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])

at summer camp on ILC, Itako, on 3rd Sep 2019

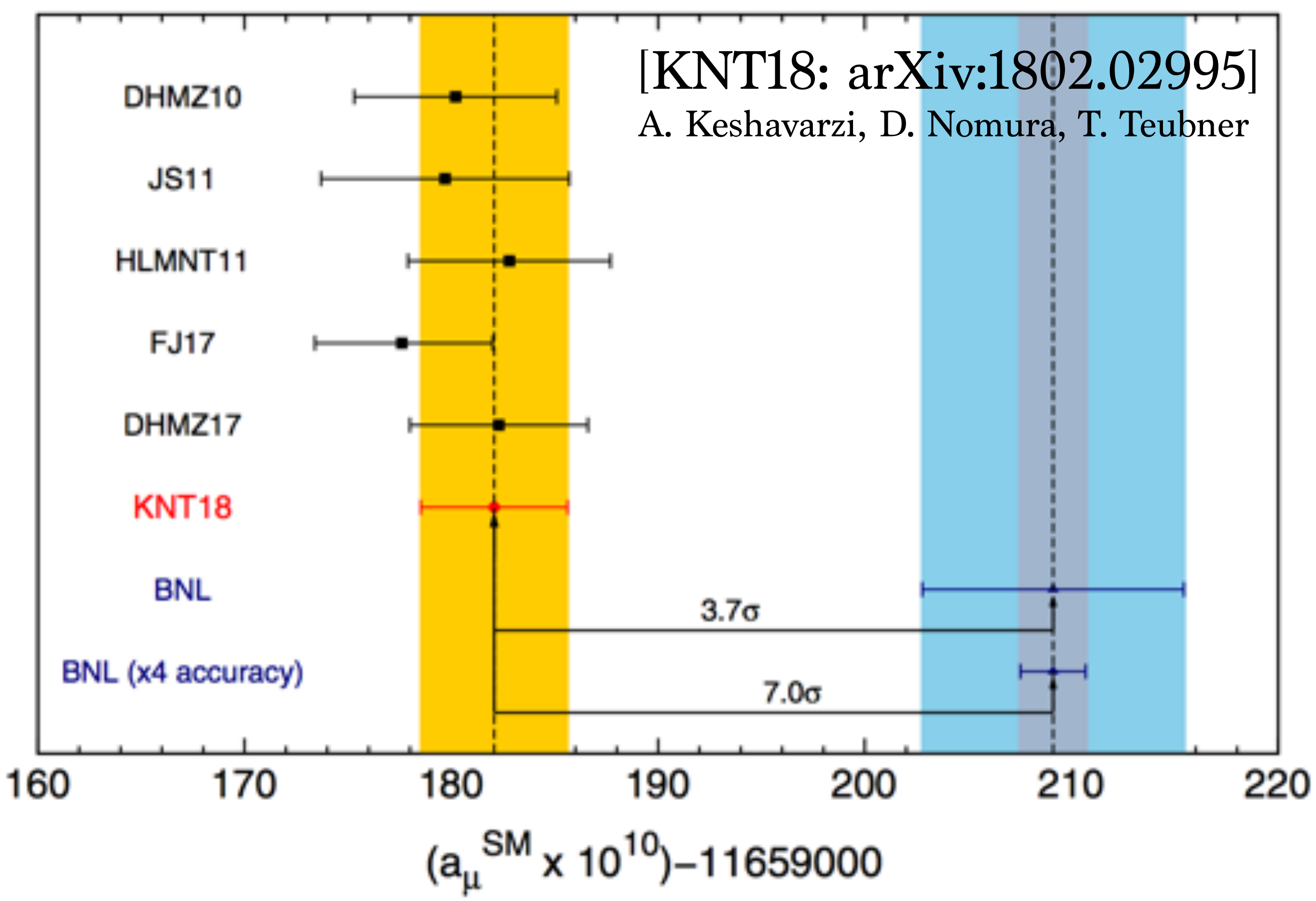
Muon g-2 : signature of BSM?

Magnetic moment

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

anomalous magnetic moment

$$a_\mu = (g_\mu - 2)/2 \qquad \mathcal{L} = a_\mu \frac{e}{4m_\mu}\bar{\psi}\sigma_{\mu\nu}\psi F^{\mu\nu}$$



anomaly in anomalous magnetic moment

$g = 2$ tree level, Dirac equation

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

$g = 2.002\ 331\ 83$ hadronic 

$g = 2.002\ 331\ 836\ 6$ EW

$\times 10^{-10}$

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

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

New contribution of the size of the EW-contribution required,

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

New particles at O(100GeV) ?

Two Higgs Doublet Models (2HDM)

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

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

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

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

8 d.o.f. : $h, H, A, H^{\pm}$ + 3 Nambu-Goldston bosons (W, Z longitudinal modes)

Yukawa interactions

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

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

To avoid tree-level FCNC by Yukawa interactions, certain parity structure is often introduced

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	$\cot\beta$	$-\tan\beta$	$\cot\beta$

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

Higgs-gauge couplings identical to the SM in the limit $c_{\beta-\alpha} = 0$ (aligned limit)

Yukawa interactions to heavy higgses simplified in the limit

g-2 in 2HDM

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

2.6×10^{-9}

Flavor dependent contribution : yukawa type

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

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

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

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

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

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

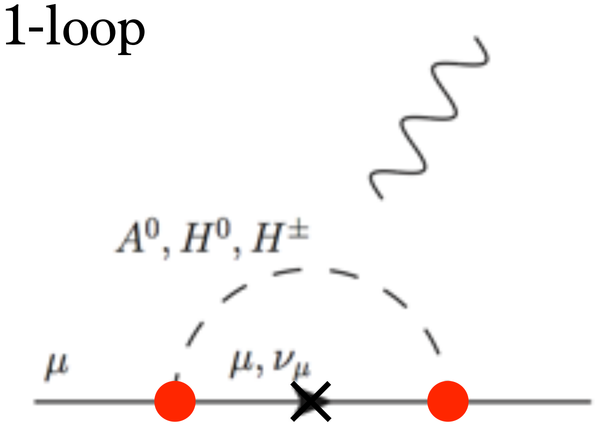
1-loop

$$\Delta a_\mu^{\mathrm{VAM,1-loop}} = \underbrace{\boxed{\frac{G_F m_\mu^2}{4\sqrt{2}\pi^2}}}_{\sim 10^{-9}} \sum_i^{h,H,A,H^\pm} (\boxed{\xi_{\mu\mu}^i})^2 \underbrace{r_\mu^i f_i(r_\mu^i)}_{\sim 10^{-7}}$$

$m_H = 1\mathrm{TeV}$

cf.) muon-specific 2HDM $\xi_\mu \sim 3000$

[T. Abe, R. Sato, K. Yagyu, arXiv:1705.01469]

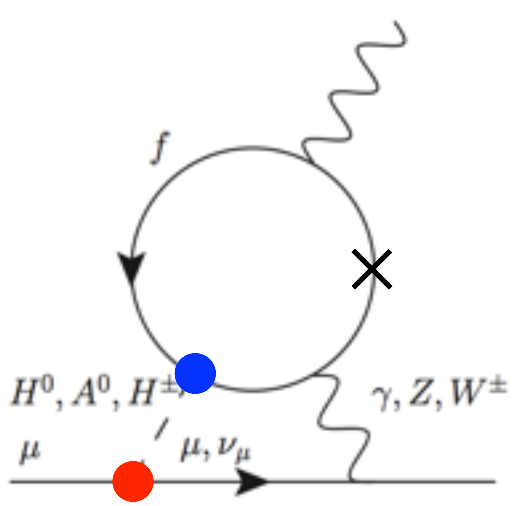


$\propto m_\mu^3/m_H^2$ ➡ LFV enhance with $m_\tau^3/m_\mu^3 \sim 5000$, $\xi_{\mu\tau}^2$ $\quad \xi_{\mu\tau}\xi_{\tau\mu}/m_H^2[\mathrm{TeV}] \sim 10^4$ required

---

2-loop (Barr-Zee)

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



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	$(-87, 105)$	$(-1.5, 1.8) \times 10^{-3}$	$(-1.1, 1.4) \times 10^{-6}$	$(-, \boxed{+})$
	τ	$(-109, 130)$	$(-3.4, 4.1) \times 10^{-4}$	$(-8.0, 9.6) \times 10^{-7}$	$(-, \boxed{+})$

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]

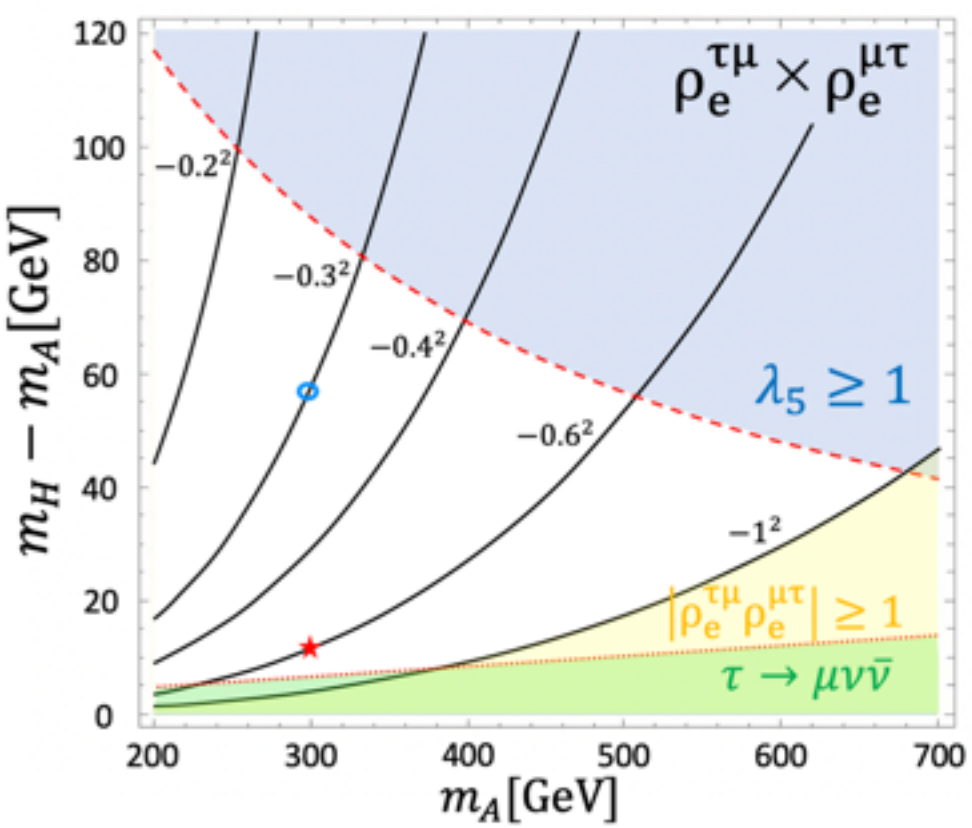
$$\mathcal{L} = -\bar{Q}_L^i H_1 y_d^i d_R^i - \bar{Q}_L^i H_2 \rho_d^{ij} d_R^j - \bar{Q}_L^i (V^\dagger)^{ij} \tilde{H}_1 y_u^j u_R^j - \bar{Q}_L^i (V^\dagger)^{ij} \tilde{H}_2 \rho_u^{jk} u_R^k$$
$$- \bar{L}_L^i H_1 y_e^i e_R^i - \bar{L}_L^i H_2 \rho_e^{ij} e_R^j + \text{h.c.}.$$

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

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

$\Delta_{H-A} = m_H - m_A$

$\xi_{\mu\tau}\xi_{\tau\mu}/m_H^2[\text{TeV}] \sim 10^4$ required



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

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

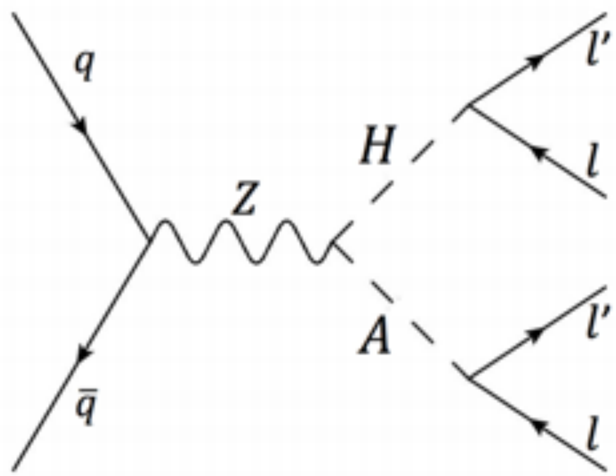
perturbativity, stability $0 < \lambda_5 < 1$ $|\rho^{\mu\tau}|, |\rho^{\tau\mu}| < 1$

we consider $m_A \leq m_H = m_{H^\pm}$

then the parameter region available is finite

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

g-2 via lepton flavor violation — LHC signatures

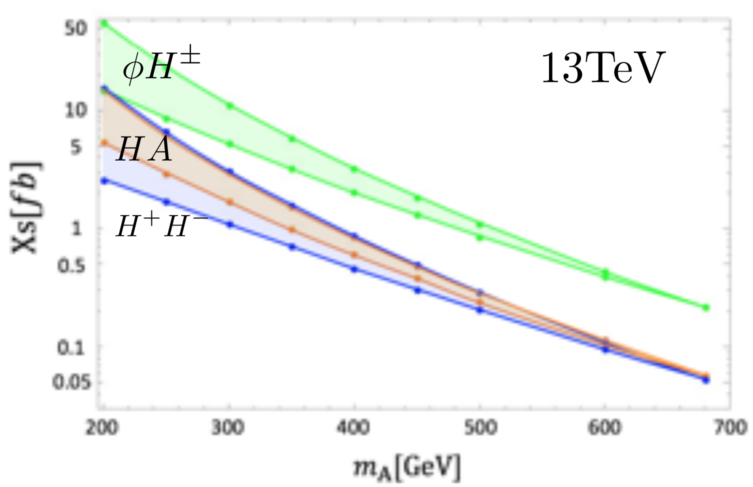


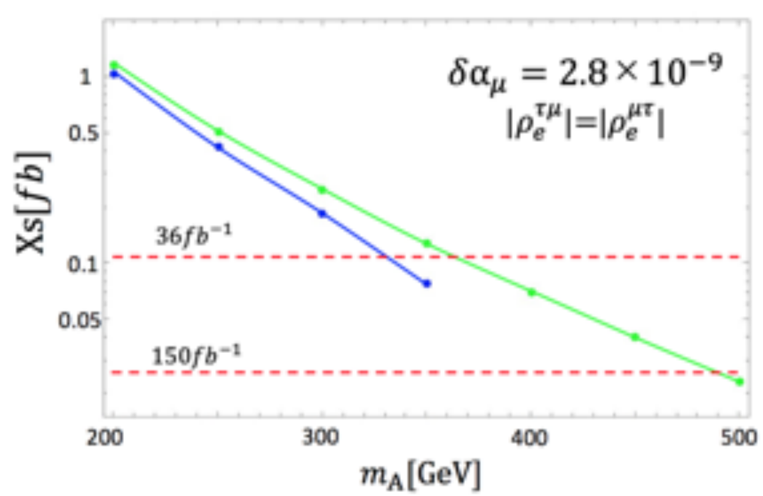
no coupling to colored particles: most difficult case at LHC

Heavy higgses produced in pair via Drell-Yan production through SU(2) coupling

the three production processes, HA, $\phi H^\pm$, and H^+H^-, where $\phi = H, A$.

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

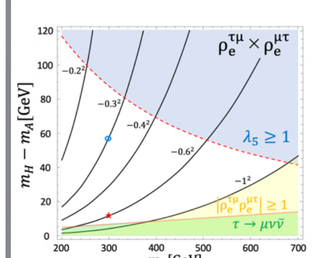




multi-lepton $2\mu 2\tau$ channels

should already be sensitive at LHC

OSOF pair gives the resonances



	m_A	m_H	$m_{H^\pm}$	$\sigma(HA)$	$\sigma(AH^\pm)$	$\sigma(HH^\pm)$	$\sigma(H^+H^-)$
BP1	300 GeV	358 GeV	358 GeV	2.4 fb	4.6 fb	3.3 fb	1.8 fb
BP2	300 GeV	312 GeV	312 GeV	3.3 fb	6.3 fb	5.7 fb	3.2 fb

4 leptons, 3 leptons, 2 leptons

in future at 14 TeV, signal analysis
with invariant mass distributions
can be done

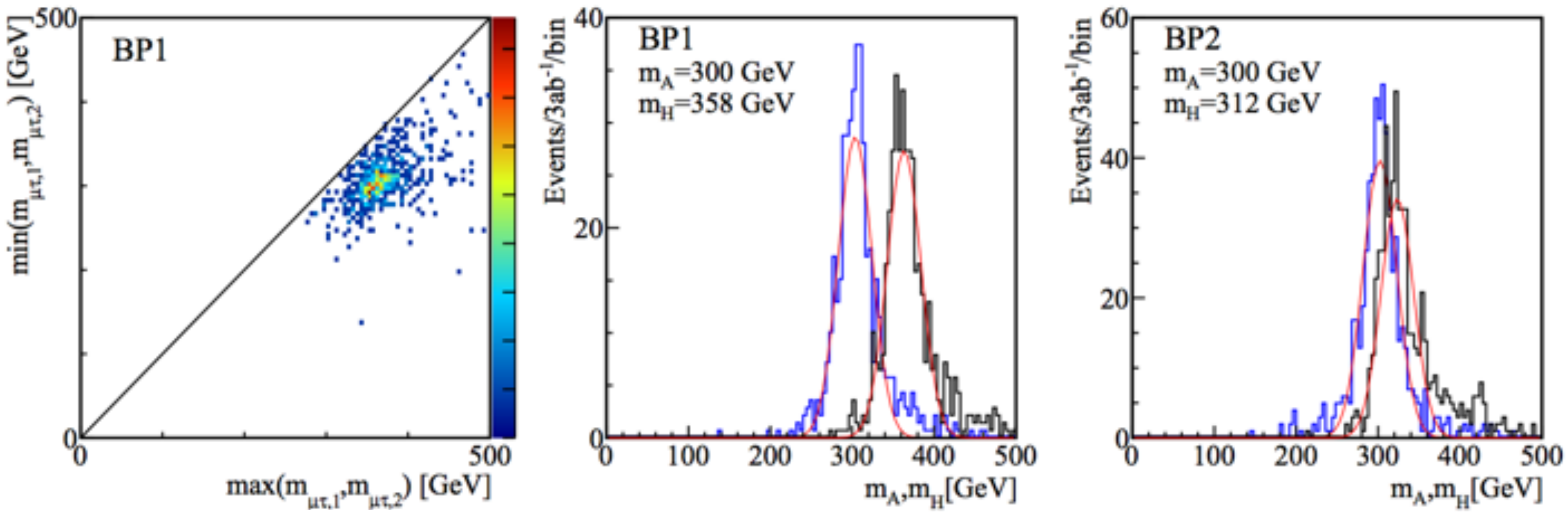
g-2 via LFV — mass reconstruction at LHC

4 leptons from HA production

$\mu^\pm\mu^\pm\tau^\mp\tau^\mp$ same-sign di-muon di-tau (50%)

$\mu^+\mu^-\tau^+\tau^-$ opposite-sign di-muon di-tau (50%)

mu-tau pair results in resonances H, A



$\mathcal{O}(200-300)$ events for 3 ab^{-1}

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

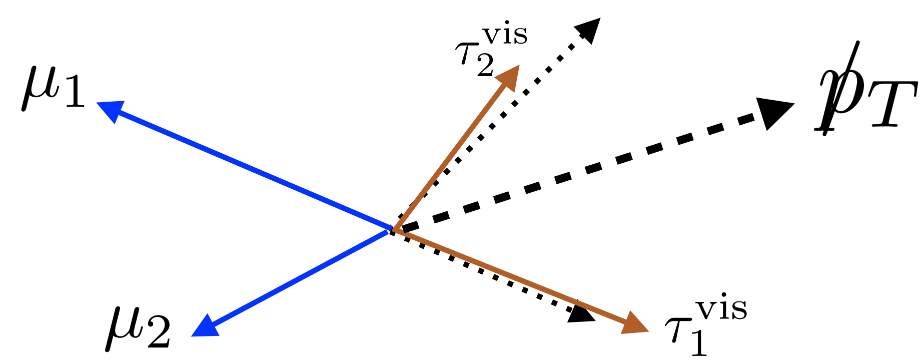
$\mu_1, \mu_2, \tau_1^{\mathrm{vis}}$, and τ_2^{vis} in p_T-order

two possible combinations : select the one minimizing the sum of $\chi_i^2(m_A, m_H) = (m_{\mu\tau,i}^{\min} - m_A)^2/\sigma_{\mathrm{res}}^2 + (m_{\mu\tau,i}^{\max} - m_H)^2/\sigma_{\mathrm{res}}^2$

$$\text{combination 1} : m_{\mu_1\tau_1} \quad \text{and} \quad m_{\mu_2\tau_2}$$
$$\text{combination 2} : m_{\mu_1\tau_2} \quad \text{and} \quad m_{\mu_2\tau_1}$$

τ-momentum : collinear approx.

$$\mathbf{p}_{\tau_i} = (1+c_i)\mathbf{p}_{\tau_i}^{\mathrm{vis}}$$
$$\not{\mathbf{p}}_T = c_1\mathbf{p}_{T,\tau_1}^{\mathrm{vis}} + c_2\mathbf{p}_{T,\tau_2}^{\mathrm{vis}} \quad (c_1, c_2 > 0).$$



g-2 via LFV — mass reconstruction at LHC

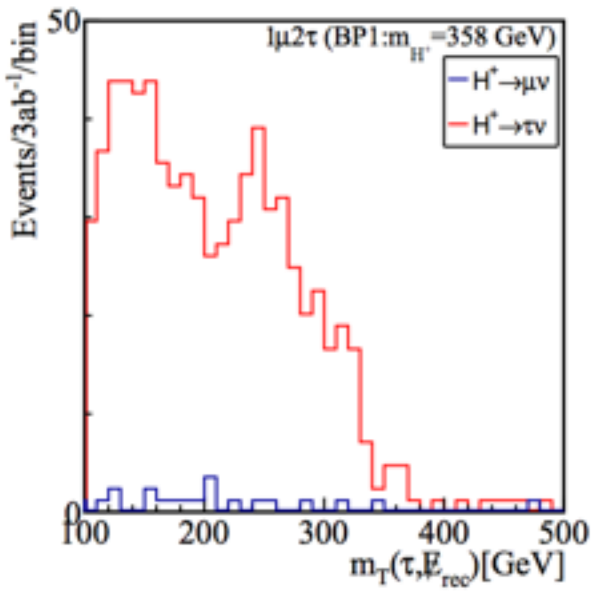
3 leptons from $\phi H^{\pm}$ production

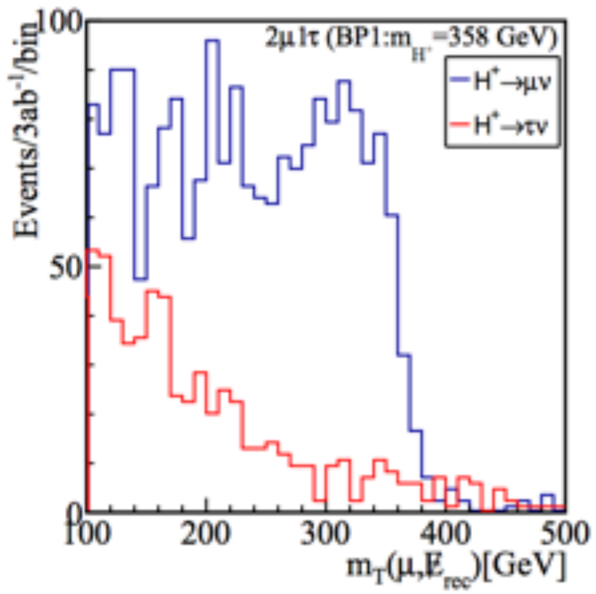
$\mu^{\pm}\tau^{\mp}\tau\nu$

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

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

part of the tau-mode contribute to the mu-mode





(two possible production A/H) x (two possible τμ combinations)

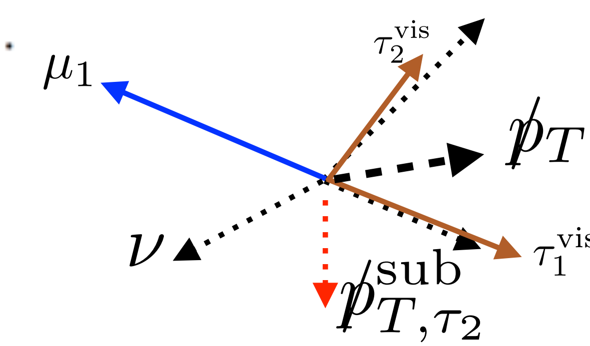
$$\mathbf{p}_{\tau_i}^{\rm rec}=(1+c_{\tau_i\phi})\mathbf{p}_{\tau_i}^{\rm vis},\quad (c_{\tau_i\phi}>0).$$

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

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

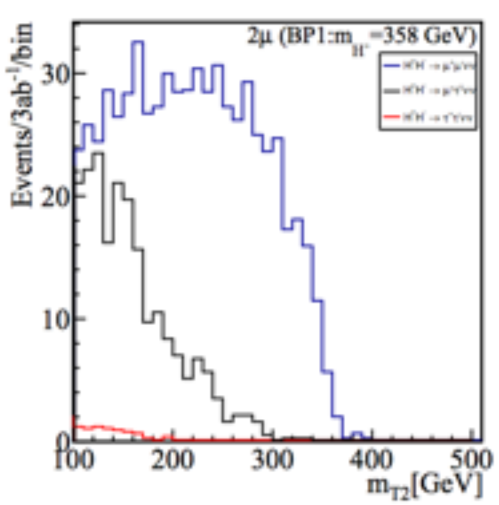
$$m_{T,\tau_i\phi}=m_T(\mathbf{p}^{\rm vis}_{\tau_{i'}},\not{\mathbf{p}}^{\rm sub}_{T,\tau_i\phi}),$$

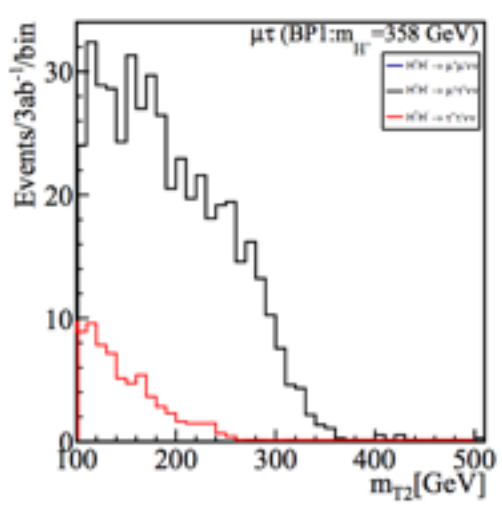
$$m^{\rm min}_{T,\tau}=\min(m_{T,\tau_1 A},m_{T,\tau_1 H},m_{T,\tau_2 A},m_{T,\tau_2 H}).$$

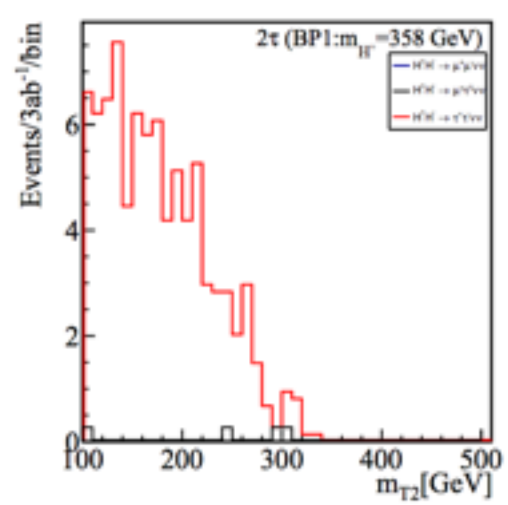


2 leptons from H^+H^- production

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







event number ratios among various modes sensitive to the BR

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 $H/A \to b\bar{b}$

g-2 in 2HDM

$\mathcal{O}(10^{-9})$ $\boxed{\text{positive}}$ contribution required
2.6×10^{-9}

Flavor dependent contribution : yukawa type

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

1-loop

$$\Delta a_\mu^{\mathrm{VAM,1-loop}} = \underbrace{\boxed{\frac{G_F m_\mu^2}{4\sqrt{2}\pi^2}}}_{\sim 10^{-9}} \sum_i^{h,H,A,H^\pm} (\boxed{\xi^i_{\mu\mu}})^2 \underbrace{r^i_\mu f_i(r^i_\mu)}_{\sim 10^{-7}}$$

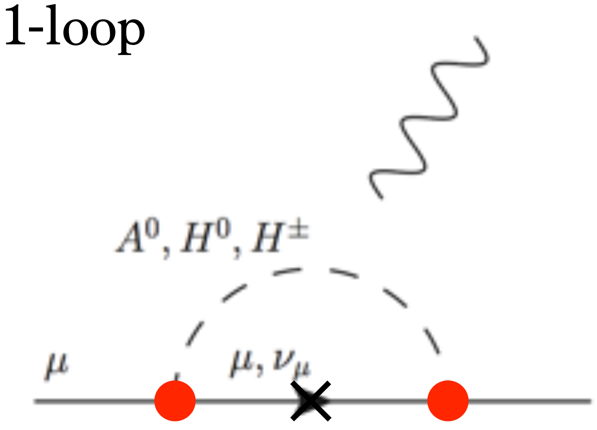
$\sim 10^{-7}$
$m_H = 1\mathrm{TeV}$

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

$$r^i_f = m_f^2/m_i^2$$

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

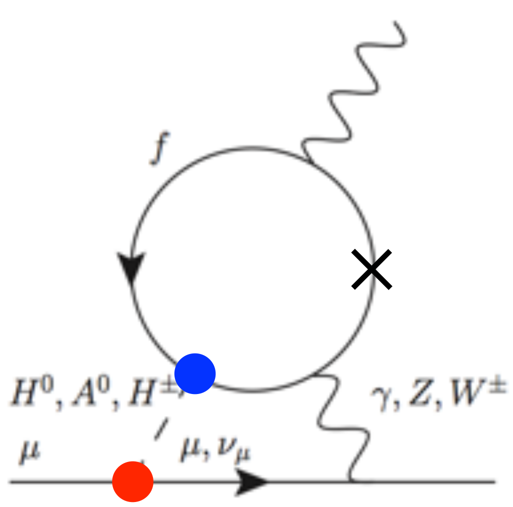
$$g_{h,H}(r) = \int_0^1 dx \frac{2x(1-x)-1}{x(1-x)-r} \ln\frac{x(1-x)}{r},$$
$$g_A(r) = \int_0^1 dx \frac{1}{x(1-x)-r} \ln\frac{x(1-x)}{r}.$$



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

2-loop (Barr-Zee)

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



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

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

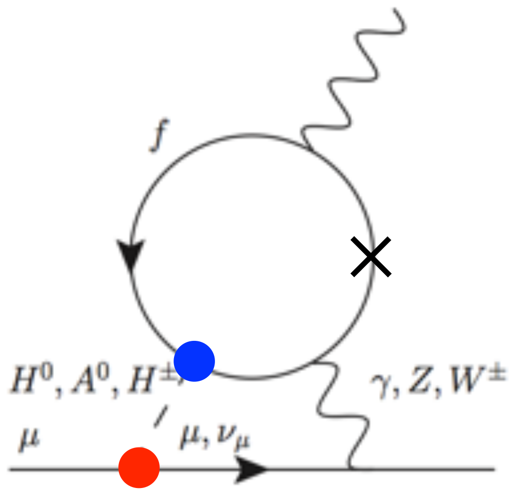
	Fermion	(g_f^H, g_f^A)	$(r_f^H g_f^H, r_f^A g_f^A)$	$\times \alpha N_f^c Q_f^2/\pi$	Sign of (δ_H, δ_A)
One loop	μ	$(17, -16)$	$(1.9, -1.8) \times 10^{-7}$	$(1.9, -1.8) \times 10^{-7}$	$(+, -)$
	t	$(-12, 15.9)$	$(-3.6, 4.7) \times 10^{-1}$	$(-1.1, 1.5) \times 10^{-3}$	$(-, -)$
	c	$(-118, 140)$	$(-1.9,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

g-2 in 2HDM via 2-loop

$\mathcal{O}(10^{-9})$ $\boxed{\text{positive}}$ contribution required
2.6×10^{-9}

2-loop (Barr-Zee)

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



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

heavy fermion contributions enhance at 2-loop

$\xi_\mu \xi_\tau / m_H^2 [\text{TeV}] \sim 10^6$ required

	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	$(-87, 105)$	$(-1.5, 1.8) \times 10^{-3}$	$(-1.1, 1.4) \times 10^{-6}$	$(-, \boxed{+})$
	τ	$(-109, 130)$	$(-3.4, 4.1) \times 10^{-4}$	$(-8.0, 9.6) \times 10^{-7}$	$(-, \boxed{+})$

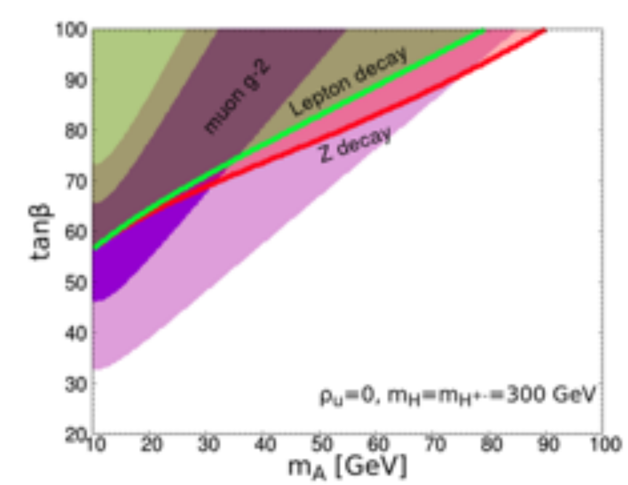
In lepton-specific 2HDM model (type X), tanβ enhanced tau contribution is crucial.

mA ~ 30GeV and tanβ ~ 40 will give a enough contribution

tension : Lepton Universality measurements

LHC constraints are weak as all quark couplings to heavier bosons suppressed

Drell-Yan productions : the dominant production modes we can constrain at LHC
As light A, constraints from Z -> tau tau A (LEP)



type II with light mA and large tanβ is disfavored by LHC bbA production and also by Bs→μμ

motivation in quark sector of 2HDM

Strong CP problem

↓

PQ solution with axion

very attractive, provide good DM candidate

timely: rapid progress of axion DM searches

↓

invisible axion models

$$\mathcal{L}_Q = -y_Q \bar{Q}_L \Phi Q_R + \text{h.c.}$$

KSVZ $N_{DM} = 1$ heavy Q introduced
no problem but no low energy phenomenology (not interesting)

(Kim 1979,
Shifman, Vainshtein, Zakharov 1980)

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

two Higgs doublet model,
no new fermion necessary introduced
can discuss low energy phenomenology

(Zhitnitsky1980,
Dine, Fischler, Srednicki 1981)

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

but suffer from Domain wall problem

↓

Variant Axion model $N_{DM} = 1$

only 1 quark coupled to PQ-Higgs
domain wall problem absent

Strong CP problem

QCD Lagrangian contains the total derivative term: θ-term

$$\mathcal{L}_\theta = \frac{\theta}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu} \quad \longleftrightarrow \quad |\theta> = \sum_{n=-\infty}^{\infty} e^{in\theta}|n> \quad \theta\text{-vacuum}$$

$|n> \rightarrow |m>$ but $|\theta> \rightarrow |\theta>$ gauge inv.

Note that θ is physical $0 \leq \theta < 2\pi$

Furthermore, chiral tr. $q \rightarrow e^{i\alpha\gamma_5} q$ induces $\theta \rightarrow \theta - 2\alpha$

massive fermion mass term is also changed.

$$\theta_{\rm eff} = \theta + \arg\det[M^u M^d] \quad \text{is invariant under the chiral tr.}$$

$$\propto \arg\det[v^6 Y^u Y^d]$$

$\theta_{\rm eff}$ can be measured from Neutron EDM $|d_n| = 4.5 \times 10^{-15}\theta_{\rm eff} e\text{cm}$

$$|d_n^{\rm obs}| < 2.9 \times 10^{-26} e\text{cm}$$

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

while the origin of θ and arg M is completely different

Fine tuning problem

Peccei-Quinn mechanism and domain wall problem

[R. D. Peccei, H. R. Quinn, PhysRevLett.38.1440]

If the theory has $U(1)_{PQ}$, which spontaneously breakdowns to provide axion, at η.

Due to the anomaly, $\mathrm{U}(1)_{PQ}$ current is not conserved, $\partial^\mu j_\mu^{\mathrm{PQ}} = -\frac{g^2}{32\pi^2} A G^{a\mu\nu}\tilde{G}^a_{\mu\nu}$,

$\eta e^{i\theta_{PQ}} \sim \eta + ia$

$\frac{a}{\eta} \to \frac{a}{\eta} + \epsilon$ induces $\delta\mathcal{L} = -\frac{g^2}{32\pi^2}\epsilon A G^{a\mu\nu}\tilde{G}^a_{\mu\nu}$, induce the potential in the effective Lagrangian

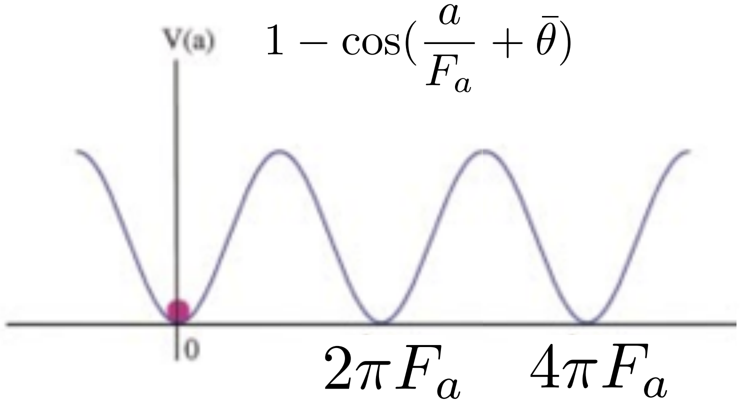
$$\boxed{\mathcal{L}_{\text{eff}} = -\frac{1}{4}G^{a\mu\nu}G^a_{\mu\nu} - \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{g^2}{32\pi^2}\frac{a}{F_a}G^{a\mu\nu}\tilde{G}^a_{\mu\nu} - \frac{\bar{\theta}g^2}{32\pi^2}G^{a\mu\nu}\tilde{G}^a_{\mu\nu}}$$

$$F_a = \eta/A$$

A depends on the model ($\sim N$)

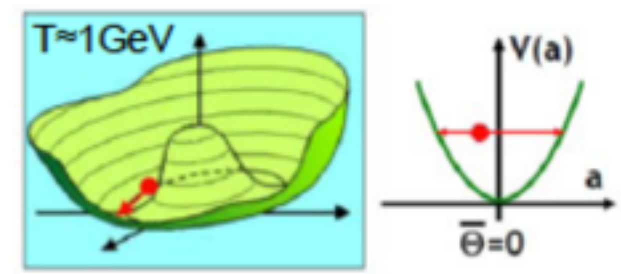
at low temperature, QCD instanton effects give an axion a potential and minimizing it gives $<a> = -\bar{\theta}F_a$.

$1 - \cos(\frac{a}{F_a} + \bar{\theta})$ $\qquad \bar{\theta} = \theta_{\text{strong}} + \theta_{\text{EM}}$

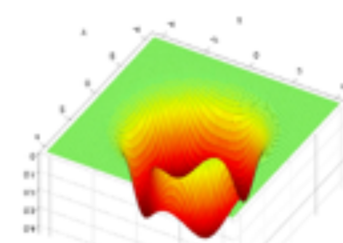


$$a' \equiv a + \bar{\theta}F_a$$

in theta space



in <a> space



$$\theta_{\text{eff}} = \bar{\theta} + \frac{<a>}{F_a} = \frac{<a'>}{F_a} = 2n\pi(n = 1, \ldots, N)$$

$U(1)_{PQ} \to Z_N, \quad N = |\sum_{PQ}(2q_i + u_i + d_i)|$

$N_{\text{DW}} = N_{\text{PQ}}$ [C.Q. Geng, J. N. Ng, PhysRevD.41.3848]

Variant Axion model $\quad N_{\text{PQ}} = 1$ is free from the domain wall problem

[R.D. Peccei, T.T. Wu and T. Yanagida, Phys. Lett. B172, 435 (1986)]
[C-R Chen, P. Frampton, F. Takahashi, T. T. Yanagida JHEP1006(2010)059]

up-type specific Variant Axion model

σ field integrated out, the effective theory is just a 2HDM

	Φ_1	Φ_2	t_R	c_R	u_R	d_R	Q_L	ℓ_R	L_L
top-specific VA Model	+	−	−	+	+	+	+	−	+
charm-specific VA Model	+	−	+	−	+	+	+	−	+
up-specific VA Model	+	−	+	+	−	+	+	−	+

to avoid domain wall problem,
we have to assign PQ charge only one quark.

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

For example, up-specific case,

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

mix with β

in higgs basis

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

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

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

Φ_2 only couple with u_R, e_R

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

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

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

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

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

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

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

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

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

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

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

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

mixing eff. : $\zeta_{uu}\uparrow, \zeta_{tt}\downarrow$

g-2 in Lepton-specific 2HDM with VAM

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

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

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

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

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

g-2 in Lepton-specific 2HDM with VAM

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

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

to avoid non-perturbativity

g-2 in Lepton-specific 2HDM with VAM

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

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

e

μ

τ

$\Phi_1(\mathrm{PQ}=+1)$

to enhance lepton yukawa

$v_2 \ll v_1$

$\Phi_2(\mathrm{PQ}=0)$

u_R, d_R

c_R, s_R

t_R, b_R

to avoid non-perturbativity

to avoid domain wall

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

g-2 in Lepton-specific 2HDM with VAM

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

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

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

g-2 in Lepton-specific 2HDM with VAM

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

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

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

to enhance lepton yukawa

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

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

to avoid non-perturbativity

g-2 in Lepton-specific 2HDM with VAM

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

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

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

Bs -> mumu constraints

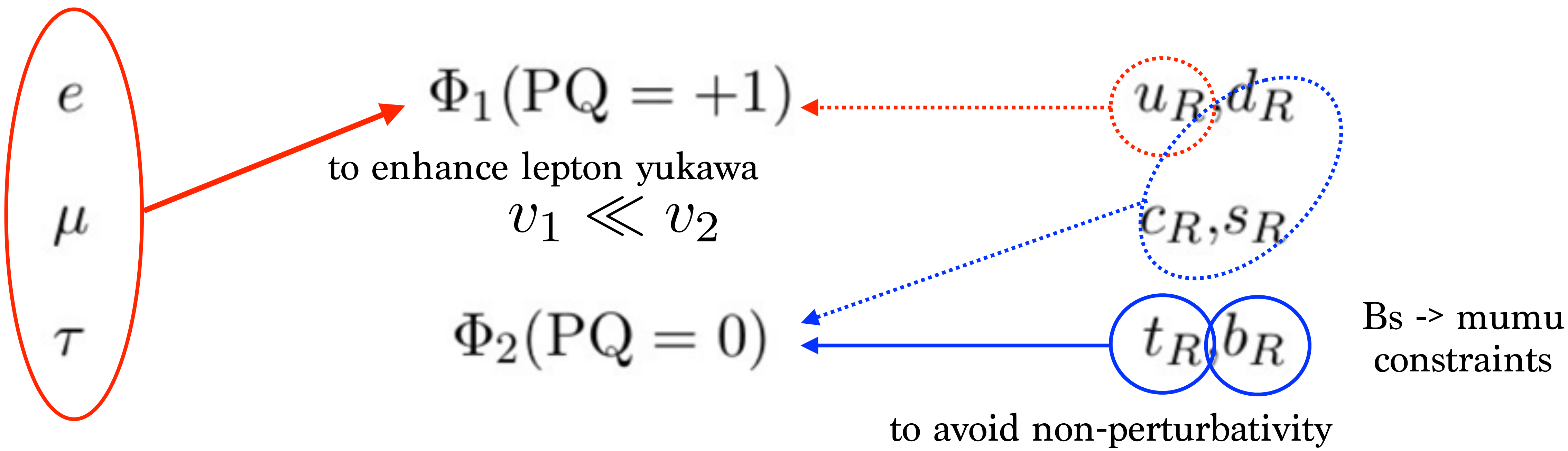
to avoid non-perturbativity

g-2 in Lepton-specific 2HDM with VAM

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

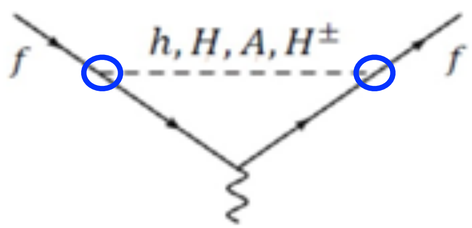
lepton sector is irrelevant to the strong CP problem nor domain wall problem

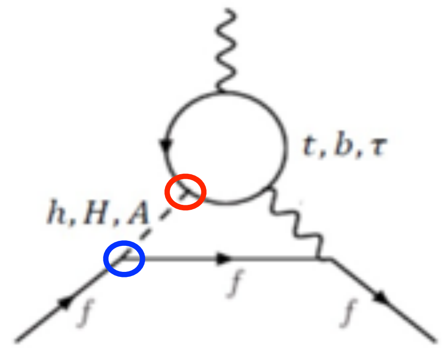
lepton yukawa has to be enhanced to accommodate muon g-2 ⇔ corresponding VEV is small (tanβ>>1)



several choices, but up-specific is most interesting possibility

g-2 in Lepton-specific 2HDM with VAM





$$\Delta a_\mu = a_\mu^{\rm EXP} - a_\mu^{\rm SM} = (262 \pm 85) \times 10^{-11}$$

order 10^{-9} positive deviation

without pre-factor, O(1) positive contribution required

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

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

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

each numerical contribution without the pre-factor (m=1 TeV)

	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)
1-loop	μ	$(17, -16)$	$(1.9, -1.8)\cdot 10^{-7}$	$(1.9, -1.8)\cdot 10^{-7}$	$(+, -)$
	t	$(-12, 15.9)$	$(-3.6, 4.7)\cdot 10^{-1}$	$(-1.1, 1.5)\cdot 10^{-3}$	$(-, -)$
	c	$(-118, 140)$	$(-1.9, 2.3)\cdot 10^{-4}$	$(-5.9, 7.1)\cdot 10^{-7}$	$(-, -)$
2-loop	u	$(-282, 330)$	$(-1.5, 1.7)\cdot 10^{-9}$	$(-4.6, 5.4)\cdot 10^{-12}$	$(-, -)$
	b	$(-87, 105)$	$(-1.5, 1.8)\cdot 10^{-3}$	$(-1.1, 1.4)\cdot 10^{-6}$	$(-, +)$
	τ	$(-109, 130)$	$(-3.4, 4.1)\cdot 10^{-4}$	$(-8.0, 9.6)\cdot 10^{-7}$	$(-, +)$

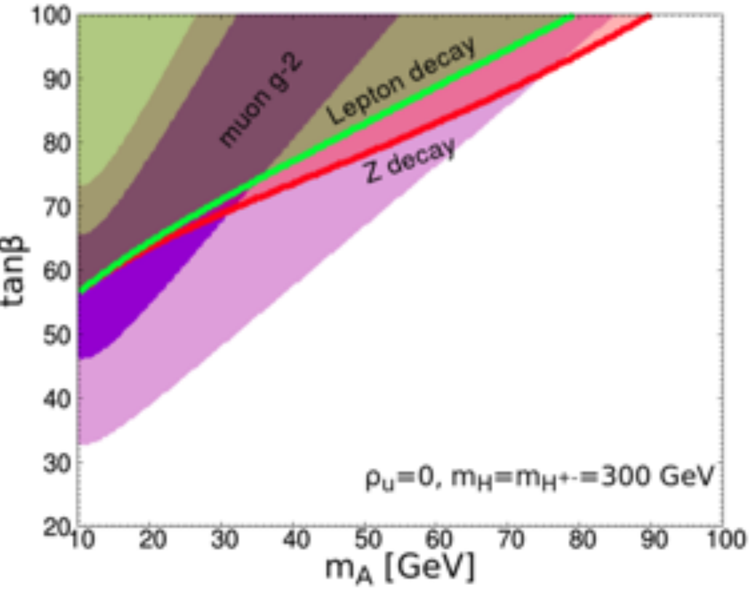
$$\xi_{ff'}^h \equiv s_{\beta-\alpha}\delta_{ff'} + c_{\beta-\alpha}\zeta_{ff'} ,$$
$$\xi_{ff'}^H \equiv c_{\beta-\alpha}\delta_{ff'} - s_{\beta-\alpha}\zeta_{ff'} ,$$
$$\xi_{ff'}^A \equiv (2T_3^f)\zeta_{ff'} ,$$

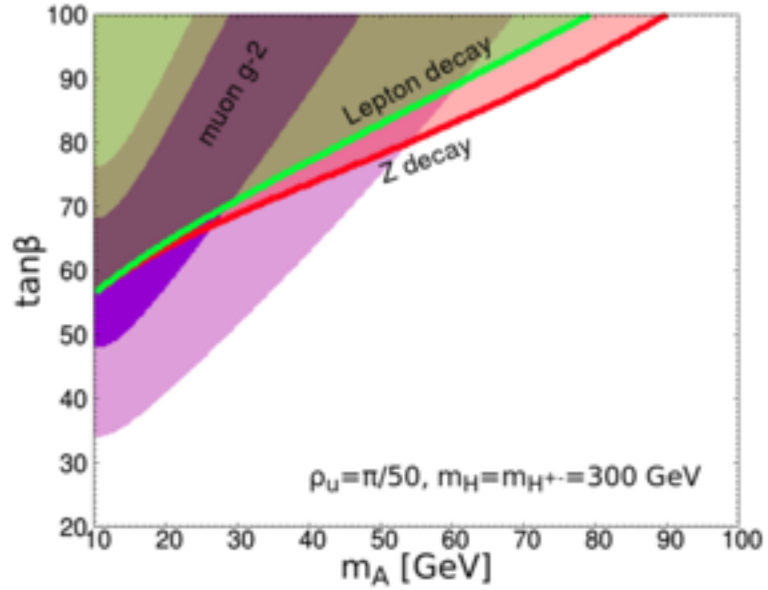
$$\zeta_{uu} \equiv -\tan\beta - (\tan\beta + \cot\beta)\frac{\cos\rho_u - 1}{2} ,$$
$$\zeta_{cc} \equiv \cot\beta ,$$
$$\zeta_{tt} \equiv \cot\beta - (\tan\beta + \cot\beta)\frac{1 - \cos\rho_u}{2} ,$$
$$\zeta_{ut} = \zeta_{tu} = (\tan\beta + \cot\beta)\frac{\sin\rho_u}{2} .$$

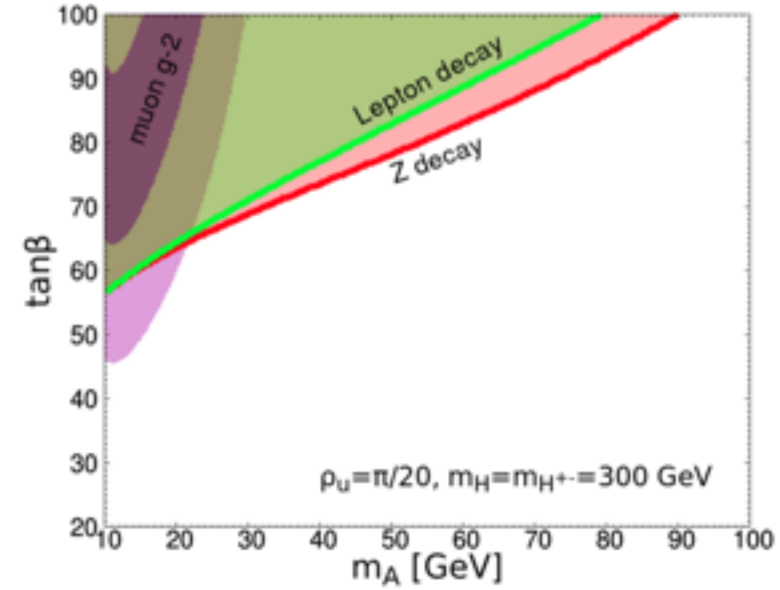
2-loop ∝ $1/m^2$ ⇒ mA ~ 15GeV gives 4×10^3 enhancement, with $(\tan\beta \sim 40)^2$ gives another 2×10^3 enhancement

c: opposite sign, b: disfavored by Bs→μμ, so τ would be the only possibility ⇒ u is only possibility PQ charged

g-2 in Lepton-specific 2HDM with VAM







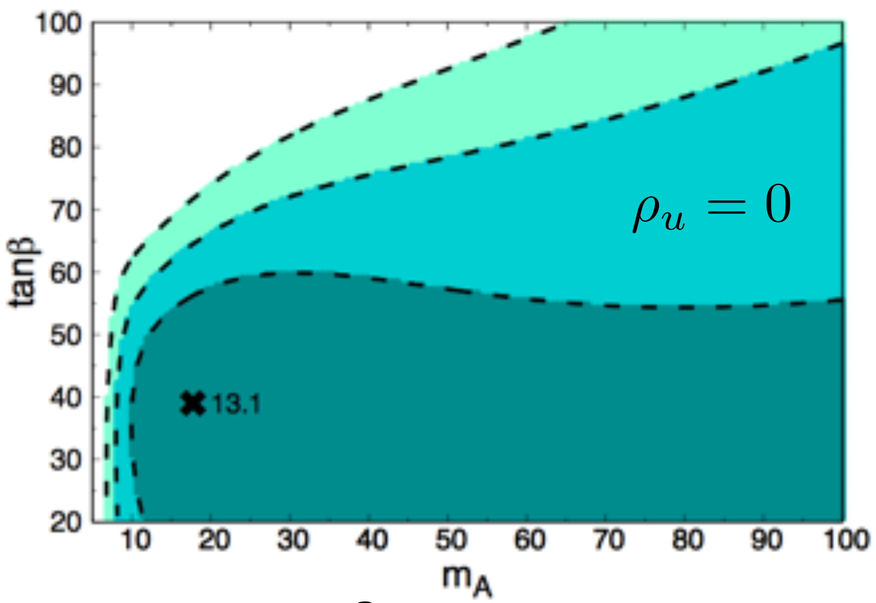
introducing mixing require larger tanβ

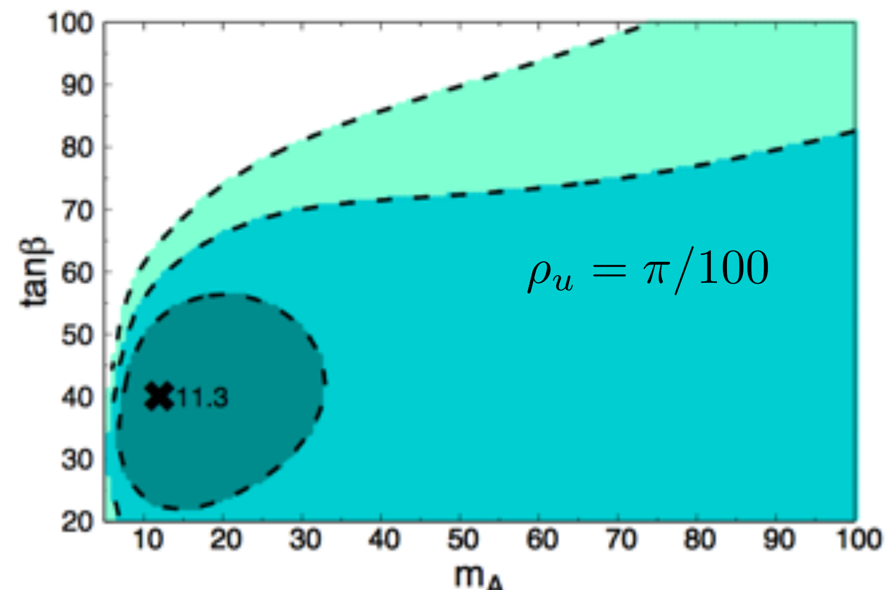
lepton universality : no mixing dep.

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

$$\xi^h_{ff'} \equiv s_{\beta-\alpha}\delta_{ff'} + c_{\beta-\alpha}\zeta_{ff'} ,$$
$$\xi^H_{ff'} \equiv c_{\beta-\alpha}\delta_{ff'} - s_{\beta-\alpha}\zeta_{ff'} ,$$
$$\xi^A_{ff'} \equiv (2T^f_3)\zeta_{ff'} ,$$

$$\zeta_{uu} \equiv -\tan\beta - (\tan\beta + \cot\beta)\frac{\cos\rho_u - 1}{2} ,$$
$$\zeta_{cc} \equiv \cot\beta ,$$
$$\zeta_{tt} \equiv \cot\beta - (\tan\beta + \cot\beta)\frac{1 - \cos\rho_u}{2} ,$$
$$\zeta_{ut} = \zeta_{tu} = (\tan\beta + \cot\beta)\frac{\sin\rho_u}{2} .$$





2-loop ∝ $1/m^2$ ⇒ mA ~ 15GeV gives 4×10^3 enhancement, with $(\tan\beta\sim40)^2$ gives another 2×10^3 enhancement

c: opposite sign, b: disfavored by Bs→μμ, so τ would be the only possibility ⇒ u is only possibility PQ charged

for muon g-2 introducing mixing doesn't help to accommodate the lepton universality constraints

including Bs→μμ, small mixing $\rho_u = \pi/100$ slightly improves the fit, large mixing is disfavored

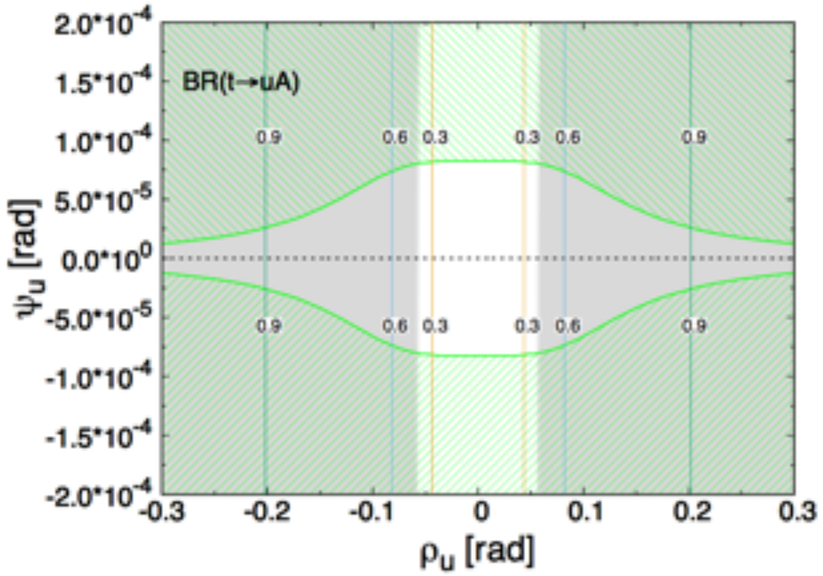
$$\bar{R}_{s\mu} \equiv \frac{\overline{\mathrm{BR}}(B^0_s \to \mu^+\mu^-)_{\mathrm{EXP}}}{\overline{\mathrm{BR}}(B^0_s \to \mu^+\mu^-)_{\mathrm{SM}}} = 0.79 \pm 0.20$$

$$\frac{\mathcal{M}}{\mathcal{M}^{\mathrm{SM}}} = 1 + \frac{\mathcal{M}^{u\mathrm{VAM}}}{\mathcal{M}^{\mathrm{SM}}} \sim 1 - 0.21\underbrace{\xi^A_{tt}\xi^A_{\mu\mu}}_{-\xi_t\xi_\mu \sim 1-(\tan\beta\rho_u/2)^2}\left(\frac{15\mathrm{GeV}}{m_A}\right)^2$$

$\rho_u = 0$:worse, $\rho_u \simeq 2\cot\beta$: better

t -> u A , A -> tautau

$$\Gamma_{t\to uA/cA} \propto\sim \sin^2\rho_u \tan^2\beta \qquad \Gamma_{t,\text{tot}} \leq 2.5\text{GeV} \to BR(t\to uA/cA) \lesssim 40\%$$
$$|\rho_u| \lesssim 0.06$$

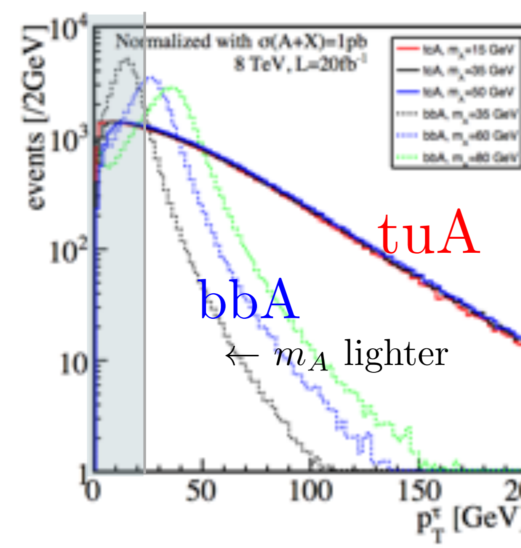


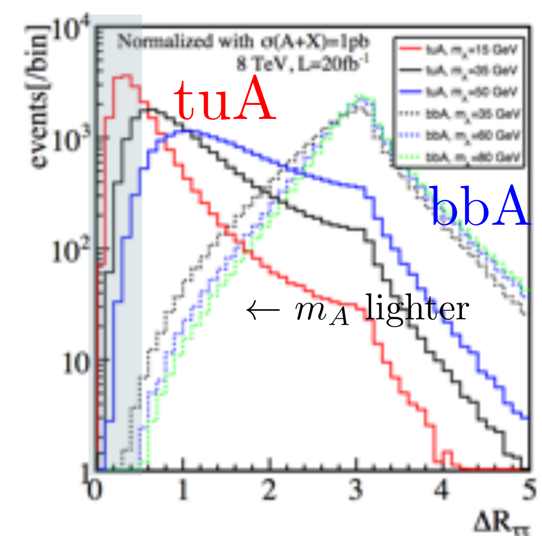
even for a slight mixing provides large BR(t→uA) ~ O(10%)
A decays dominantly to ττ about 100%
need to detect $t\bar{t} \to t(\bar{u}A)$

recasting the existing relevant LHC searches

LHC searches for bbA, A→ττ, in the context of MSSM.
CMS searches at 8TeV is the most constraining: using μτ, eτ, eμ modes

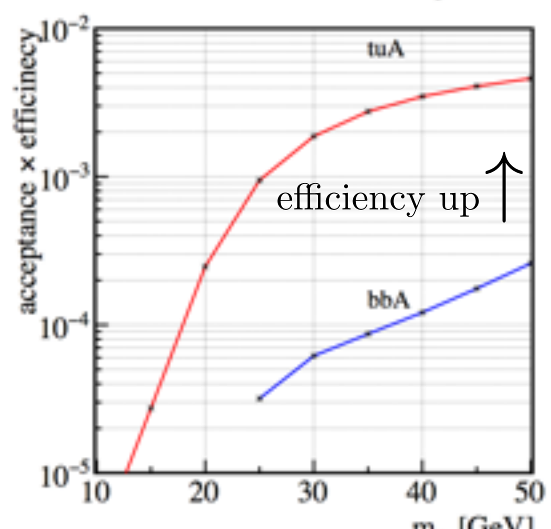
- $\mu\tau_h$ channel: exactly one μ and one τ_h with opposite charges:
  $p_{T,\mu} > 18$ GeV, $|\eta_\mu| < 2.1$ and $p_{T,\tau_h} > 22$ GeV, $|\eta_{\tau_h}| < 2.3$,
  $\boxed{\Delta R(\mu,\tau_h) > 0.5,}$ $M_T(p_{T,\mu}, \not{\vec{p}}_T) < 30$ GeV,
- $e\tau_h$ channel: exactly one e and one τ_h with opposite charges:
  $p_{T,e} > 24$ GeV, $|\eta_\mu| < 2.1$ and $p_{T,\tau_h} > 22$ GeV, $|\eta_{\tau_h}| < 2.3$,
  $\boxed{\Delta R(e,\tau_h) > 0.5,}$ $M_T(p_{T,e}, \not{\vec{p}}_T) < 30$ GeV,
- $e\mu$ channel: exactly one μ and one e with the opposite charge:
  ($p_{T,\mu} > 18$ GeV, $p_{T,e} > 10$ GeV) or ($p_{T,\mu} > 10$ GeV, $p_{T,e} > 20$ GeV),
  $|\eta_\mu| < 2.1$ and $|\eta_e| < 2.3$
  $\boxed{\Delta R(e,\mu) > 0.5,}$ $M_T(p_{T,e} + p_{T,\mu}, \not{\vec{p}}_T) < 25$ GeV, $P_\zeta - 1.85 P_\zeta^{\text{vis}} > -40$ GeV,

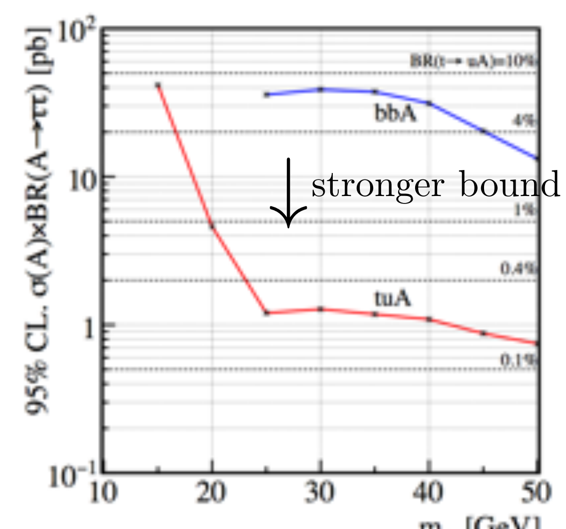




kinematics is different between tuA and bbA

— efficiency for tuA
higher due to $p_{T,\tau}$ cut
quickly goes down as $m_A \to 0$ due to ΔR cut



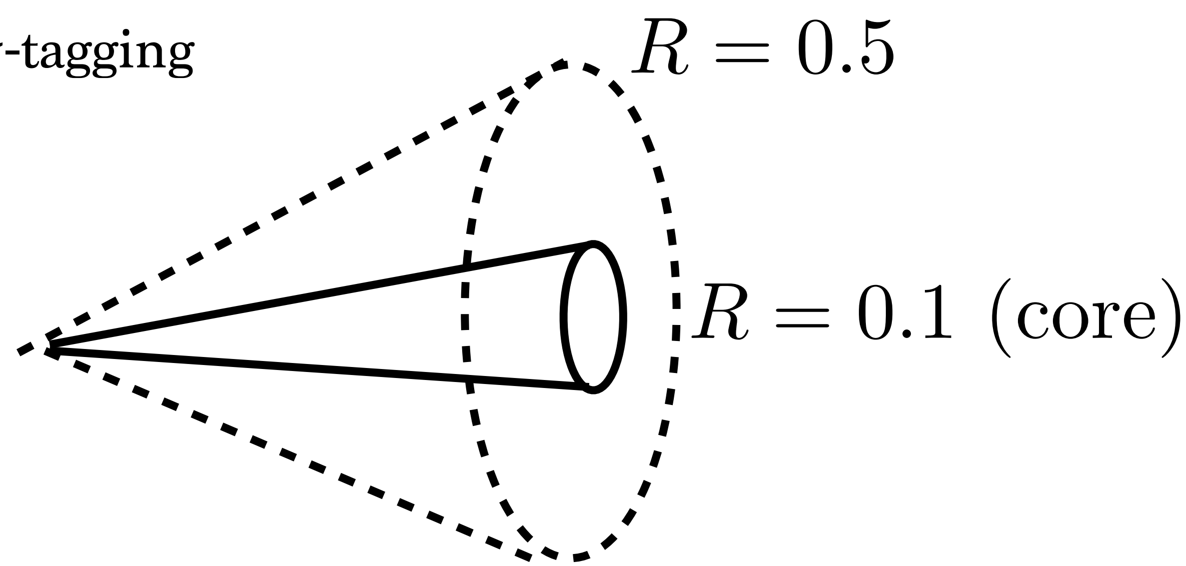


BR(t→uA) < 0.2% (mA>25GeV), 10% (mA=15GeV)

boosted A -> tautau

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

τ-tagging

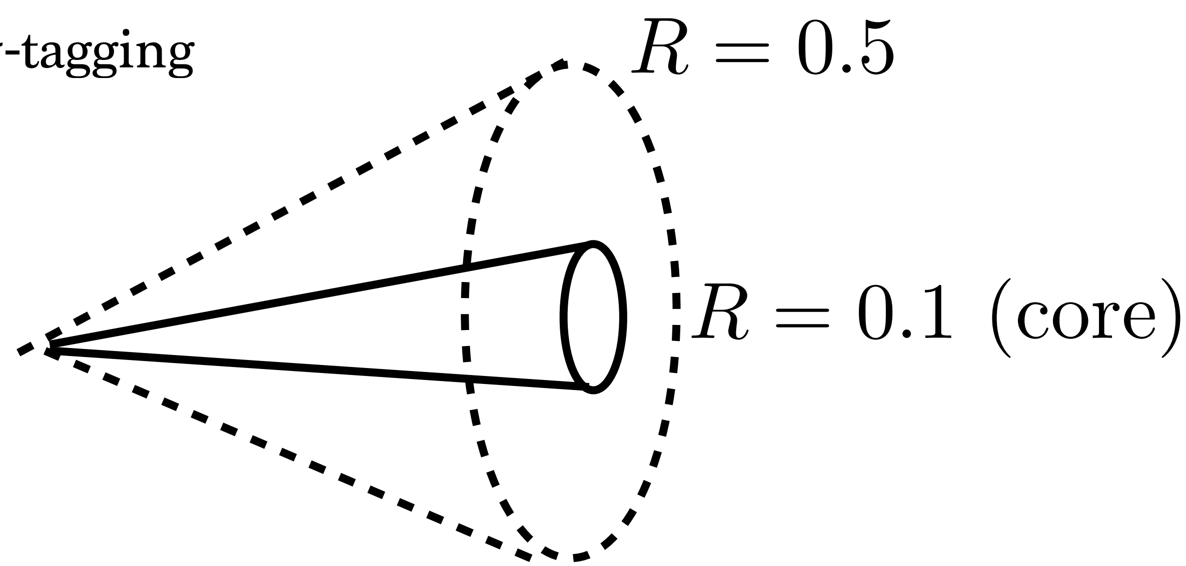


$$f = \frac{E(R=0.1)}{E(R=0.5)} > 0.95$$

boosted A -> tautau

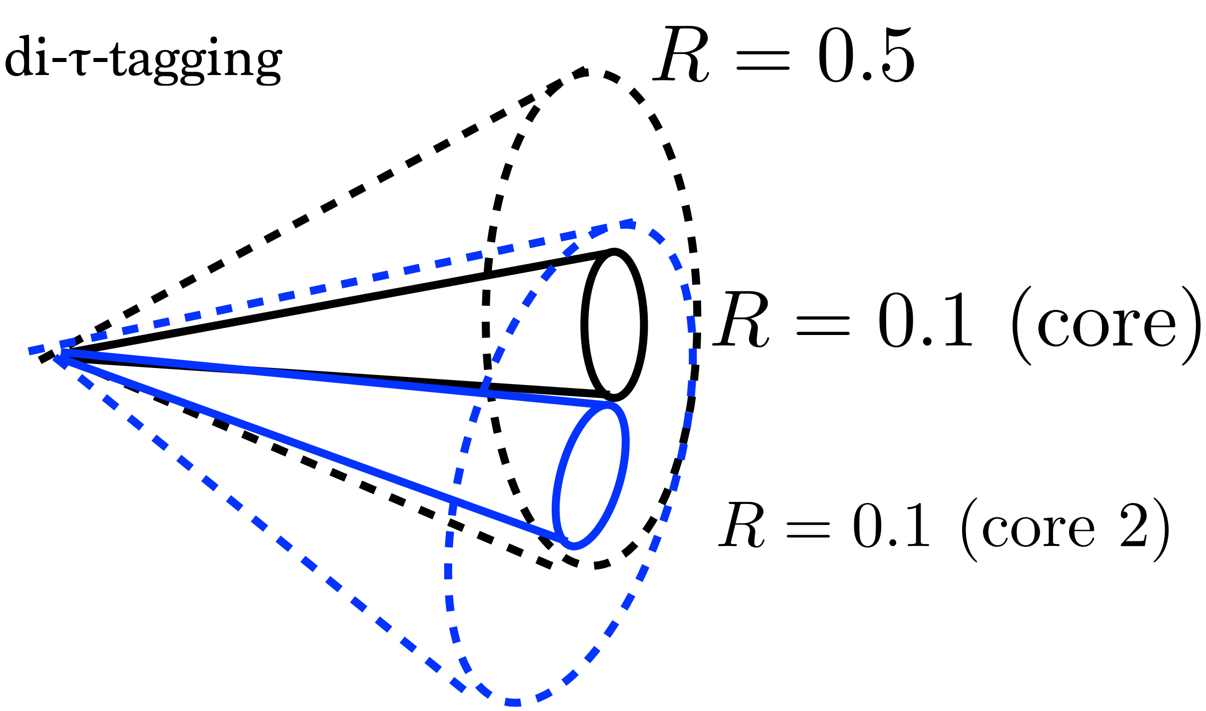
The reason for rapid drop of the efficiency is due to the overlapping τ's due to the boost

τ-tagging



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

di-τ-tagging



usual isolation fails

mutual isolation

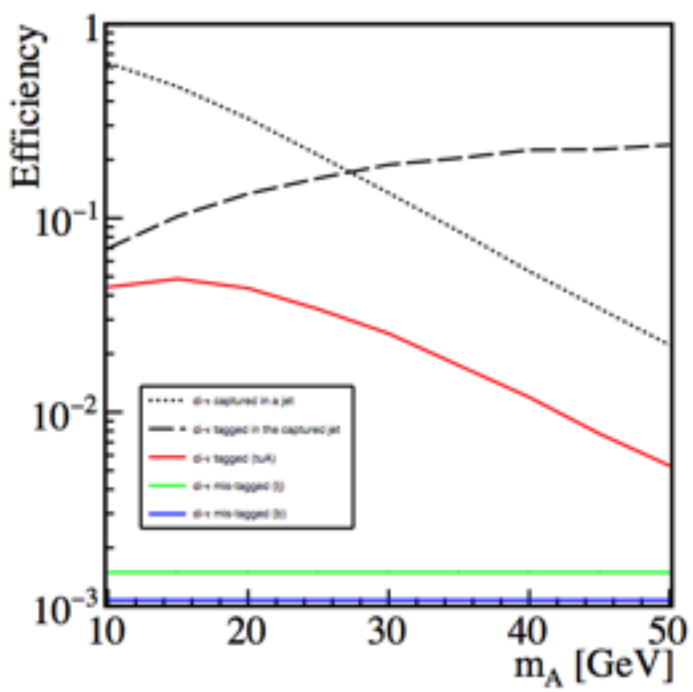
[A. Katz, M. Son, B. Tweedie, PRD 83, 114033(2011).]

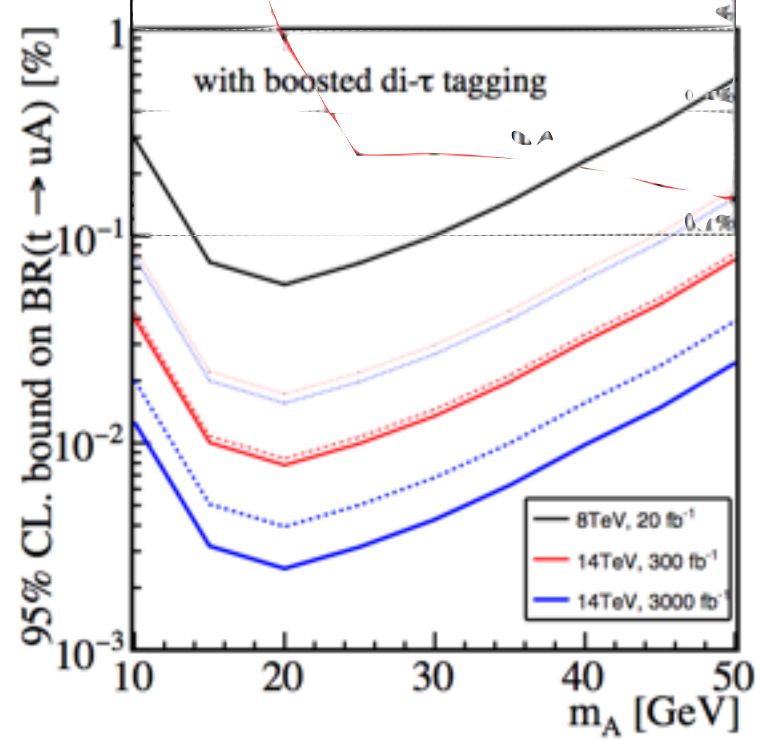
if core 1 is removed, the rest is τ-tagged

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

boosted A -> tautau

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



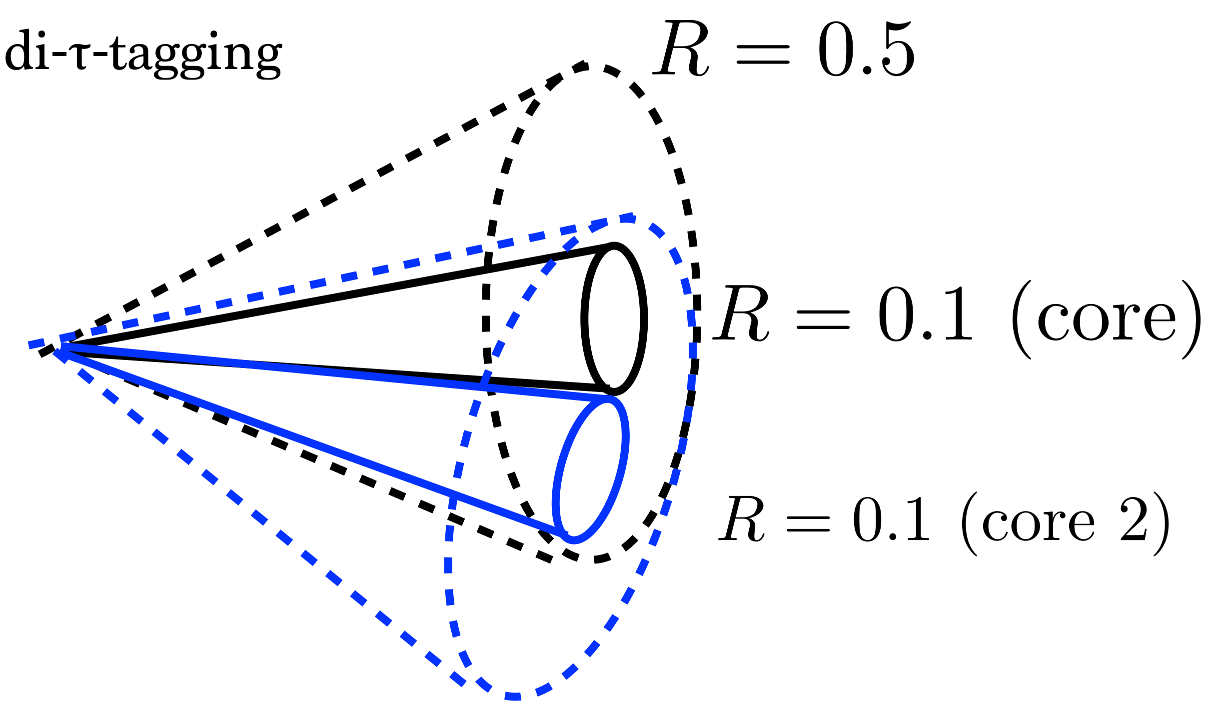


BR(t→uA) < 0.08% at mA=15GeV

(BR(t→uA) < 10% at mA=15GeV by CMS study)

BR(t→uA) < 0.003-0.01% in future

di-τ-tagging



usual isolation fails

mutual isolation

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

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

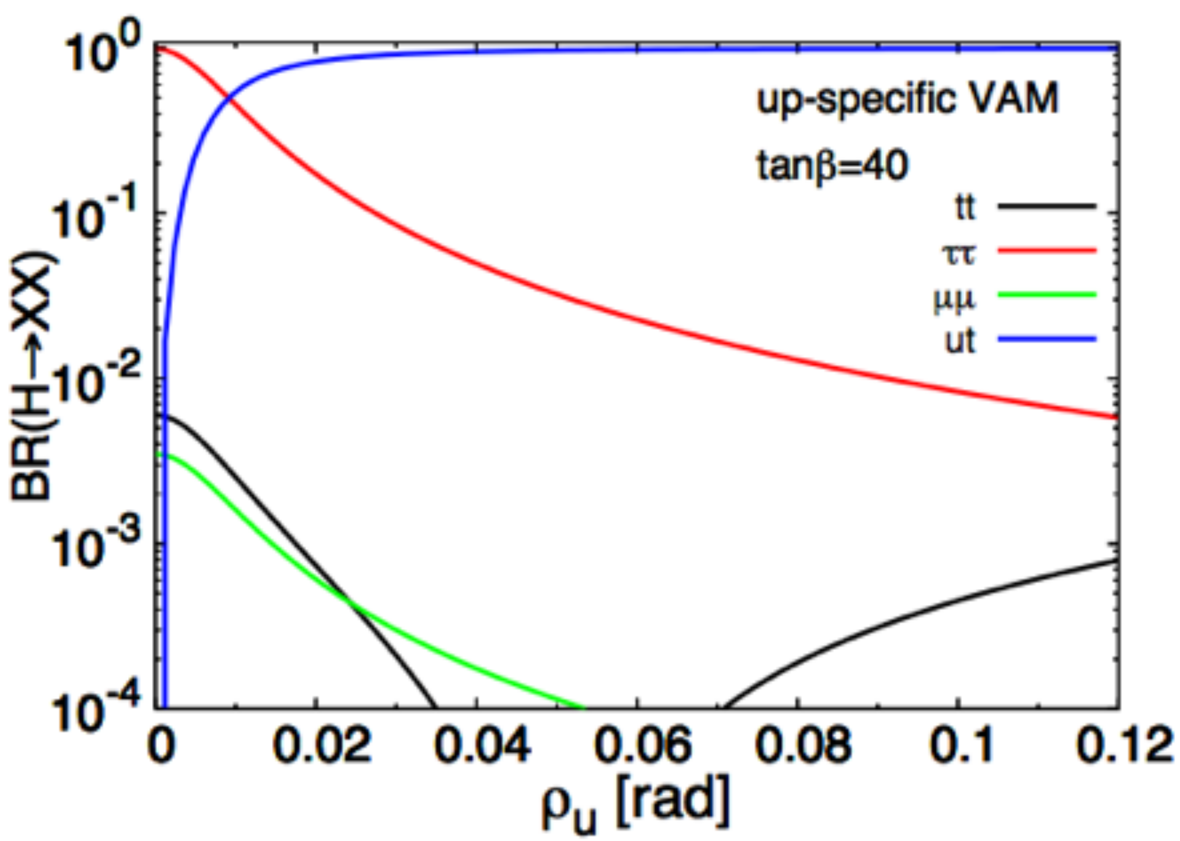
if core 2 is removed, the rest is also τ-tagged

Flavor violating Heavy higgs decays

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

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

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



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

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

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

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

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

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

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

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

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

very striking signature of the model

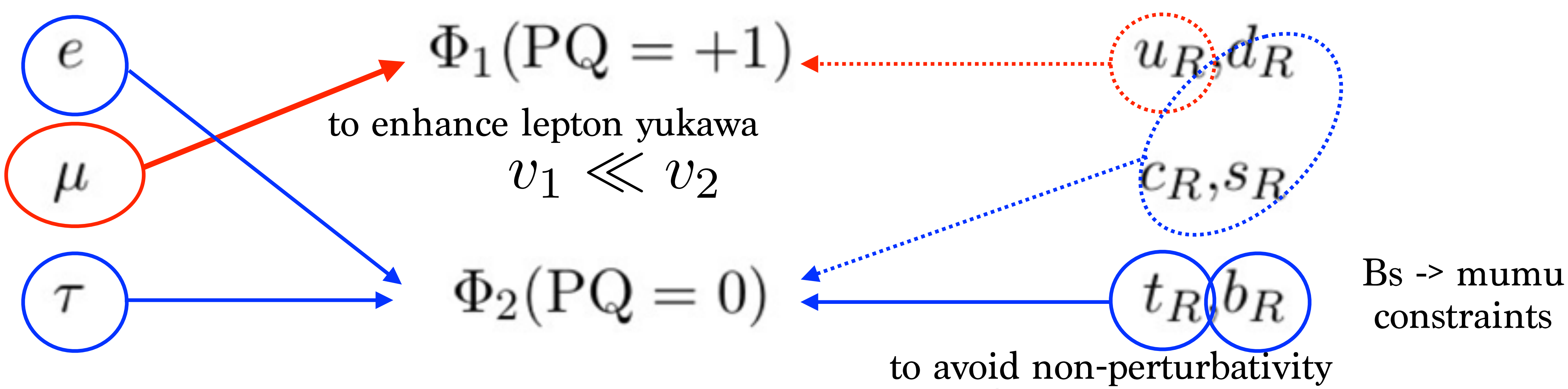
u-specific VAM with muon-specific lepton sector

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%)

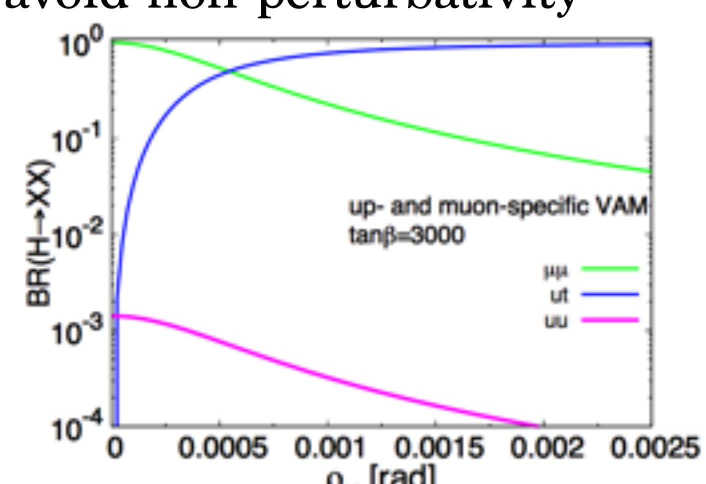
VAM is essentially just a 2HDM with various PQ charge assignments (only one q_R PQ charged)

- 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

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



Conclusions

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

to explain the anomaly in the muon g-2 in 2HDM, require LFV in g2HDM, or lepton-specific 2HDM

With Lepton Flavor Violation

$m_A < 700$ GeV, $10\text{GeV} < m_H - m_A < 100$ GeV

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

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 $m_A \sim 15$GeV, $\tan\beta \sim 40$

by assign PQ charge only to muon $m_A \sim 1$ TeV, $\tan\beta \sim 3000$

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 would be also the distinctive signatures of this model