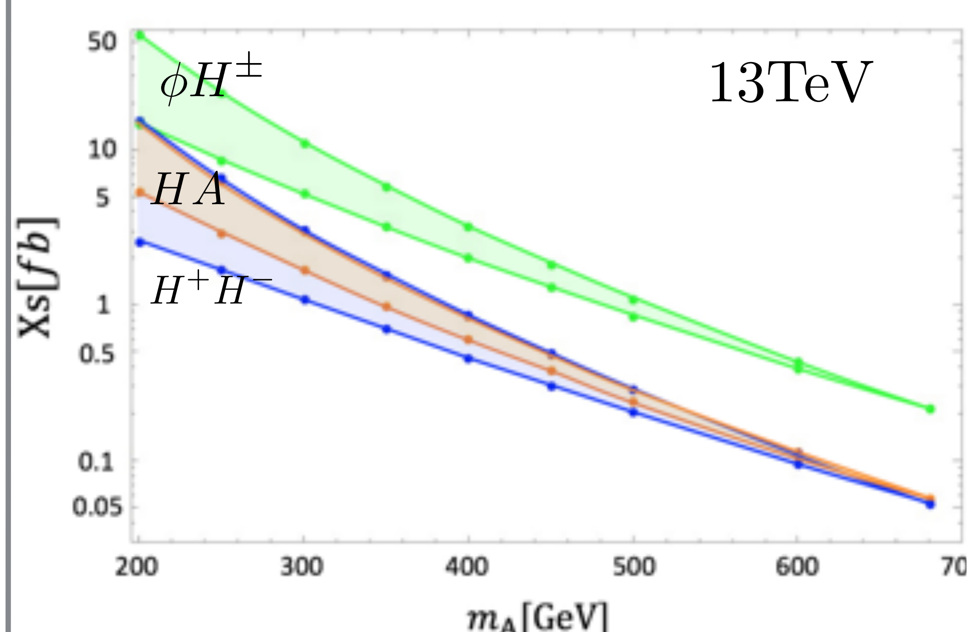


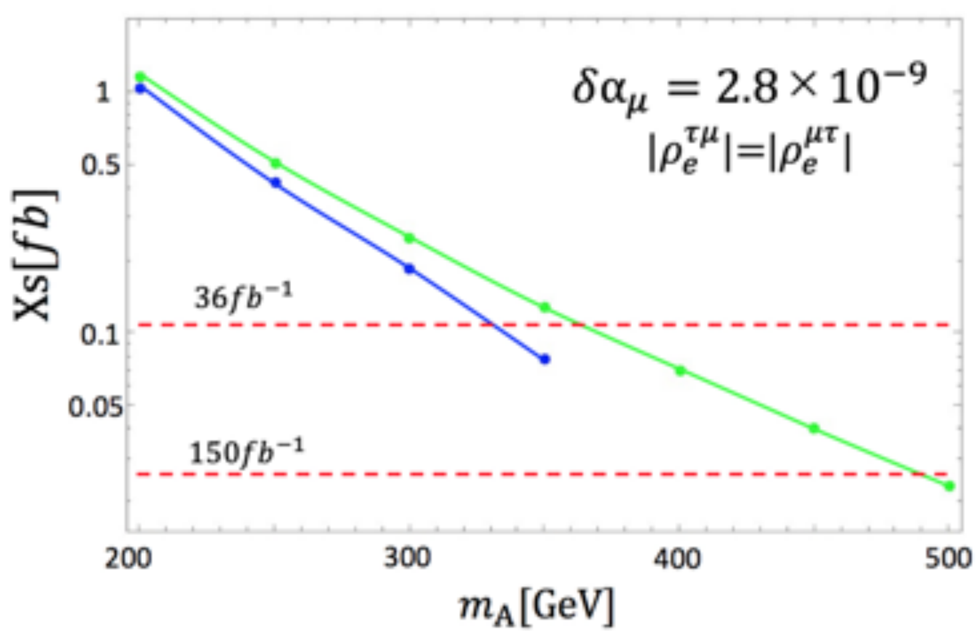
no QCD coupling : small but still sizable rate via SU(2) coupling

Heavy higgses produced in pair via Drell-Yan, HA, $\phi H^{\pm}$, and H^+H^-, where $\phi = H, A$.

$$BR(\phi \to \tau^+\mu^-) = BR(\phi \to \tau^-\mu^+) = 0.5,$$
$$BR(H^{\pm} \to \tau^{\pm}\nu) = 1 - BR(H^{\pm} \to \mu^{\pm}\nu) = \frac{|\rho_e^{\mu\tau}|^2}{|\rho_e^{\tau\mu}|^2 + |\rho_e^{\mu\tau}|^2} \equiv r.$$

they result in 4 leptons, 3 leptons, 2 leptons





multi-lepton $2\mu 2\tau$ channels

Especially $\mu^{\pm}\mu^{\pm}\tau^{\mp}\tau^{\mp}$

current data should already be sensitive at LHC up to 500 GeV

g-2 via LFV — mass reconstruction at LHC

[S.Iguro, Y. Omura, MT arXiv:1907.09845]

in future at 14 TeV, ~2fb (300 GeV) with 3 ab ⇒ ~ 6000 HA pair produced, other modes similarly produced

4 leptons from HA production

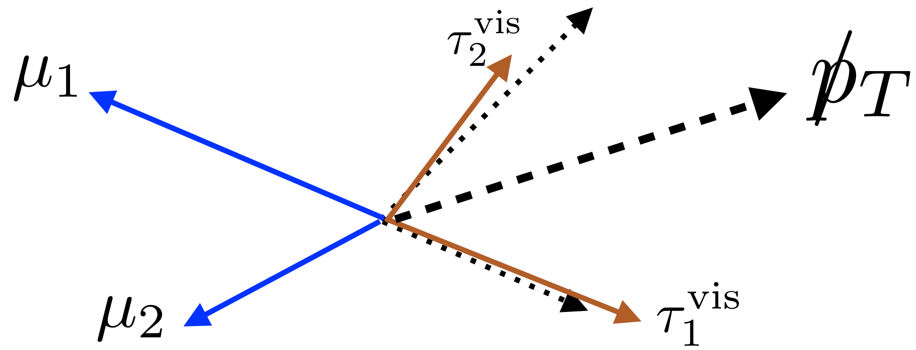
$\mu^\pm\mu^\pm\tau^\mp\tau^\mp$ same-sign di-muon di-tau (50%) — $\mathcal{O}(200-300)$ events for 3 ab^{-1}

$\mu^+\mu^-\tau^+\tau^-$ opposite-sign di-muon di-tau (50%) — OSOF pair gives the resonances (almost BG free)

τ-momentum : collinear approx.

$$\mathbf{p}_{\tau_i} = (1+c_i)\mathbf{p}^{\rm vis}_{\tau_i}$$

$$\not{\mathbf{p}}_T = c_1\mathbf{p}^{\rm vis}_{T,\tau_1} + c_2\mathbf{p}^{\rm vis}_{T,\tau_2} \qquad (c_1, c_2 > 0).$$



for $\mu^\pm\mu^\pm\tau^\mp\tau^\mp$

two possible combinations :

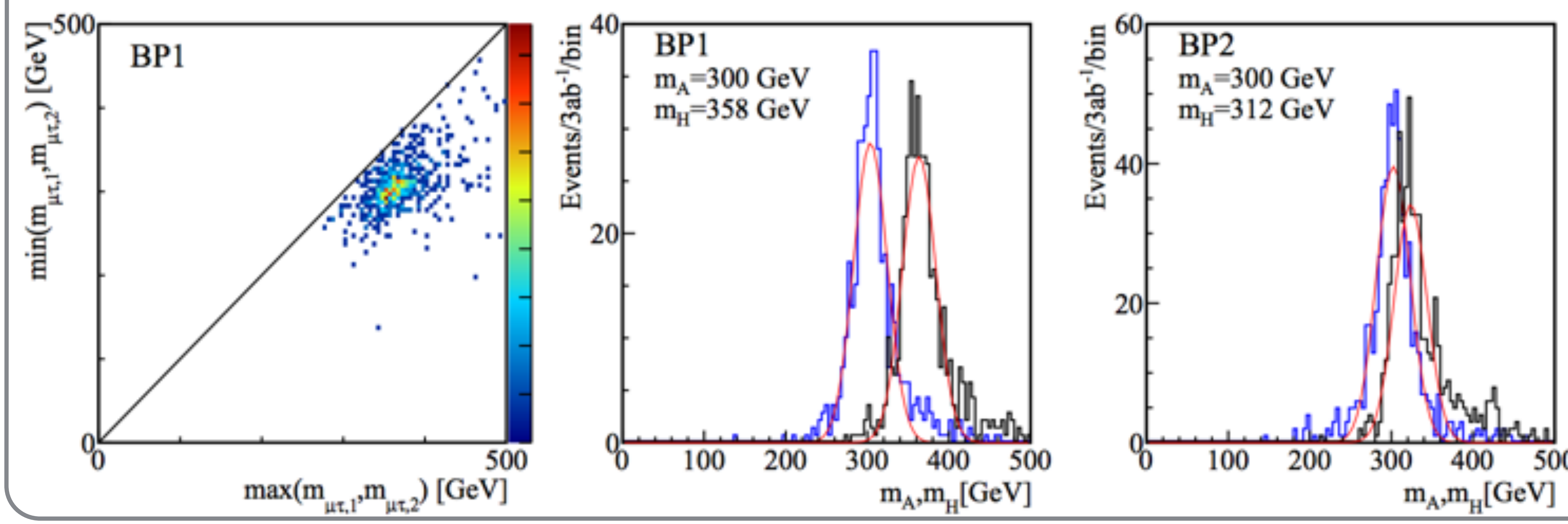
combination 1 : $m_{\mu_1\tau_1}$ and $m_{\mu_2\tau_2}$

combination 2 : $m_{\mu_1\tau_2}$ and $m_{\mu_2\tau_1}$

$\mu_1, \mu_2, \tau_1^{\rm vis}$, and $\tau_2^{\rm vis}$ in p_T-order

select the one minimizing the sum of

$$\chi_i^2(m_A, m_H) = (m^{\rm min}_{\mu\tau,i} - m_A)^2/\sigma^2_{\rm res} + (m^{\rm max}_{\mu\tau,i} - m_H)^2/\sigma^2_{\rm res}$$



can reconstruct two invariant masses mA and mH

$\sigma_{\rm res} \sim 20\mathrm{GeV}$

cf.) $10\mathrm{GeV} \lesssim \Delta_{H-A} \lesssim 100\mathrm{GeV}$

charged higgs mass from 3 and 2 lepton modes

g-2 in 2HDM via 2-loop

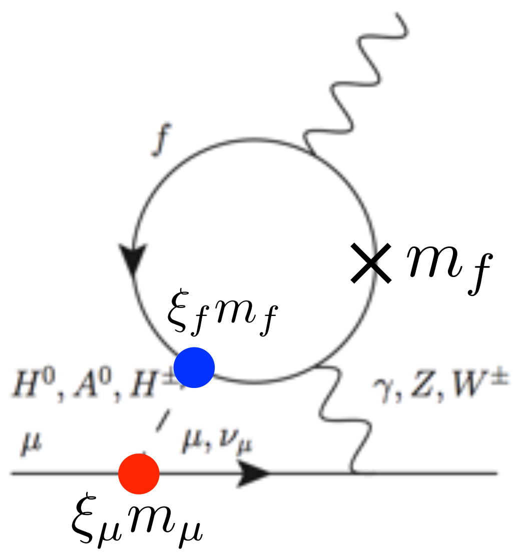
$$r_f^i = m_f^2/m_i^2$$

$$g_{h,H}(r) = \int_0^1 dx \frac{2x(1-x)-1}{x(1-x)-r}\ln\frac{x(1-x)}{r},$$

$$g_A(r) = \int_0^1 dx \frac{1}{x(1-x)-r}\ln\frac{x(1-x)}{r}.$$

2-loop (Barr-Zee) in 2HDM

enhanced by the large yukawa coupling for heavy fermions



$$\propto m_\mu m_f^2/m_H^2$$

$$\Delta a_\mu^{\rm BZ} = \frac{G_F m_\mu^2}{4\sqrt{2}\pi^2}\frac{\alpha_{\rm EM}}{\pi}\sum_i^{h,H,A}\sum_f^{t,b,c,\tau} N_f^c Q_f^2 \xi_\mu^i \xi_f^i \frac{m_f^2}{m_i^2} g_i(r_f^i)$$

$\sim 10^{-9}$

	$\times\alpha N_f^c Q_f^2/\pi$	Sign of (δ_H, δ_A)
t	$(-1.1, 1.5)\times 10^{-3}$	$(-,-)$
c	$(-5.9, 7.1)\times 10^{-7}$	$(-,-)$
u	$(-4.6, 5.4)\times 10^{-12}$	$(-,-)$
b	$(-1.1, 1.4)\times 10^{-6}$	$(-,+)$
τ	$(-8.0, 9.6)\times 10^{-7}$	$(-,+)$

$\mathcal{O}(10^{-9})$ positive contribution required

positive sign only for A with down-type fermion

⇒ τ is only the possibility $\xi_\mu \xi_\tau / m_H^2[\rm TeV] \sim 10^6$ required

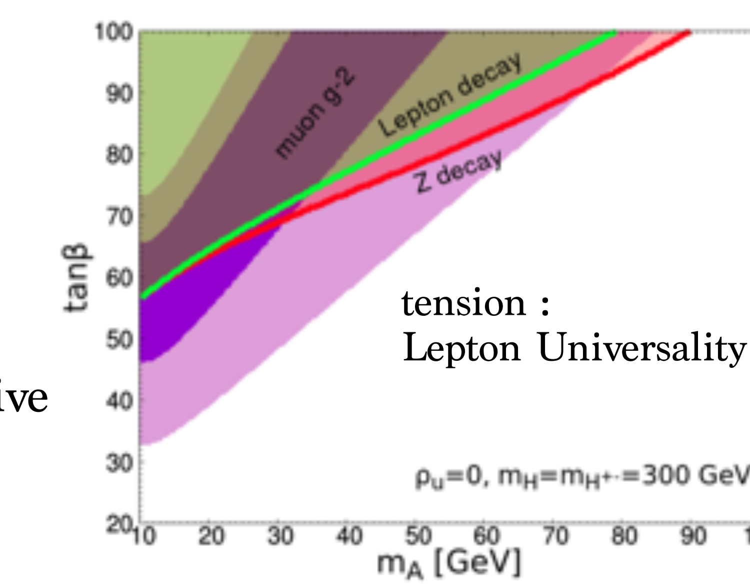
bottom (type II) disfavored by bbA at LHC and Bs→μμ

In lepton-specific 2HDM model, where all leptons tanβ enhanced

mA ~ 30GeV and tanβ ~ 40 will give an appropriate g-2 contribution

LHC constraints for additional higgs bosons suppressed with no QCD coupling

In future, Drell-Yan productions ⇒ multi-taus (4 tau, 3tau, 2tau) events would be sensitive



We extend this scenario to a well motivated model (Variant Axion Model)

2HDM as the solution for strong CP problem

Strong CP problem

θ-vacuum

$$|\theta>= \sum_{n=-\infty}^{\infty} e^{in\theta}|n> \quad \Leftrightarrow \quad \mathcal{L}_\theta = \frac{g^2\theta}{32\pi^2} G^{\mu\nu}\tilde{G}_{\mu\nu}$$

$\theta_{\rm eff} = \theta + \arg\det[M^u M^d]$

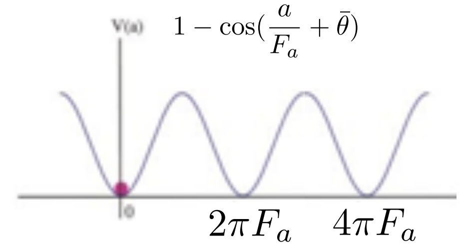
Why $\theta_{\rm eff} < 10^{-11}$?

PQ solution with axion

assume spontaneously broken U(1) $\eta e^{i\theta_{PQ}} \sim \eta + ia$ to introduce axion field

triangle diagram (N: n. of coupled quarks), $\delta\mathcal{L} = -\frac{g^2}{32\pi^2} N \frac{a}{\eta} G^{\mu\nu}\tilde{G}_{\mu\nu}$ induced

after QCD PT, $< G^{\mu\nu}\tilde{G}_{\mu\nu} > \sim \Lambda^4_{\rm QCD}$ the potential



$\bar{\theta} = \theta_{\rm strong} + \theta_{\rm EM}$

$$\theta_{\rm eff} = \theta + \arg\det[M^u M^d] + \frac{< a >}{F_a}$$

very attractive, a also play a good CDM role

$a' \equiv a + \bar{\theta} F_a$

invisible axion models

KSVZ heavy Q introduced $\mathcal{L}_Q = -y_Q \bar{Q}_L \Phi Q_R + \text{h.c.}$ $N_{DM} = 1$

(no problem but no low energy phenomenology, not interesting)

(Kim 1979, Shifman, Vainshtein, Zakharov 1980)

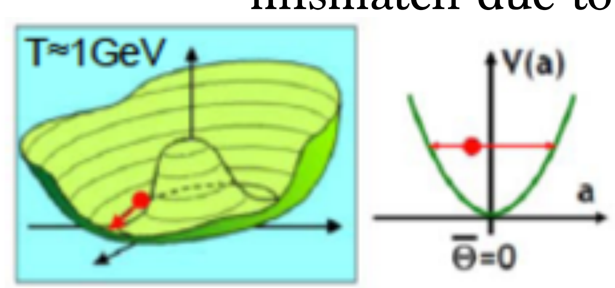
ZDFS two Higgs doublet model

$\Phi_1^\dagger \Phi_2 \sigma^2$ $N_{DM} = 6$

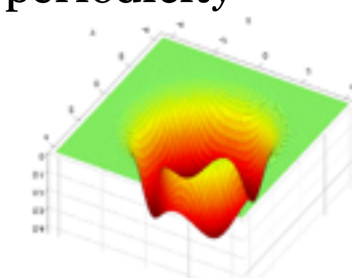
$m\Phi_1^\dagger \Phi_2 \sigma$ $N_{DM} = 3$

(Zhitnitsky1980,
Dine, Fischler, Srednicki 1981)

mismatch due to the different periodicity



in θ space



in $\frac{a}{\eta} = \frac{a}{NF_a}$ space

Variant Axion model domain wall problem absent if only 1 quark coupled to PQ-Higgs $N_{DM} = 1$

[R.D. Peccei, T.T. Wu and T. Yanagida, Phys. Lett. B172, 435 (1986)]

g-2 in Lepton-specific 2HDM with VAM

[arxiv:1807.00593, C.-W. Chiang, MT, P.-Y. Tseng, T. T. Yanagida]

VAM is a 2HDM at low energy, there is a choice which one quark is PQ charged.

quark sector : domain wall problem ⇒ only one q_R PQ charged

lepton sector : lepton yukawa has to be enhanced for muon g-2 ⇔ corresponding VEV is small (tanβ>>1)

(lepton sector is irrelevant to domain wall problem)

e	$\Phi_1(\mathrm{PQ}=+1)$	u_R, d_R
μ		c_R, s_R
τ	$\Phi_2(\mathrm{PQ}=0)$	t_R, b_R

g-2 in Lepton-specific 2HDM with VAM

[arxiv:1807.00593, C.-W. Chiang, MT, P.-Y. Tseng, T. T. Yanagida]

VAM is a 2HDM at low energy with various PQ charge assignments.

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e	$\Phi_1(PQ = +1)$	u_R, d_R
μ	to enhance lepton yukawa $v_2 \ll v_1$	c_R, s_R
τ	$\Phi_2(PQ = 0)$	t_R, b_R

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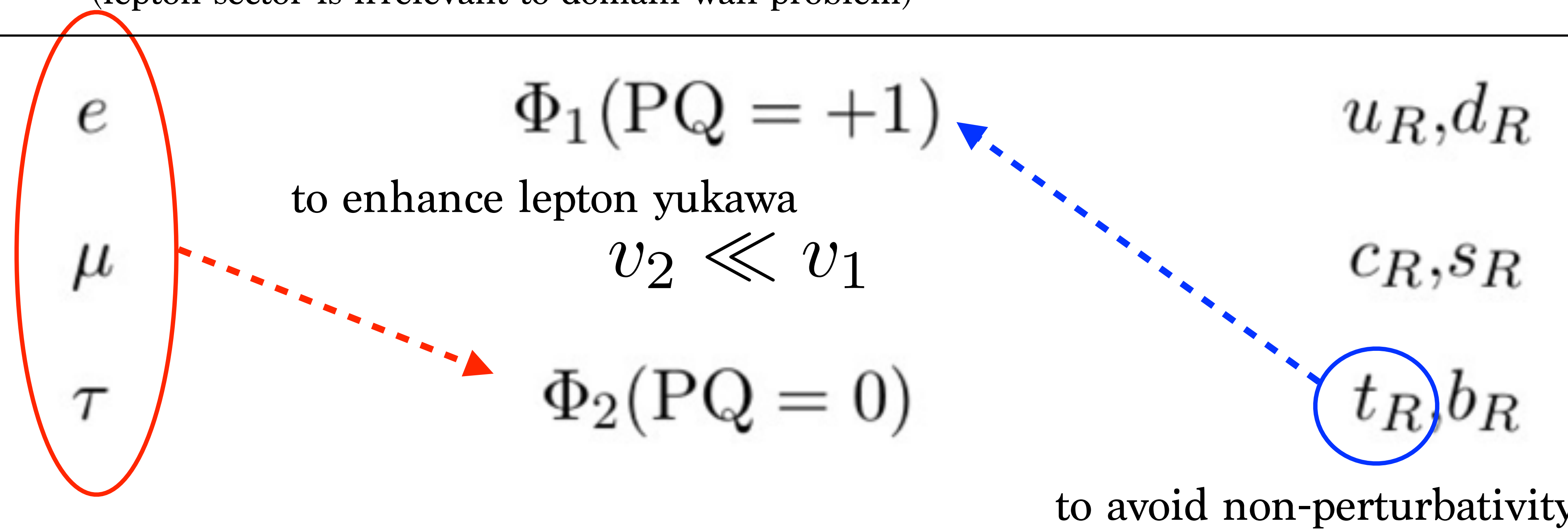

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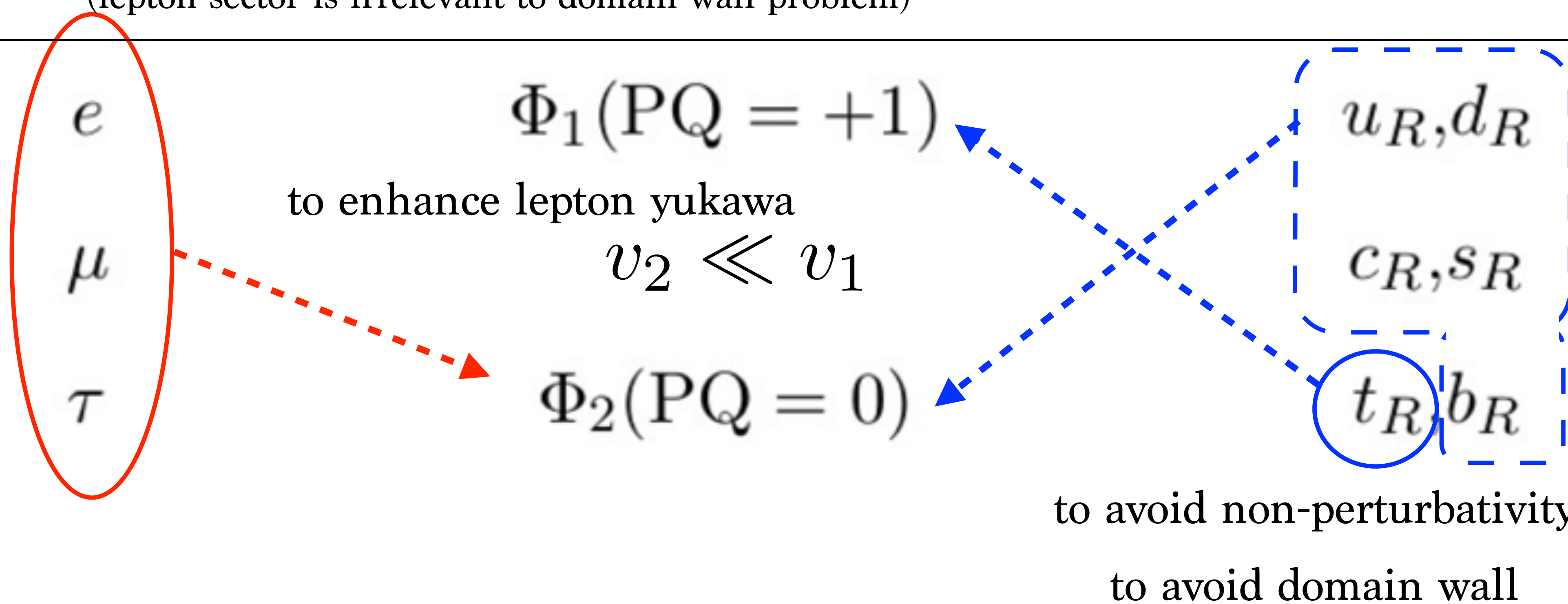

the 3rd gen. part becomes identical to the type II 2HDM ⇒ very constrained by LHC via bbA production

also by Bs→μμ

⇒ not viable possibility

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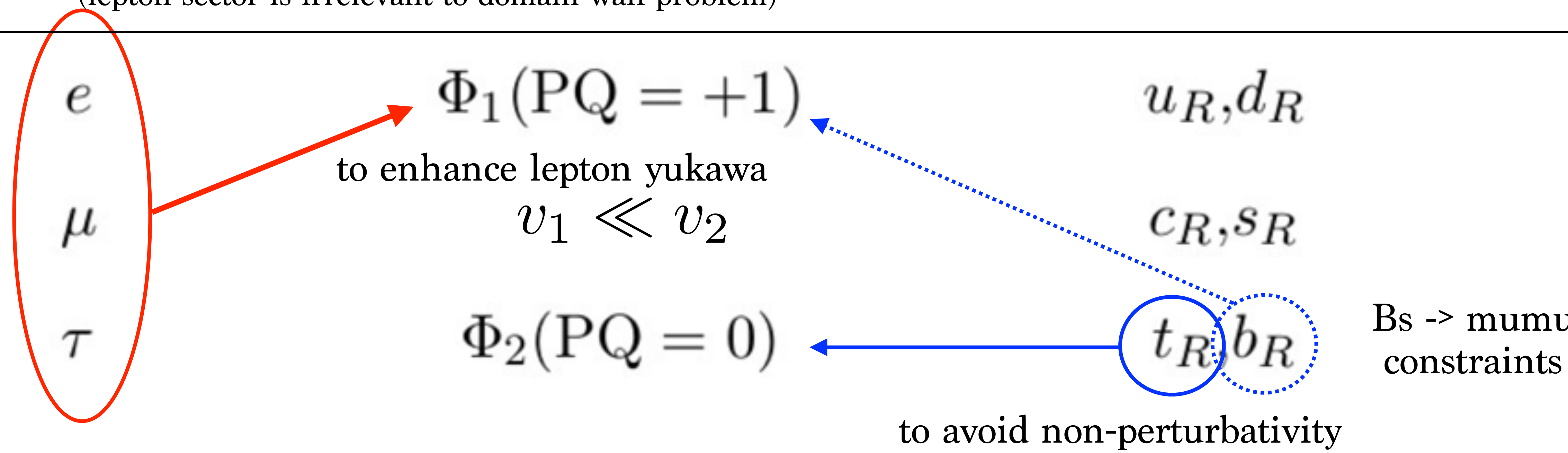

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e $\qquad$ $\Phi_1(\mathrm{PQ}=+1)$ $\qquad$ u_R, d_R

to enhance lepton yukawa

μ $\qquad$ $v_1 \ll v_2$ $\qquad$ c_R, s_R

τ $\qquad$ $\Phi_2(\mathrm{PQ}=0)$ $\qquad$ t_R, b_R $\qquad$ Bs -> mumu constraints

to avoid non-perturbativity

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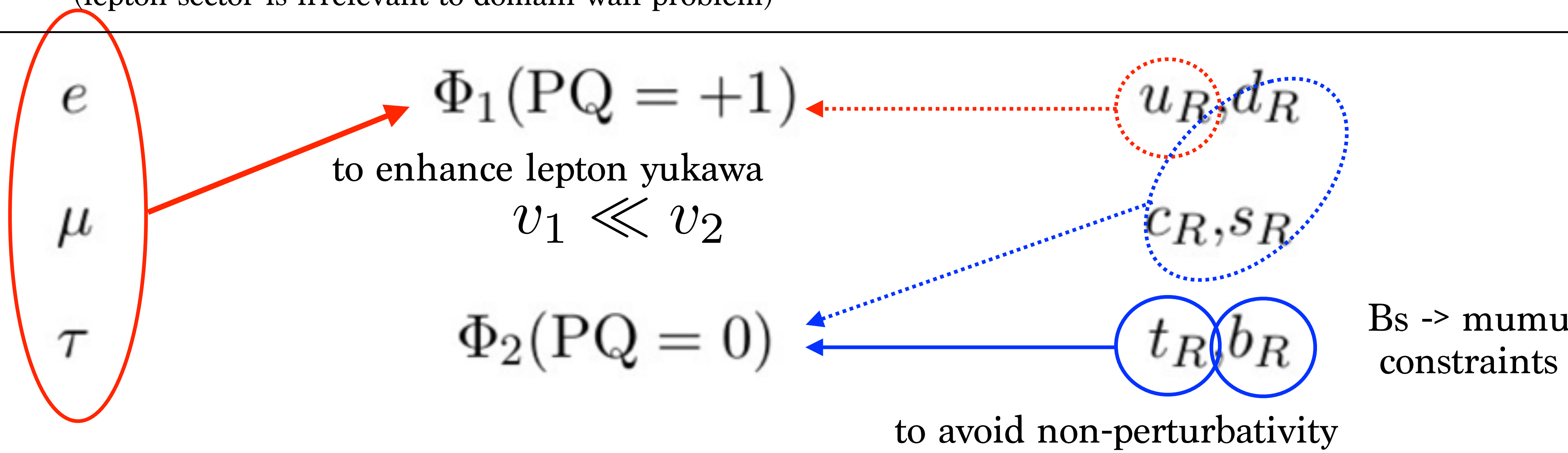


several choices, but up-specific is most interesting possibility

charm-specific : opposite sign for g-2

down/strange-specific : very constrained by Kaon physics

up-type specific Variant Axion model

[arxiv:1807.00593, C.-W. Chiang, MT, P.-Y. Tseng, T. T. Yanagida]

Φ_1	Φ_2	u_R	c_R	t_R	d_R	Q_L	ℓ_R	L_L
+	−	−	+	+	+	+	−	+

when we take up-type VAM,
top/charm/up FCNC is the generic prediction

For up-specific VAM,

$$L^u = -\Phi_1 \overline{u}_{Ra}[Y_{u1}]_{ai} Q_i - \Phi_2 \overline{u}_{R3}[Y_{u2}]_i Q_i + \text{h.c.}$$

Φ_2 only couple with u_R, e_R

$$Y_{u1} = \begin{pmatrix} * & * & * \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \text{and} \quad Y_{u2} = \begin{pmatrix} 0 & 0 & 0 \\ * & * & * \\ * & * & * \end{pmatrix},$$

mix with β

Higgs basis
(only $\Phi^{\rm SM}$ has a VEV)

$$\mathcal{L} = -\Phi^{\rm SM} \bar{u}_{Rj} [Y_u^{\rm SM}]_{ji} Q_i - \Phi' \bar{u}_{Ra} [Y'_u]_{ji} Q_i$$

$$Y'_u = -s_\beta Y_{u1} + c_\beta Y_{u2} = \begin{pmatrix} -\tan\beta & & \\ & \cot\beta & \\ & & \cot\beta \end{pmatrix} Y_u^{\rm SM}$$

$$Y'_e = -\tan\beta \ Y_e^{\rm SM},$$

$$Y'_d = \cot\beta \ Y_d^{\rm SM}.$$

diagonalizing mass matrix

$$Y_u^{\prime,\rm diag} = \begin{pmatrix} -\tan\beta & & \\ & \cot\beta & \\ & & \cot\beta \end{pmatrix} Y_u^{\rm diag} + (\tan\beta + \cot\beta) H_u Y_u^{\rm diag},$$

$$H_u = V_u \begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix} V_u^\dagger - \begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix} = \begin{pmatrix} \frac{\cos\rho_u - 1}{2} & 0 & \frac{\sin\rho_u}{2} \\ 0 & 0 & 0 \\ \frac{\sin\rho_u}{2} & 0 & \frac{1-\cos\rho_u}{2} \end{pmatrix}.$$

consider u-t mixing for simplicity

$$\zeta_{uu} \equiv -\tan\beta - (\tan\beta + \cot\beta)\frac{\cos\rho_u - 1}{2},$$

$$\zeta_{cc} \equiv \cot\beta,$$

$$\zeta_{tt} \equiv \cot\beta - (\tan\beta + \cot\beta)\frac{1 - \cos\rho_u}{2},$$

$$\zeta_{ut} = \zeta_{tu} = (\tan\beta + \cot\beta)\frac{\sin\rho_u}{2}.$$

$$\xi^h_{ff'} \equiv s_{\beta-\alpha}\delta_{ff'} + c_{\beta-\alpha}\zeta_{ff'},$$

$$\xi^H_{ff'} \equiv c_{\beta-\alpha}\delta_{ff'} - s_{\beta-\alpha}\zeta_{ff'},$$

$$\xi^A_{ff'} \equiv (2T_3^f)\zeta_{ff'},$$

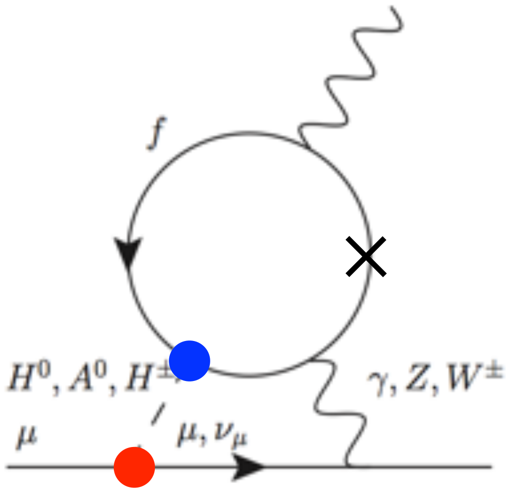
leptons and up: tan beta enhanced

FV $\propto\sim \sin\rho \tan\beta$

mixing eff. : ζ_{uu}: $-\tan\beta \nearrow$, ζ_{tt} : $\cot\beta \searrow -\tan\beta$

g-2 in Lepton-specific 2HDM with VAM

[arxiv:1807.00593, C.-W. Chiang, MT, P.-Y. Tseng, T. T. Yanagida]



$\propto m_\mu m_f^2/m_H^2$

$$\Delta a_\mu^{\rm BZ} = \frac{G_F m_\mu^2}{4\sqrt{2}\pi^2} \frac{\alpha_{\rm EM}}{\pi} \sum_i^{h,H,A} \sum_f^{t,b,c,\tau} N_f^c Q_f^2 \xi_\mu^i \xi_f^i \frac{m_f^2}{m_i^2} g_i(r_f^i)$$

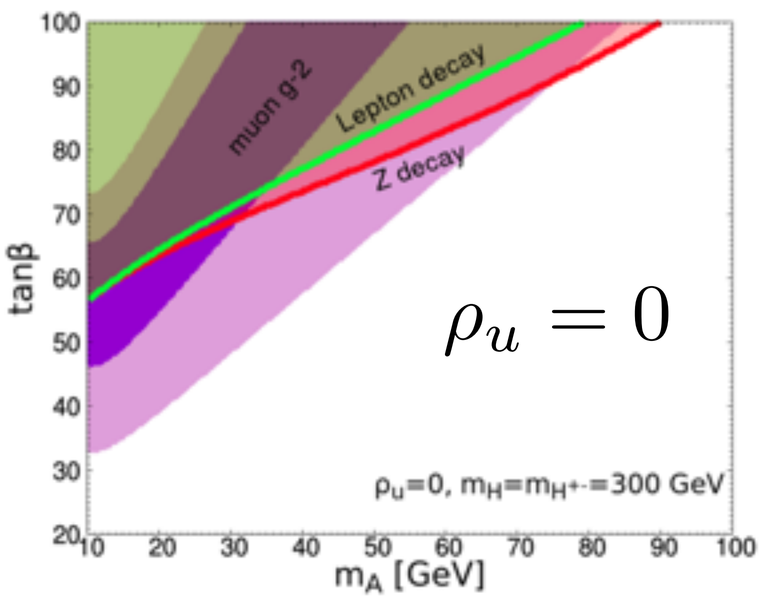
$\sim 10^{-9}$

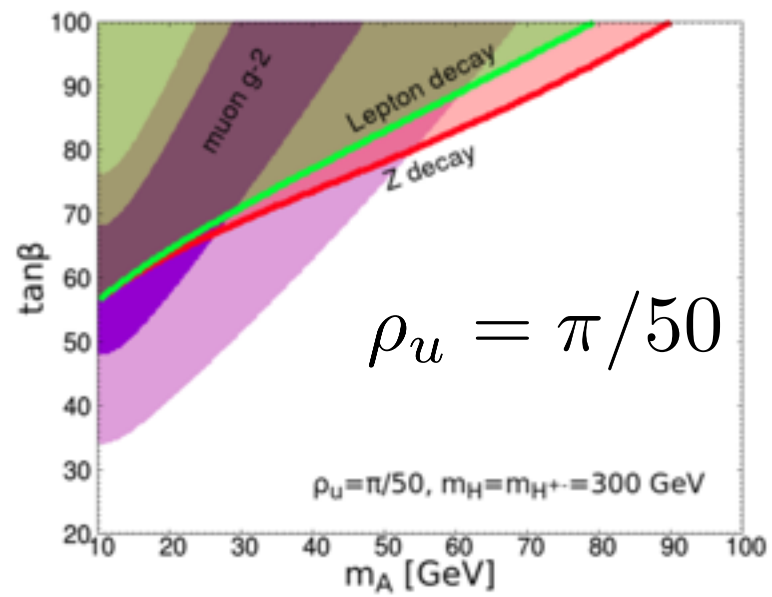
	$\times \alpha N_f^c Q_f^2/\pi$	Sign of (δ_H, δ_A)
t	$(-1.1, 1.5) \times 10^{-3}$	$(-,-)$
c	$(-5.9, 7.1) \times 10^{-7}$	$(-,-)$
u	$(-4.6, 5.4) \times 10^{-12}$	$(-,-)$
b	$(-1.1, 1.4) \times 10^{-6}$	$(-,+)$
τ	$(-8.0, 9.6) \times 10^{-7}$	$(-,+)$

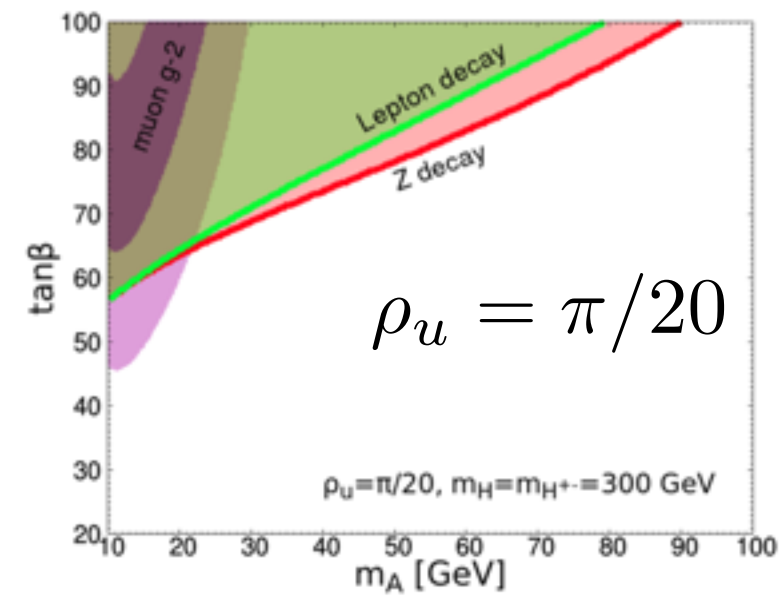
opposite sign contributions -tan β enhanced for up-type ⇒ only up negligible

LFV doesn't contribute directly to g-2, but affects the diagonal elements

FV $\propto\!\sim \sin\rho \tan\beta$ mixing eff. : ζ_{uu}: $-\tan\beta$ ↗, ζ_{tt} : $\cot\beta$ ↘ $-\tan\beta$







switching on LFV coupling induces negative top-loop contribution ⇒ rather disfavored by g-2

but acceptable as long as a small mixing

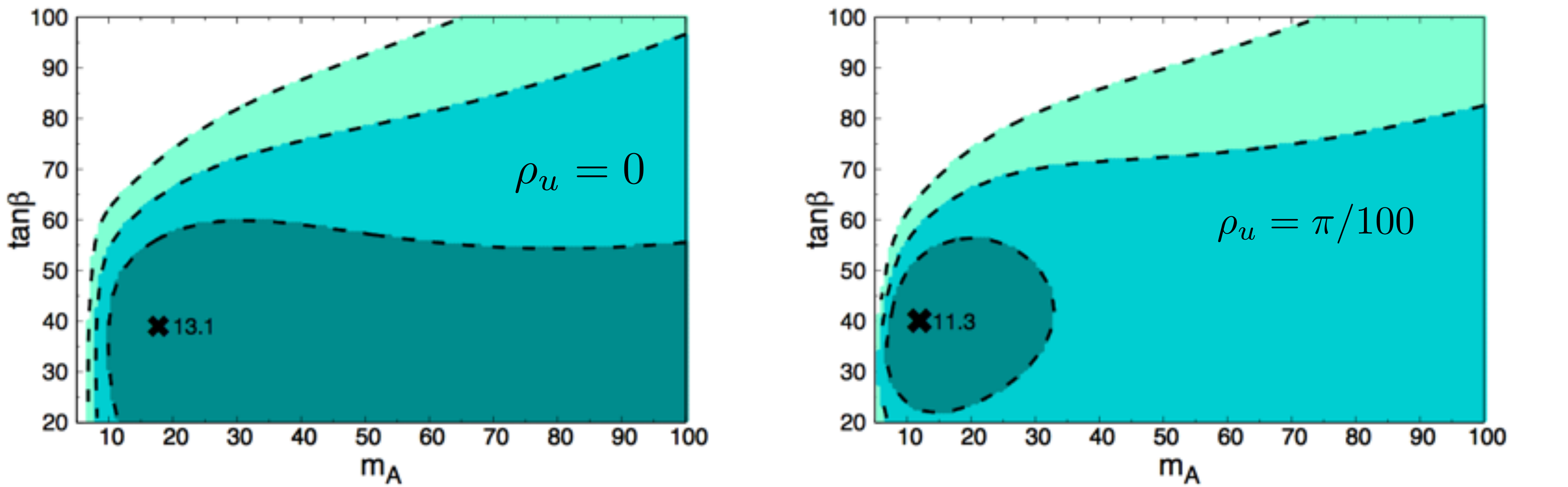
g-2 in Lepton-specific 2HDM with VAM

[arxiv:1807.00593, C.-W. Chiang, MT, P.-Y. Tseng, T. T. Yanagida]

Bs→μμ observation exhibit a slight deficit from the SM prediction

$$\bar{R}_{s\mu} \equiv \frac{\overline{\mathrm{BR}}(B_s^0 \to \mu^+\mu^-)_{\mathrm{EXP}}}{\overline{\mathrm{BR}}(B_s^0 \to \mu^+\mu^-)_{\mathrm{SM}}} = 0.79 \pm 0.20$$

$$\frac{\mathcal{M}}{\mathcal{M}^{\mathrm{SM}}} = 1 + \frac{\mathcal{M}^{u\mathrm{VAM}}}{\mathcal{M}^{\mathrm{SM}}} \sim 1 - 0.21\xi_{tt}^A\xi_{\mu\mu}^A\left(\frac{15\mathrm{GeV}}{m_A}\right)^2 \sim 1.21 - 0.05\rho_u^2\tan^2\beta$$



for combined χ^2-fit including Bs→μμ, small mixing $\rho_u = \pi/100$ slightly improves the fit

mA ~ 15GeV, tanβ~40, $\rho_u \sim 0.03$ will give a best fit

[arxiv:1807.00593, C.-W. Chiang, MT, P.-Y. Tseng, T. T. Yanagida]

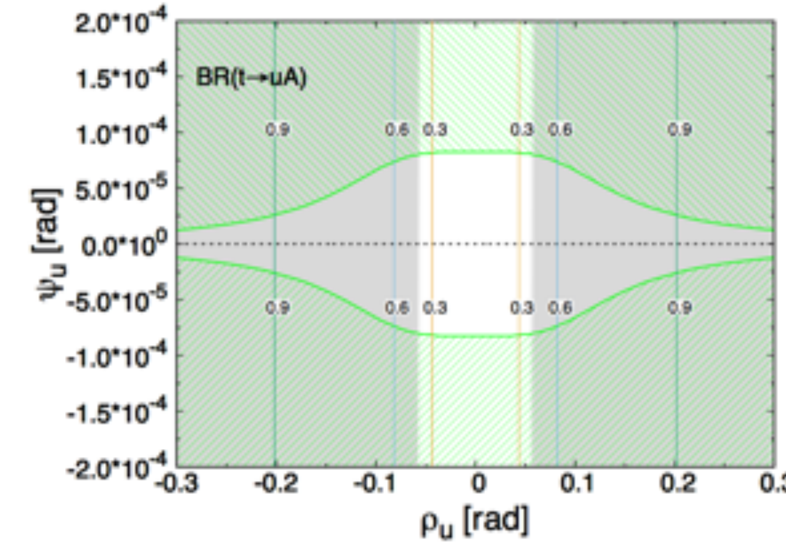
$t \to u A$, $A \to \tau\tau$

even for a slight mixing ρ~0.03 induces large *BR(t→uA)* ~O(10%)

$$\Gamma_{t\to uA/cA} \propto\sim \sin^2\rho_u \tan^2\beta$$

A decays dominantly to $\tau\tau$ about 100%

important signal from top pair production : $t\bar{t} \to t\bar{u}A,\, A \to \tau\tau$



$\Gamma_{t,\mathrm{tot}} \leq 2.5\mathrm{GeV} \to BR(t\to uA/cA) \lesssim 40\%$ $|\rho_u| \lesssim 0.06$

recast the LHC searches for *bbA*, *A*→$\tau\tau$, in the context of MSSM (type II)

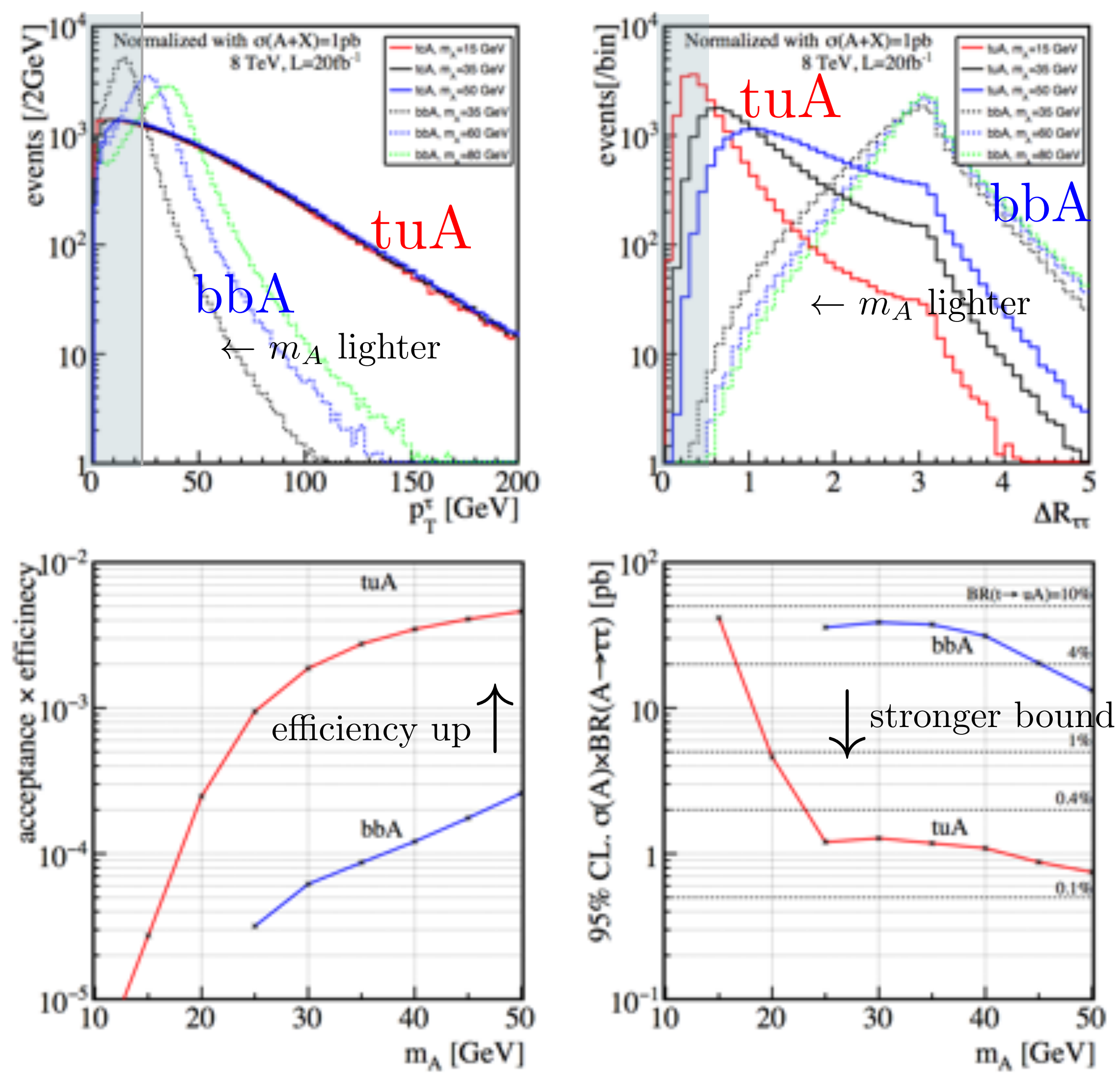
(CMS at 8TeV in μτ, eτ, eμ modes)

kinematics is different between *tuA* and *bbA*

— efficiency for *tuA*

higher due to $p_{T,\tau}$ cut

quickly goes down as $m_A \to 0$ due to ΔR cut



we estimate 8 TeV sensitivity,

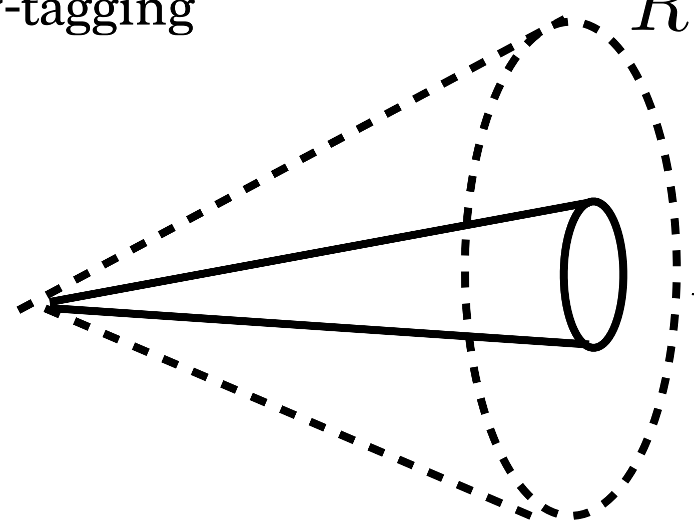
BR(t→uA) < 0.2% (*mA*>25GeV), 10% (*mA*=15GeV) : marginal

boosted A → $\tau\ \tau$

[arxiv:1807.00593, C.-W. Chiang, MT, P.-Y. Tseng, T. T. Yanagida]

The reason for rapid drop of the efficiency is due to the overlapping τ's due to the boost

τ-tagging

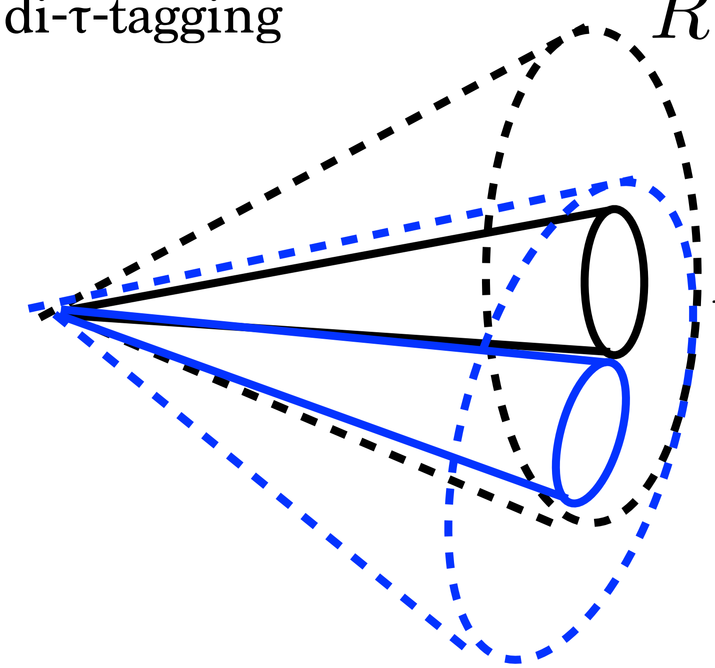


require energy deposit in the core part

$$f = \frac{E(R=0.1)}{E(R=0.5)} > 0.95$$

for boosted tau pair the usual isolation fails

di-τ-tagging

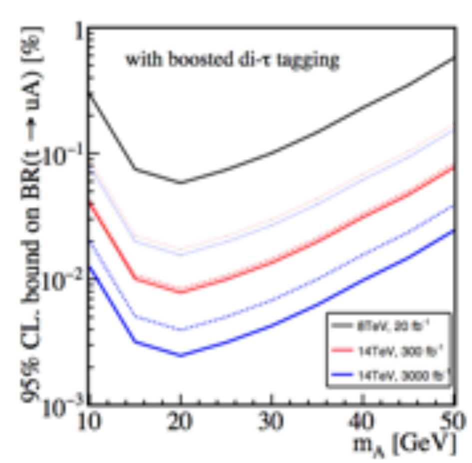


mutual isolation

[A. Katz, M. Son, B. Tweedie, PRD 83, 114033(2011).]

if core 1 is removed, the rest is τ-tagged

if core 2 is removed, the rest is also τ-tagged



For mA=15GeV

$BR(t \to uA)$ < 0.08%

(10% by CMS study)

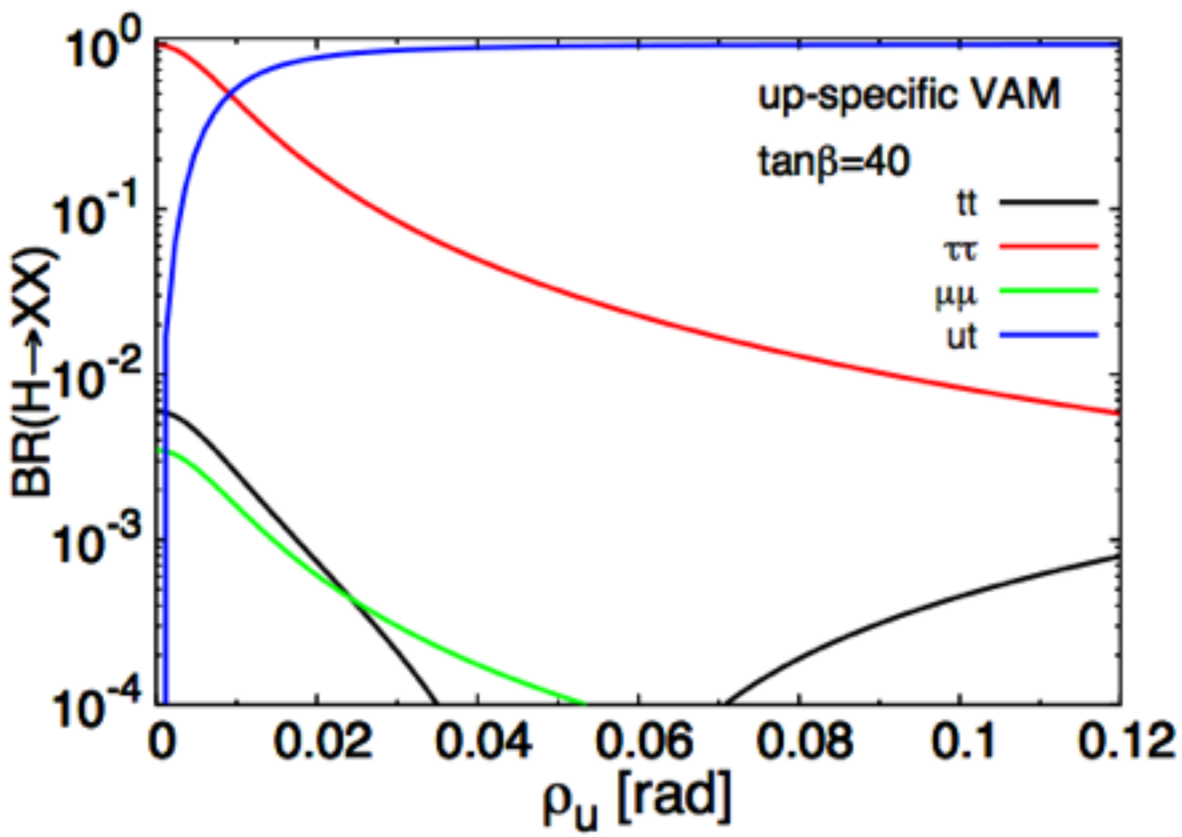
0.003-0.01% in future

Flavor violating Heavy higgs decays

[arxiv:1807.00593, C.-W. Chiang, MT, P.-Y. Tseng, T. T. Yanagida]

For $m_H \gg m_t$ and $\tan \gg 1$, we have

$$\frac{BR(H \to tu)}{BR(H \to \tau\tau)} \sim \frac{m_t^2}{m_\tau^2} \frac{3 \sin^2 \rho_u}{2} \simeq (120 \cdot \sin \rho_u)^2$$



$$\mathcal{L} \supset \sum_{f,f'}^{u,c,t,d,s,b,e,\mu,\tau} -\frac{m_{f'}}{v}(\xi^h_{ff'} h \bar{f}_R f'_L + \xi^H_{ff'} H \bar{f}_R f'_L + i \xi^A_{ff'} A^0 \bar{f}_R f'_L) + \text{h.c},$$

$$\xi^h_{ff'} \equiv s_{\beta-\alpha}\delta_{ff'} + c_{\beta-\alpha}\zeta_{ff'},$$

$$\xi^H_{ff'} \equiv c_{\beta-\alpha}\delta_{ff'} - s_{\beta-\alpha}\zeta_{ff'},$$

$$\xi^A_{ff'} \equiv (2T_3^f)\zeta_{ff'},$$

$$\zeta_{ff'} = \begin{cases} \cot\beta\,\delta_{ff'} & (\text{for } f = d, s, b), \\ -\tan\beta\,\delta_{ff'} & (\text{for } f = e, \mu, \tau) \end{cases}$$

$$\zeta_{uu} \equiv -\tan\beta - (\tan\beta + \cot\beta)\frac{\cos\rho_u - 1}{2},$$

$$\zeta_{cc} \equiv \cot\beta,$$

$$\zeta_{tt} \equiv \cot\beta - (\tan\beta + \cot\beta)\frac{1 - \cos\rho_u}{2},$$

$$\zeta_{ut} = \zeta_{tu} = (\tan\beta + \cot\beta)\frac{\sin\rho_u}{2}.$$

the flavor-violating decay $H \to tu$ dominates for $\rho_u \gtrsim 1/120$.

very striking signature of the up-specific Variant Axion Model

Conclusions

muon g-2 : long standing puzzle, the new updates coming soon

to explain the anomaly in the muon g-2 in 2HDMs

LFV in g2HDM or lepton-specific 2HDM

Lepton Flavor Violation in g2HDM

mA < 700 GeV, 10GeV < mH - mA <100 GeV

Drell-Yan production provide LFV tau-mu resonances, which would be sensitive at LHC

a well motivated extension of lepton-specific 2HDM

strong CP problem ⇒ domain wall problem

⇒ variant axion models (only 1 right-handed quark PQ charged)

lepton sector has freedom for PQ charge assignments and muon g-2 anomaly can be accommodated

by assign PQ charge to all leptons mA~ 15GeV, tanβ ~ 40

(by assign PQ charge only to muon mA~ 1 TeV, tanβ ~ 3000)

For light A case, $t \to uA$, $A \to \tau\tau$ current constraints marginal

using boosted di-tau-tagging improves sensitivity significantly

For both cases, flavor violating heavy higgs decays ($H \to \tau\mu, tu$) would be the distinctive signatures at LHC

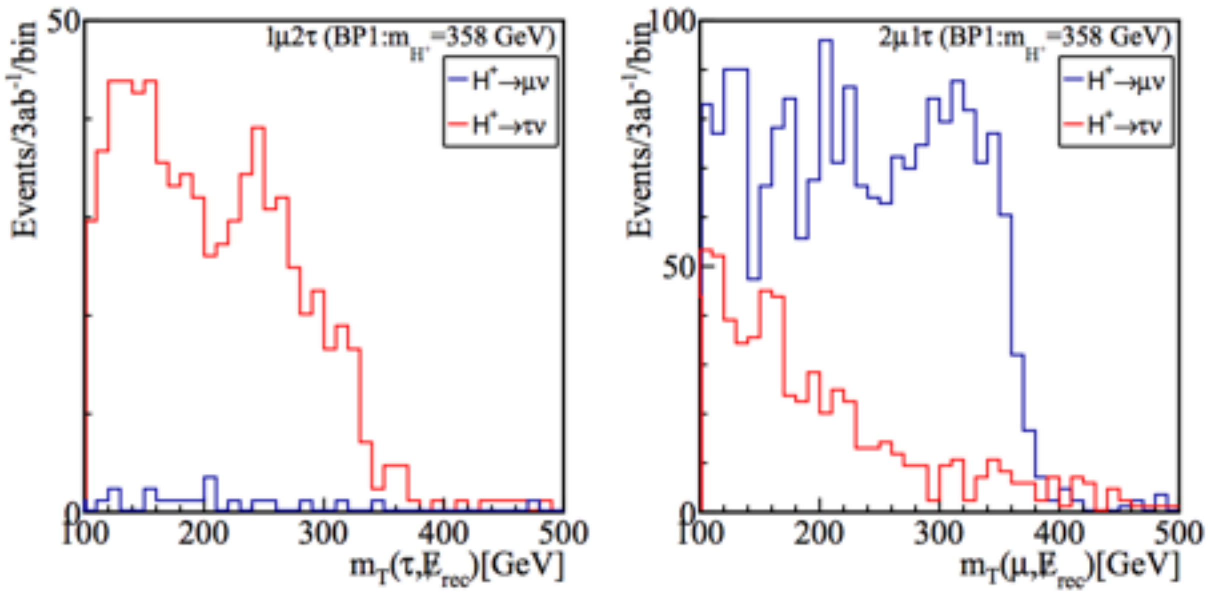
Backup

g-2 via LFV — mass reconstruction at LHC

charged Higgs mass can be reconstructed via 3 leptons from $\phi H^\pm$ production $\mu^\pm\tau^\mp\tau\nu$ and $\mu^\pm\tau^\mp\mu\nu$

ratio controlled by $BR(H^\pm\to\tau^\pm\nu) = 1 - BR(H^\pm\to\mu^\pm\nu) = \frac{|\rho_e^{\mu\tau}|^2}{|\rho_e^{\tau\mu}|^2+|\rho_e^{\mu\tau}|^2} \equiv r.$

part of τ-mode contribute to μ-mode



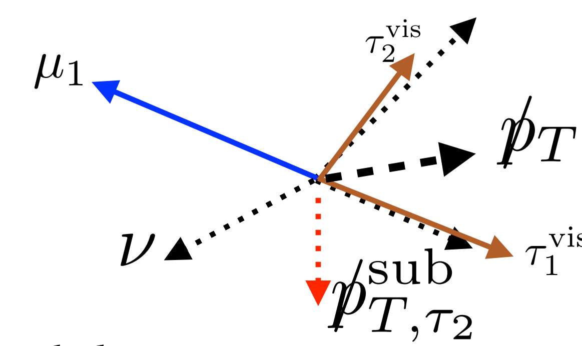
4 combinatorics : (production Φ=A, H) x (2 τμ combinations)

$$\mathbf{p}_{\tau_i}^{\rm rec} = (1 + c_{\tau_i\phi})\mathbf{p}_{\tau_i}^{\rm vis}, \quad (c_{\tau_i\phi} > 0).$$

$$m^2_{\mu\tau_i^{\rm rec}} = (p_\mu + p_{\tau_i}^{\rm rec})^2 = m_\phi^2,$$

$$\not{\mathbf{p}}_{T,\tau_i\phi}^{\rm sub} = \not{\mathbf{p}}_T - c_{\tau_i\phi}\mathbf{p}_{T,\tau'}^{\rm vis}$$

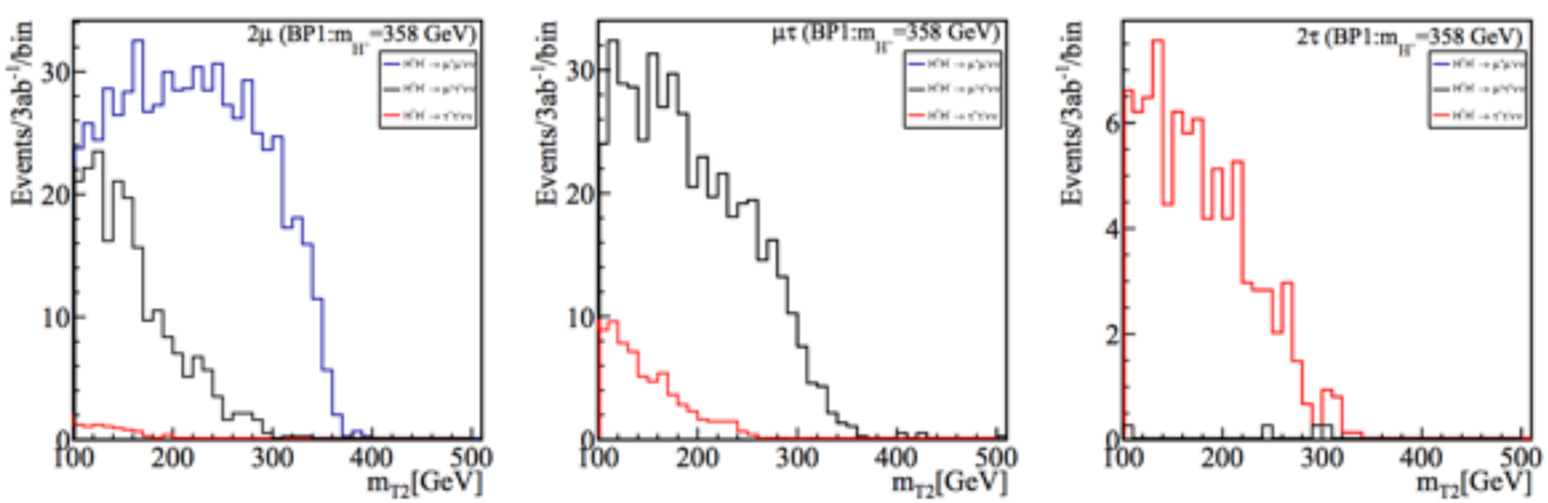
$$m_{T,\tau_i\phi} = m_T(\mathbf{p}_{\tau_{i'}}^{\rm vis}, \not{\mathbf{p}}_{T,\tau_i\phi}^{\rm sub}),$$



taking the minimum of the 4 possibilities

$$m_{T,\tau}^{\rm min} = \min(m_{T,\tau_1 A}, m_{T,\tau_1 H}, m_{T,\tau_2 A}, m_{T,\tau_2 H}).$$

also via 2 leptons from H^+H^- production



mH, mA, mH+ reconstructed by 4,3,2 lepton events

event number ratios among various modes sensitive to the BR

$$m_{T2}(\mathbf{p}_{\ell_1}, \mathbf{p}_{\ell_2}, \not{\mathbf{p}}_T) = \min_{\not{\mathbf{p}}_T = \not{\mathbf{p}}_{T,1} + \not{\mathbf{p}}_{T,2}} \{\max[m_T(\mathbf{p}_{\ell_1}, \not{\mathbf{p}}_{T,1}), m_T(\mathbf{p}_{\ell_2}, \not{\mathbf{p}}_{T,2})]\}$$

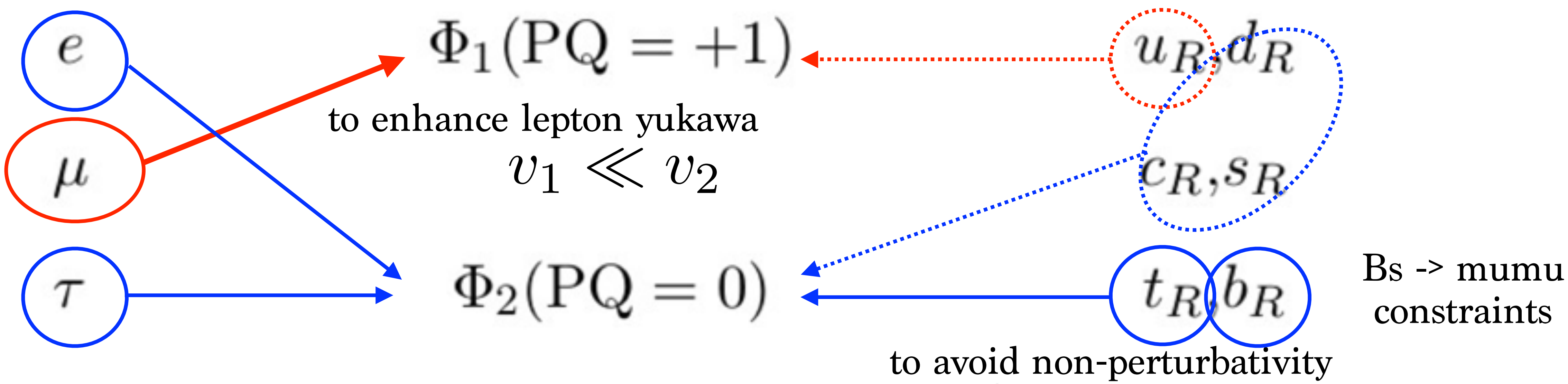
u-specific VAM with muon-specific lepton sector

An extreme model: muon-specific 2HDM to accommodate muon g-2 [T. Abe, R. Sato, K. Yagyu JHEP 1707, 012 (2017)]

- only muon yukawa is tanβ enhanced ~ 3000
- better fit against the lepton universality constraints
- constrained by multi-muon searches at LHC (A/H→μμ 100%)

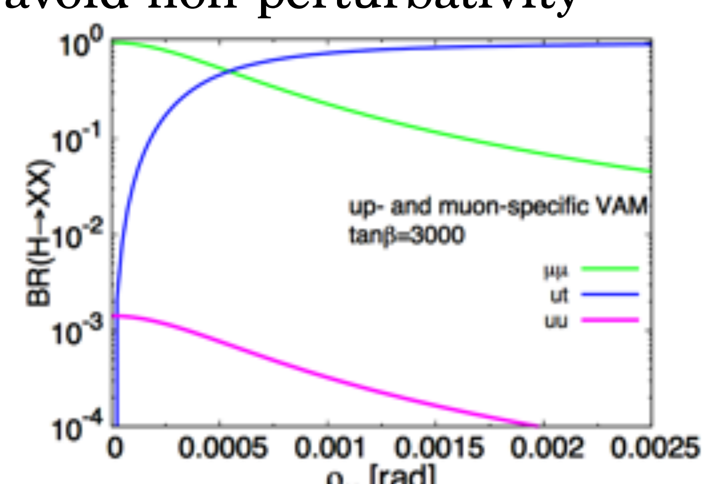
VAM is essentially just a 2HDM with various PQ charge assignments (only one q_R PQ charged)

- lepton sector is irrelevant to the strong CP problem nor domain wall problem
- muon yukawa has to be enhanced to accommodate muon g-2 ⇔ corresponding VEV is small (tanβ>>1)



in this setup, suppressed muon BR to accommodate LHC constraints

$$\frac{BR(A \to tu)}{BR(A \to \mu\mu)} \simeq \frac{BR(H \to tu)}{BR(H \to \mu\mu)} \simeq \frac{m_t^2}{m_\mu^2} \frac{3\sin^2\rho_u}{2} \simeq (2000 \cdot \rho_u)^2$$



g-2 in 2HDM

$\mathcal{O}(10^{-9})$ positive contribution required

2.6×10^{-9}

Flavor dependent contribution : yukawa type

chirality flip required $\quad \mathcal{L} = a_\mu \frac{e}{4m_\mu} \bar{\psi} \sigma_{\mu\nu} \psi F^{\mu\nu}$

$r_f^i = m_f^2 / m_i^2$

$$f_{h,H}(r) = \int_0^1 dx \frac{x^2(2-x)}{1-x+rx^2}, \quad f_A(r) = \int_0^1 dx \frac{-x^3}{1-x+rx^2}$$

$$f_{H^\pm}(r) = \int_0^1 dx \frac{-x(1-x)}{1-r(1-x)}.$$

$$g_{h,H}(r) = \int_0^1 dx \frac{2x(1-x)-1}{x(1-x)-r} \ln \frac{x(1-x)}{r},$$

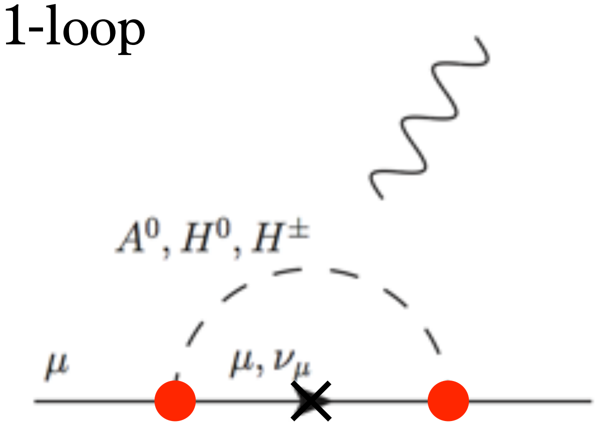
$$g_A(r) = \int_0^1 dx \frac{1}{x(1-x)-r} \ln \frac{x(1-x)}{r}.$$

1-loop

$$\Delta a_\mu^{\mathrm{VAM,1-loop}} = \frac{G_F m_\mu^2}{4\sqrt{2}\pi^2} \sum_i^{h,H,A,H^\pm} (\xi_{\mu\mu}^i)^2 r_\mu^i f_i(r_\mu^i)$$

$\sim 10^{-9}$ $\quad \sim 10^{-7}$ $\quad m_H = 1\mathrm{TeV}$

cf.) muon-specific 2HDM $\quad \xi_\mu \sim 3000$
[T. Abe, R. Sato, K. Yagyu, arXiv:1705.01469]



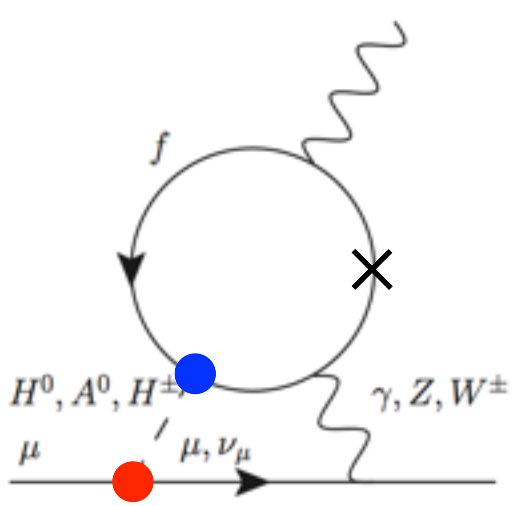
$\propto m_\mu^3 / m_H^2$ ➡ LFV enhance with $\quad m_\tau^3/m_\mu^3 \sim 5000$, $\xi_{\mu\tau}^2$ $\quad \xi_{\mu\tau}\xi_{\tau\mu}/m_H^2[\mathrm{TeV}] \sim 10^4$ required

---

2-loop (Barr-Zee)

$$\Delta a_\mu^{\mathrm{VAM,BZ}} = \frac{G_F m_\mu^2}{4\sqrt{2}\pi^2} \frac{\alpha_{\mathrm{em}}}{\pi} \sum_i^{h,H,A} \sum_f^{t,b,c,\tau} N_f^c Q_f^2 \xi_{\mu\mu}^i \xi_{ff}^i r_f^i g_i(r_f^i)$$

heavy fermion contributions enhance at 2-loop $\quad \xi_\mu \xi_\tau / m_H^2[\mathrm{TeV}] \sim 10^6$ required



$\propto m_\mu m_f^2 / m_H^2$

	Fermion	(g_f^H, g_f^A)	$(r_f^H g_f^H, r_f^A g_f^A)$	$\times \alpha N_f^c Q_f^2/\pi$	Sign of (δ_H, δ_A)
One loop	μ	$(17, -16)$	$(1.9, -1.8) \times 10^{-7}$	$(1.9, -1.8) \times 10^{-7}$	$(+, -)$
	t	$(-12, 15.9)$	$(-3.6, 4.7) \times 10^{-1}$	$(-1.1, 1.5) \times 10^{-3}$	$(-, -)$
	c	$(-118, 140)$	$(-1.9, 2.3) \times 10^{-4}$	$(-5.9, 7.1) \times 10^{-7}$	$(-, -)$
Two loop	u	$(-282, 330)$	$(-1.5, 1.7) \times 10^{-9}$	$(-4.6, 5.4) \times 10^{-12}$	$(-, -)$
	b	$(-87, 105)$	$(-1.5, 1.8) \times 10^{-3}$	$(-1.1, 1.4) \times 10^{-6}$	$(-, +)$
	τ	$(-109, 130)$	$(-3.4, 4.1) \times 10^{-4}$	$(-8.0, 9.6) \times 10^{-7}$	$(-, +)$

g-2 via lepton flavor violation — other elements

Other Yukawa elements : 1st, 2nd generations severely constrained

$$\rho_e^{\tau\tau},\ \rho_u^{tt},\ \rho_u^{tc},\ \rho_u^{ct} \text{ and } \rho_d^{bb}.$$

$BR(\tau \to \mu\gamma)$ sets $|\rho_u^{tt}| < 0.05$ and $|\rho_e^{\tau\tau}| < 0.06$.

2-loop 1-loop

$|\rho_u^{tc}| < 0.11$: lepton univ. in $B \to D\ell\nu$

ϵ_K measurements provide a severe constraint as $|\rho_u^{ct}| < 0.04$

$|\rho_d^{bb}| < 0.22$ is obtained by the flavor observables including $BR(B \to \mu\nu)$

$BR(H/A \to \mu^\pm\tau^\mp)$ is diluted by $H/A \to b\bar{b}$