g-2 with Variant Axion Models

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based on arxiv:1807.00593 (and JHEP11(2015)057 [arXiv:1507.04354],PhysRevD.97.035015 [arXiv:1711.02993])

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No signature of BSM yet

No evidence of SUSY anywhere yet: Higgs measurements, DM Direct-Detection, ...

SUSY dead? I personally think still attractive as a solution of the big hierarchy problem (don't confuse with 'little hierarchy')

attractive points:

natural WIMP DM, solve big hierarchy problem ~ $O(10^{-26})$ to $O(10^{-4})$, coupling unification, ...

Another fine tuning problem in the SM : strong CP problem – Why $\theta_{\rm eff} < 10^{-11}$? $\mathcal{L}_\theta = \frac{\theta}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$

Attractive solution : PQ mechanism $\Rightarrow$ Axion : good DM candidate

similarly attractive and don't require new particles : naturally explain the current situation

Strong CP problem

QCD Lagrangian contains the total derivative term: θ-term

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

θ-vacuum

$|n>\to|m>$ but $|\theta>\to|\theta>$

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

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

massive fermion mass term is also changed.

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

is invariant under the chiral tr.

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

$\theta_{\rm eff}$ can be measured from Neutron EDM $|d_n| = 4.5\times10^{-15}\theta_{\rm eff}\,e{\rm cm}$

$$|d_n^{\rm obs}| < 2.9\times10^{-26}\,e{\rm cm}$$

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, $\partial^\mu j^{\mathrm{PQ}}_\mu = -\frac{g^2}{32\pi^2} A G^{a\mu\nu}\tilde{G}^a_{\mu\nu}$,

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

$\frac{a}{\eta} \to \frac{a}{\eta} + \epsilon$ 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

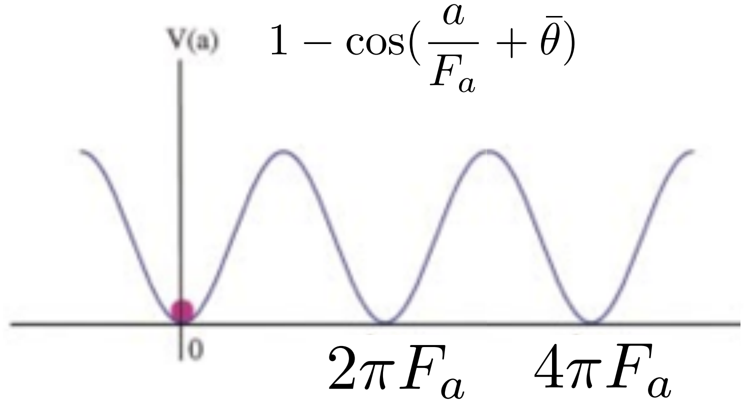
$$\boxed{\mathcal{L}_{\mathrm{eff}} = -\frac{1}{4}G^{a\mu\nu}G^a_{\mu\nu} - \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{g^2}{32\pi^2}\frac{a}{F_a}G^{a\mu\nu}\tilde{G}^a_{\mu\nu} - \frac{\bar{\theta}g^2}{32\pi^2}G^{a\mu\nu}\tilde{G}^a_{\mu\nu}}$$

$$F_a = \eta/A$$

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

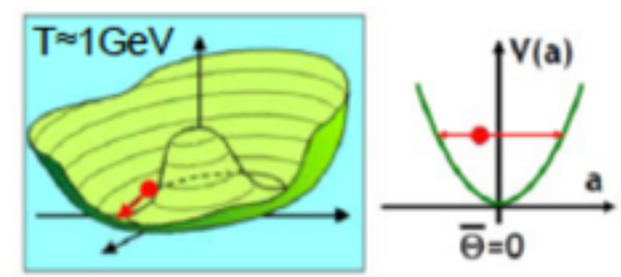
at low temperature, QCD instanton effects give an axion a potential and minimizing it gives $< a >= -\bar{\theta}F_a$.

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

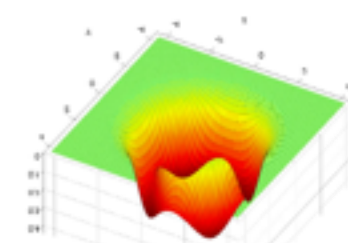


$$a' \equiv a + \bar{\theta}F_a$$

in theta space



in <a> space



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

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

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

Variant Axion model $\quad N_{\mathrm{PQ}} = 1$ 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]

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

↓

$N_{DM} = 1$

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

up-type specific Variant Axion model

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

	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q_L, L_L
Type-I	+	−	−	−	−	+
Type-II	+	−	−	+	+	+
Type-X	+	−	−	−	+	+
Type-Y	+	−	−	+	−	+

two Higgs easily results in FCNC.
Usually people impose Z2 sym. to avoid FCNC.

	Φ_1	Φ_2	t_R	c_R	u_R	d_R	ℓ_R	Q_L	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, top-specific case,

Φ_2 only couple with u_{R3}

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

other quarks only couples with Φ_1

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

mix with β

in higgs basis Y_u^{SM}, Y_u'

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

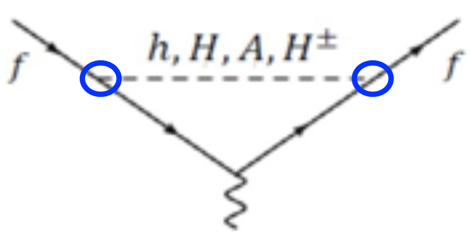
$$H_u \equiv V \begin{pmatrix} 0 & & \\ & 0 & \\ & & 1 \end{pmatrix} V^\dagger - \begin{pmatrix} 0 & & \\ & 0 & \\ & & 1 \end{pmatrix} \to \frac{1}{2} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1-\cos\rho & \sin\rho \\ 0 & \sin\rho & \cos\rho - 1 \end{pmatrix}$$

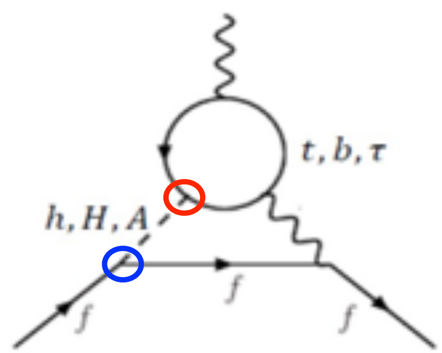
g-2 in Lepton-specific 2HDM

muon g-2, long standing 3σ level anomaly $\Delta a_\mu = a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}} = (262 \pm 85) \times 10^{-11}$

order 10^{-9} positive deviation

lepton-specific (type-X) 2HDM with light A is known as a solution





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

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

2loop can dominates by large yukawa compared with y_μ

In lepton-specific 2HDM model, tanβ enhanced tau contribution is crucial.

mA ~ 30GeV and tanβ ~ 40 will give a enough contribution -> require large tanβ

It is known that LHC constraints are weak as all quark couplings to heavier bosons are suppressed.

W -> H+ A, Z -> A H etc, and Z -> tau tau A, would be the dominant production we can constrain

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

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	to enhance lepton yukawa	
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to avoid non-perturbativity

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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 $B_s \to \mu\mu$

not viable possibility

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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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to enhance lepton yukawa

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

τ $\quad$ $\Phi_2(\mathrm{PQ}=0)$ $\longleftarrow$ t_R, b_R

Bs -> mumu constraints

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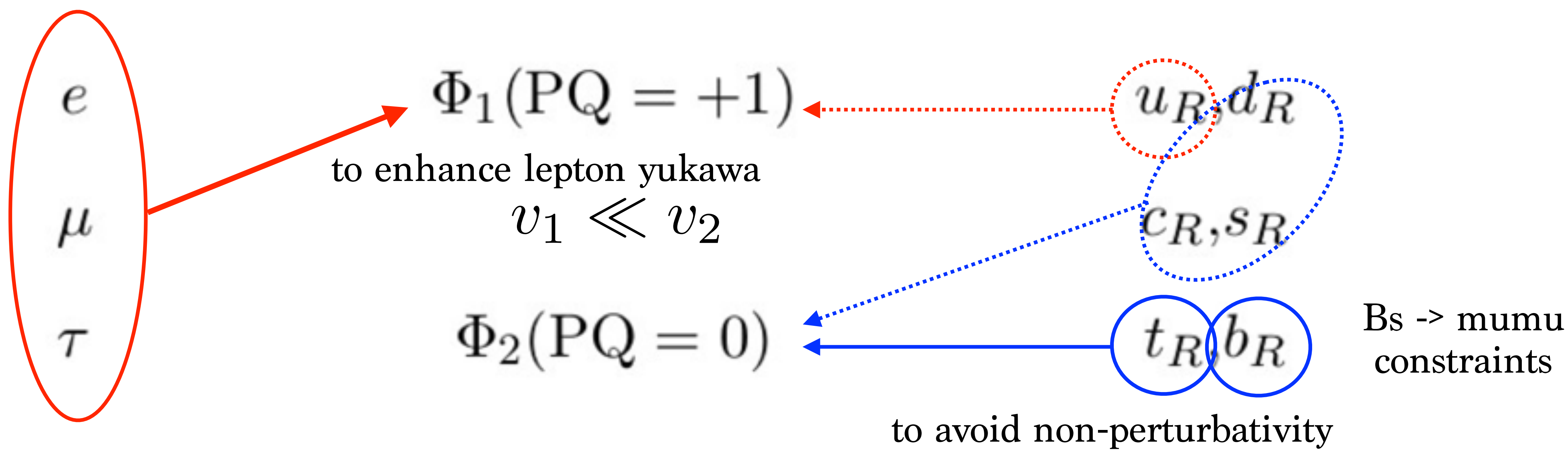
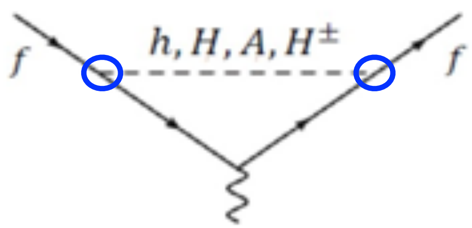
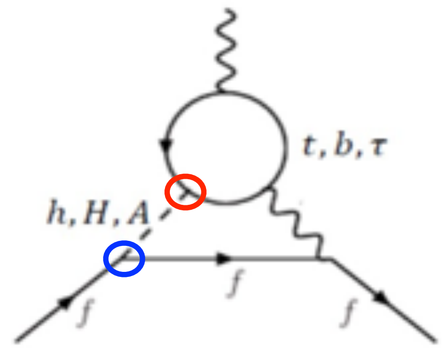


several choices, but up-specific is most interesting possibility

g-2 in Lepton-specific 2HDM with VAM





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

order 10^{-9} positive deviation

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

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

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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	$(-109, 130)$	$(-3.4, 4.1) \cdot 10^{-4}$	$(-8.0, 9.6) \cdot 10^{-7}$	$(-, +)$

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

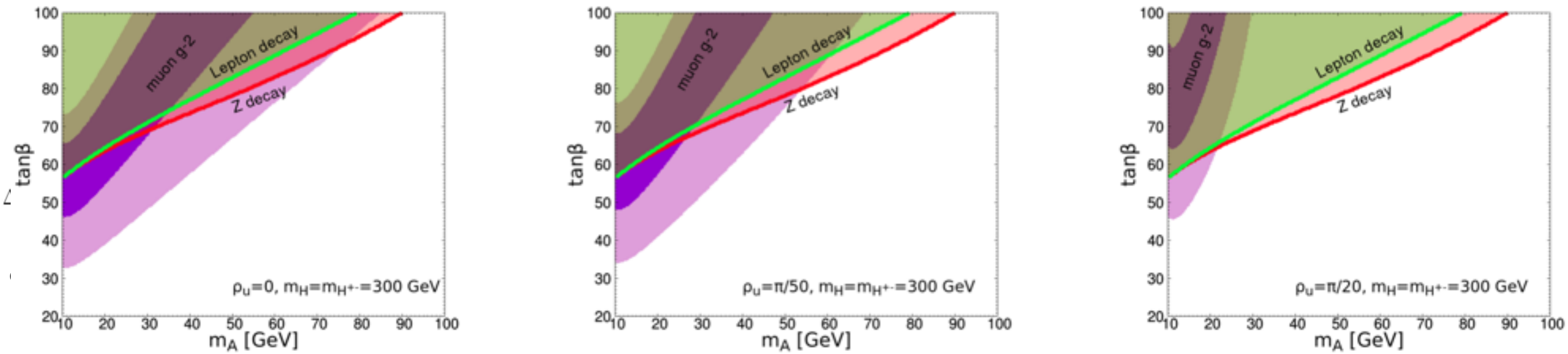
$$\xi_{ff'}^h \equiv s_{\beta-\alpha}\delta_{ff'} + c_{\beta-\alpha}\zeta_{ff'},$$
$$\xi_{ff'}^H \equiv c_{\beta-\alpha}\delta_{ff'} - s_{\beta-\alpha}\zeta_{ff'},$$
$$\xi_{ff'}^A \equiv (2T_3^f)\zeta_{ff'},$$

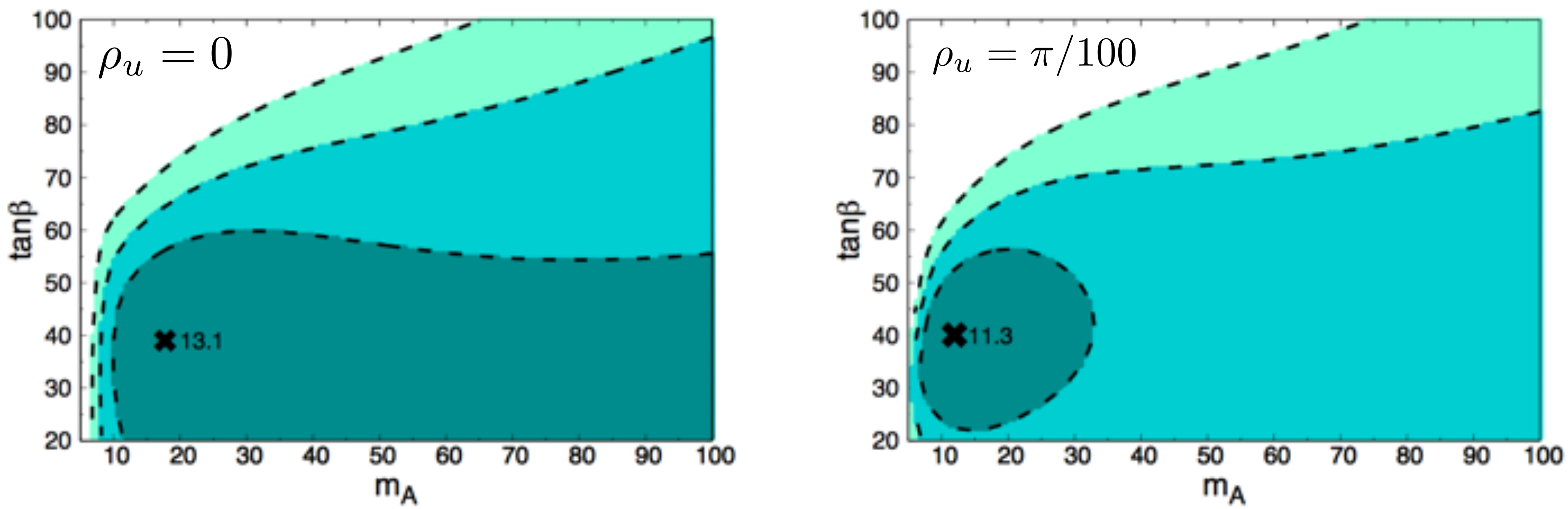
$$\zeta_{ff'} = \begin{cases} -\tan\beta\,\delta_{ff'} - (\tan\beta + \cot\beta)H_{u,ff'} & (\text{for } f = u), \\ \cot\beta\,\delta_{ff'} - (\tan\beta + \cot\beta)H_{u,ff'} & (\text{for } f = c, t), \\ \cot\beta\,\delta_{ff'} & (\text{for } f = d, s, b) \\ -\tan\beta\,\delta_{ff'} & (\text{for } f = e, \mu, \tau) \end{cases}$$

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





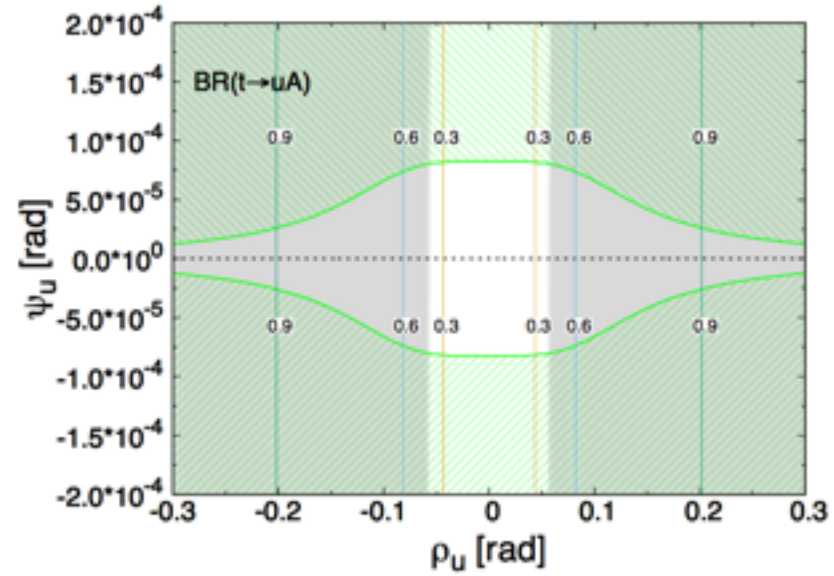
$$\xi^h_{ff'} = s_{\beta-\alpha}\delta_{ff'} + c_{\beta-\alpha}\zeta_{ff'}\,,$$
$$\xi^H_{ff'} \equiv c_{\beta-\alpha}\delta_{ff'} - s_{\beta-\alpha}\zeta_{ff'}\,,$$
$$\xi^A_{ff'} \equiv (2T^f_3)\zeta_{ff'}\,,$$

$$\begin{cases} -\tan\beta\,\delta_{ff'} - (\tan\beta + \cot\beta)H_{u,ff'} & (\text{for } f = u)\,, \\ \cot\beta\,\delta_{ff'} - (\tan\beta + \cot\beta)H_{u,ff'} & (\text{for } f = c, t)\,, \\ \cot\beta\,\delta_{ff'} & (\text{for } f = d, s, b) \\ -\tan\beta\,\delta_{ff'} & (\text{for } f = e, \mu, \tau) \end{cases}$$

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

t -> u A , A -> tautau



even for slight mixing provides large BR(t→uA) ~ O(10%)

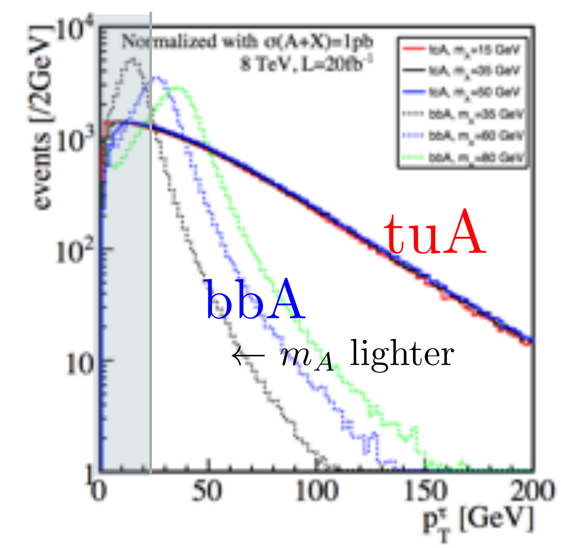
A decays dominantly to ττ about 100%

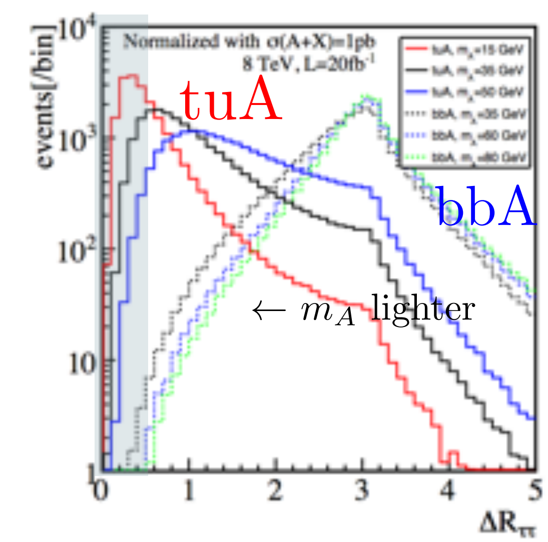
LHC searches for bbA, A→ττ, in the context of MSSM.

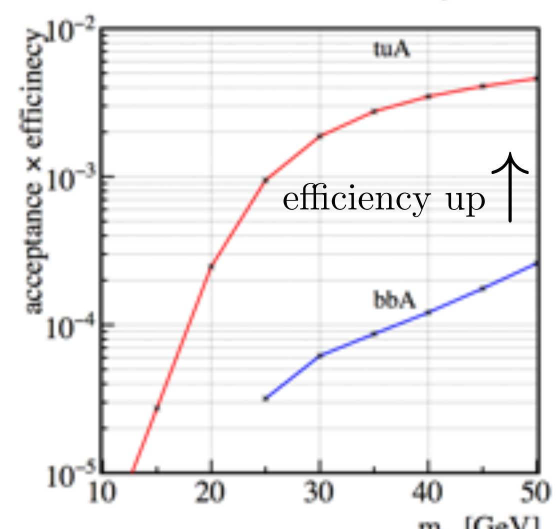
CMS searches at 8TeV is the most constraining: using μτ, eτ, eμ modes

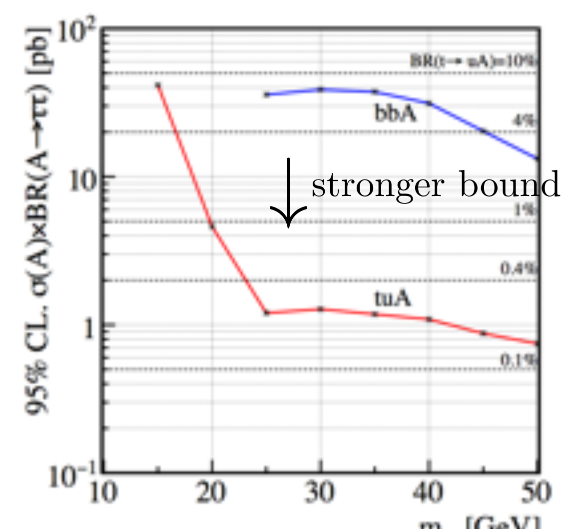
the kinematics is different between tuA and bbA

- $\mu\tau_h$ 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, $|\eta_{\tau_h}| < 2.3$,
  $\boxed{\Delta R(\mu,\tau_h) > 0.5}$, $M_T(p_{T,\mu}, \not{p}_T) < 30$ 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, $|\eta_{\tau_h}| < 2.3$,
  $\boxed{\Delta R(e,\tau_h) > 0.5}$, $M_T(p_{T,e}, \not{p}_T) < 30$ 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 $|\eta_e| < 2.3$
  $\boxed{\Delta R(e,\mu) > 0.5}$, $M_T(p_{T,e} + p_{T,\mu}, \not{p}_T) < 25$ GeV, $P_\zeta - 1.85 P_\zeta^{\rm vis} > -40$ GeV,









efficiency is in general higher due to $p_{T,\tau}$ cut

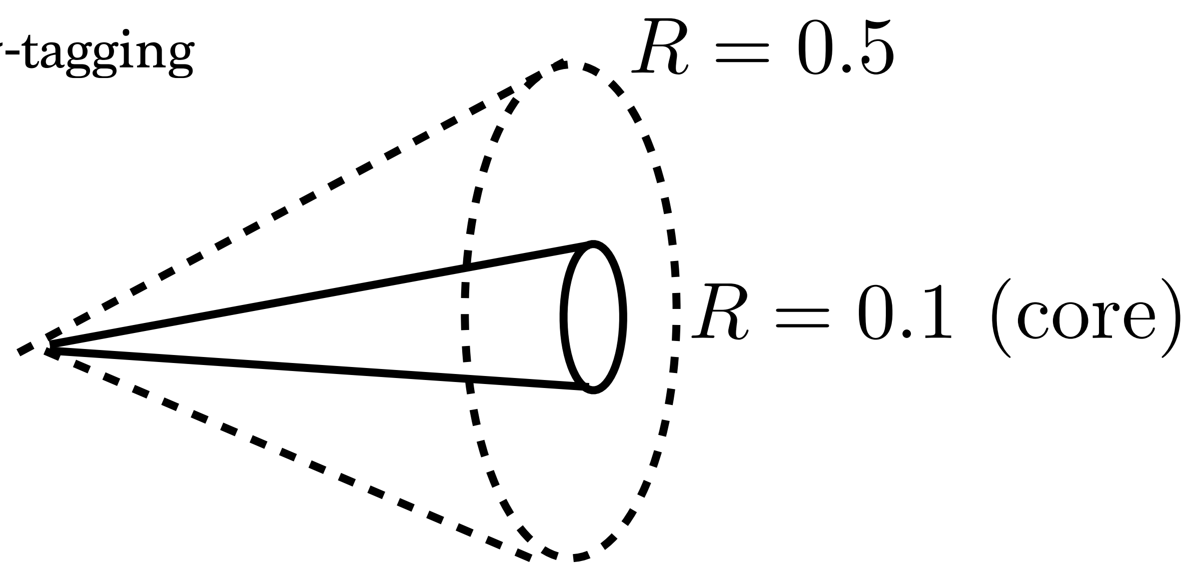
efficiency quickly goes down due to ΔR cut when $m_A \to 0$

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



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

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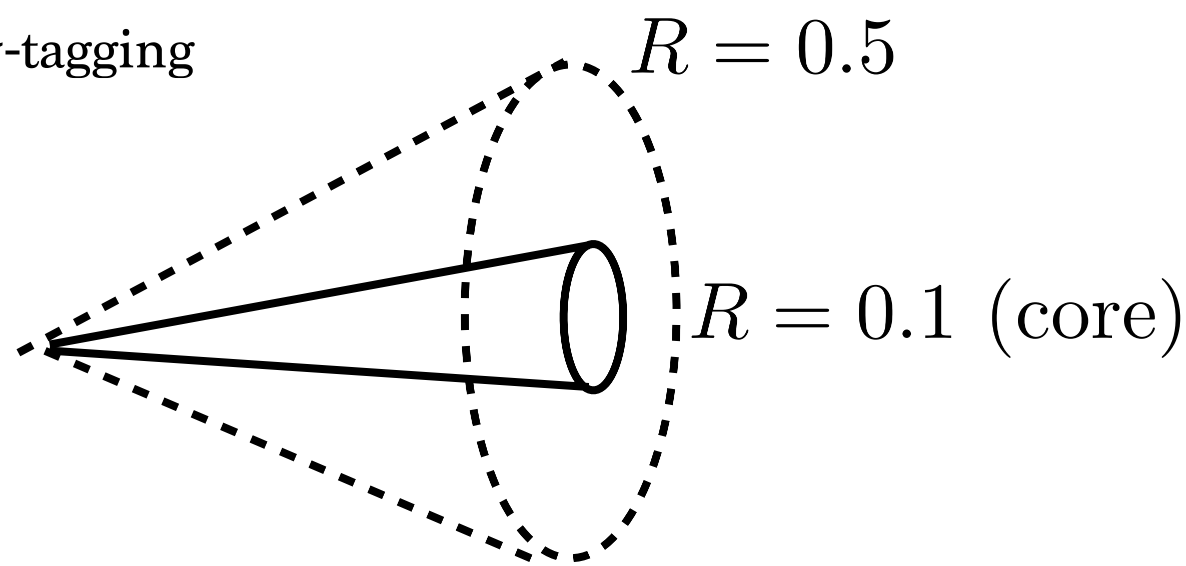

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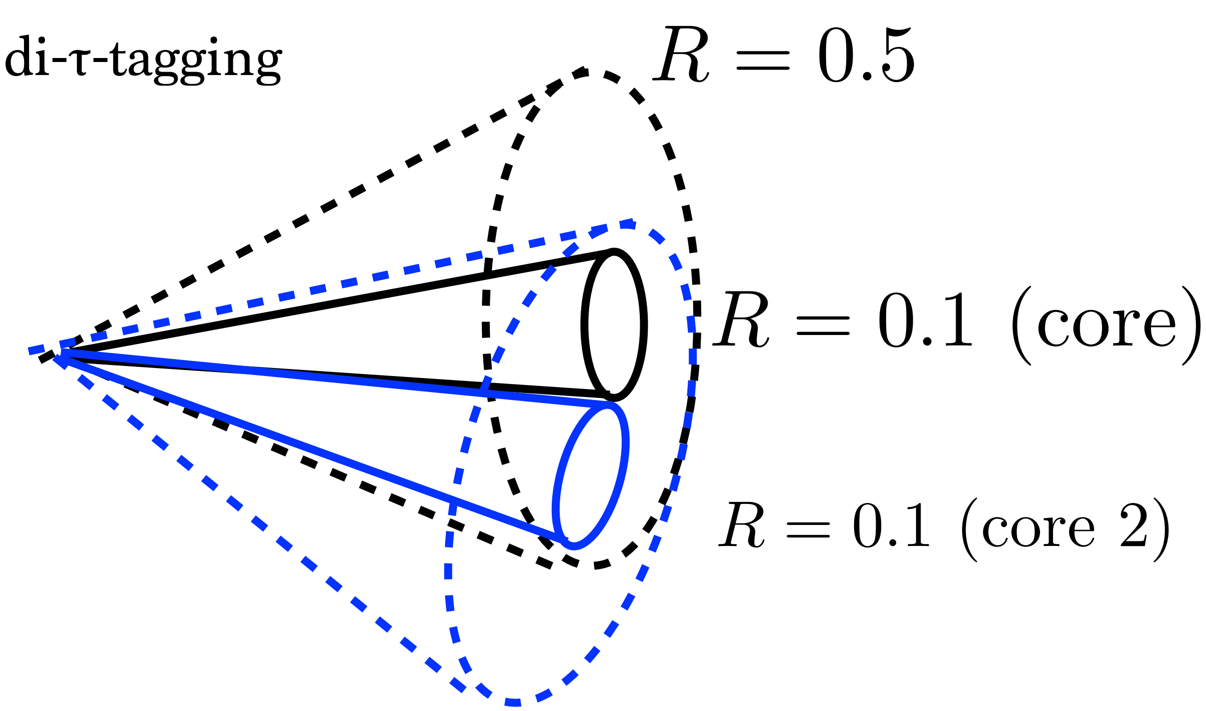
di-τ-tagging



usual isolation fails

mutual isolation

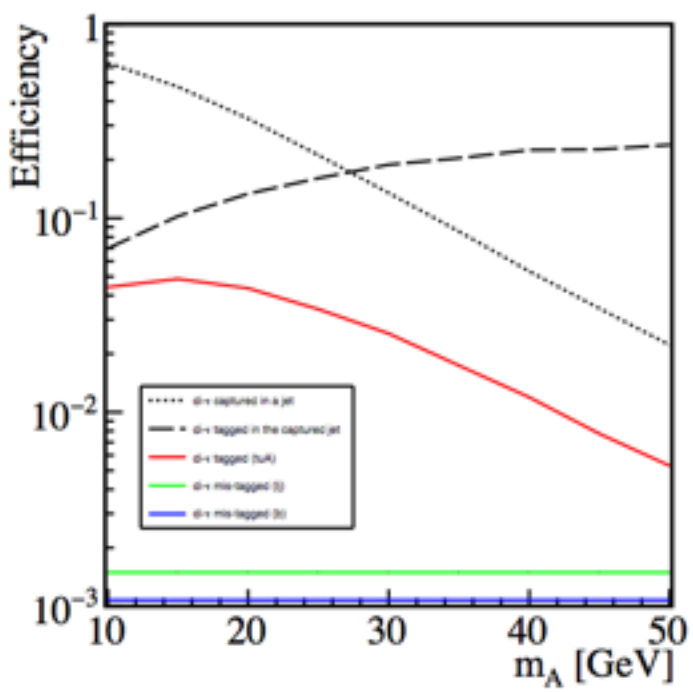
[A. Katz, M. Son, B. Tweedie, PRD 83, 114033(2011).]

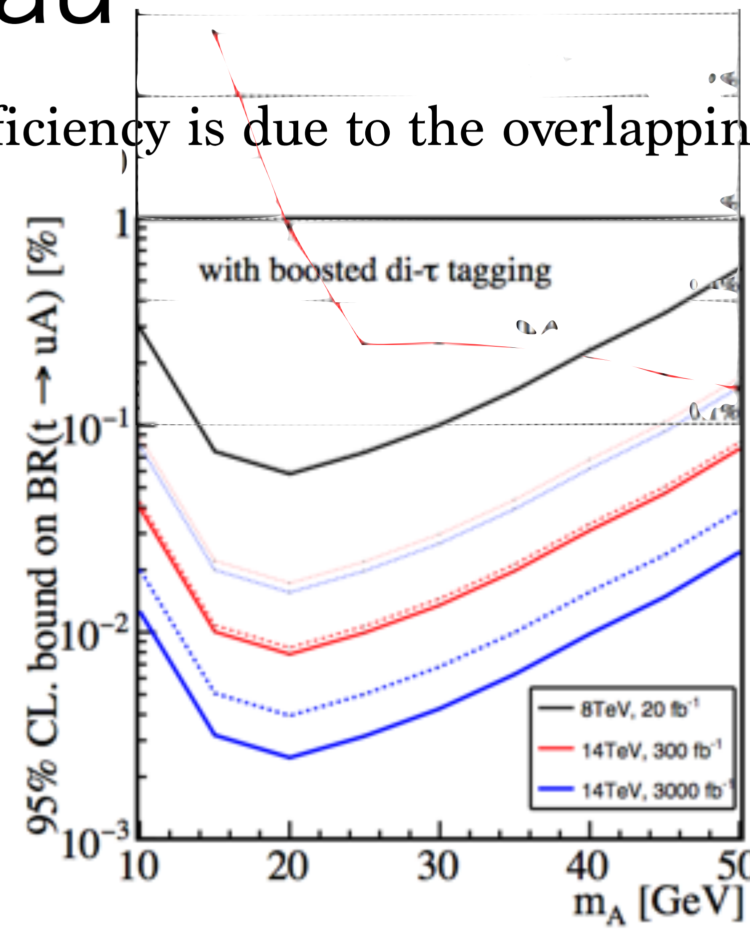
if core 1 is removed, the rest is τ-tagged

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



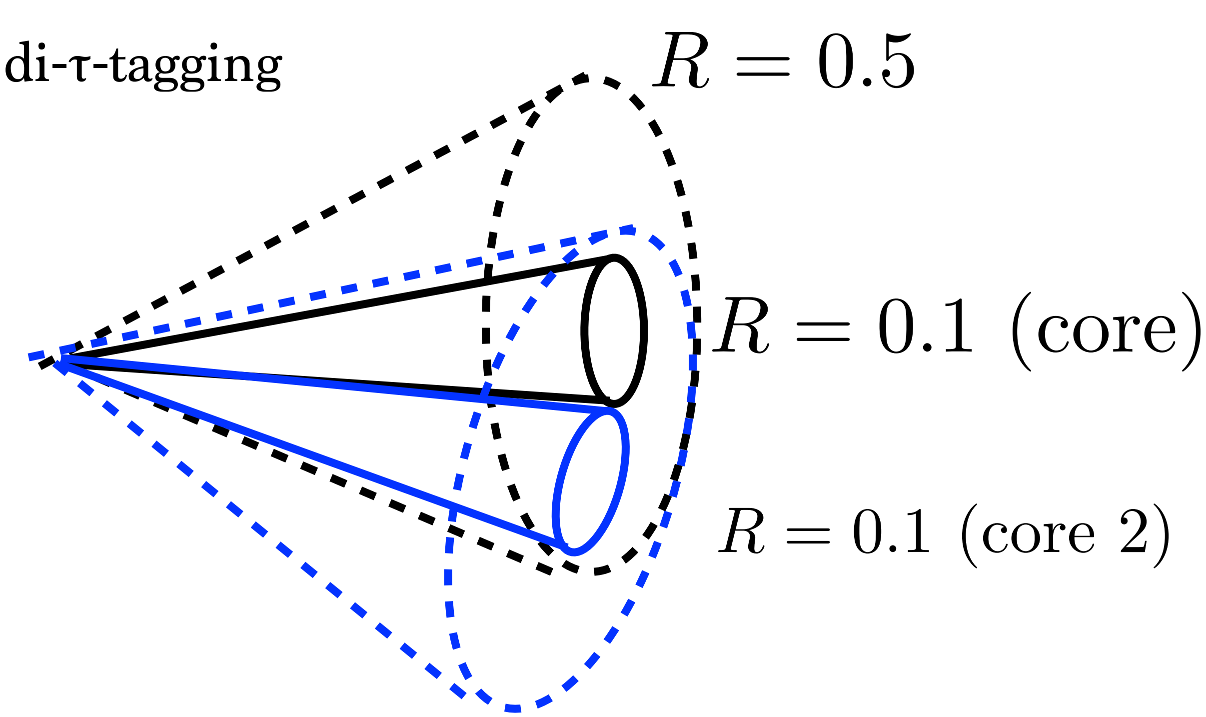


BR(t→uA) < 0.08% at mA=15GeV

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

BR(t→uA) < 0.003-0.01% in future

di-τ-tagging



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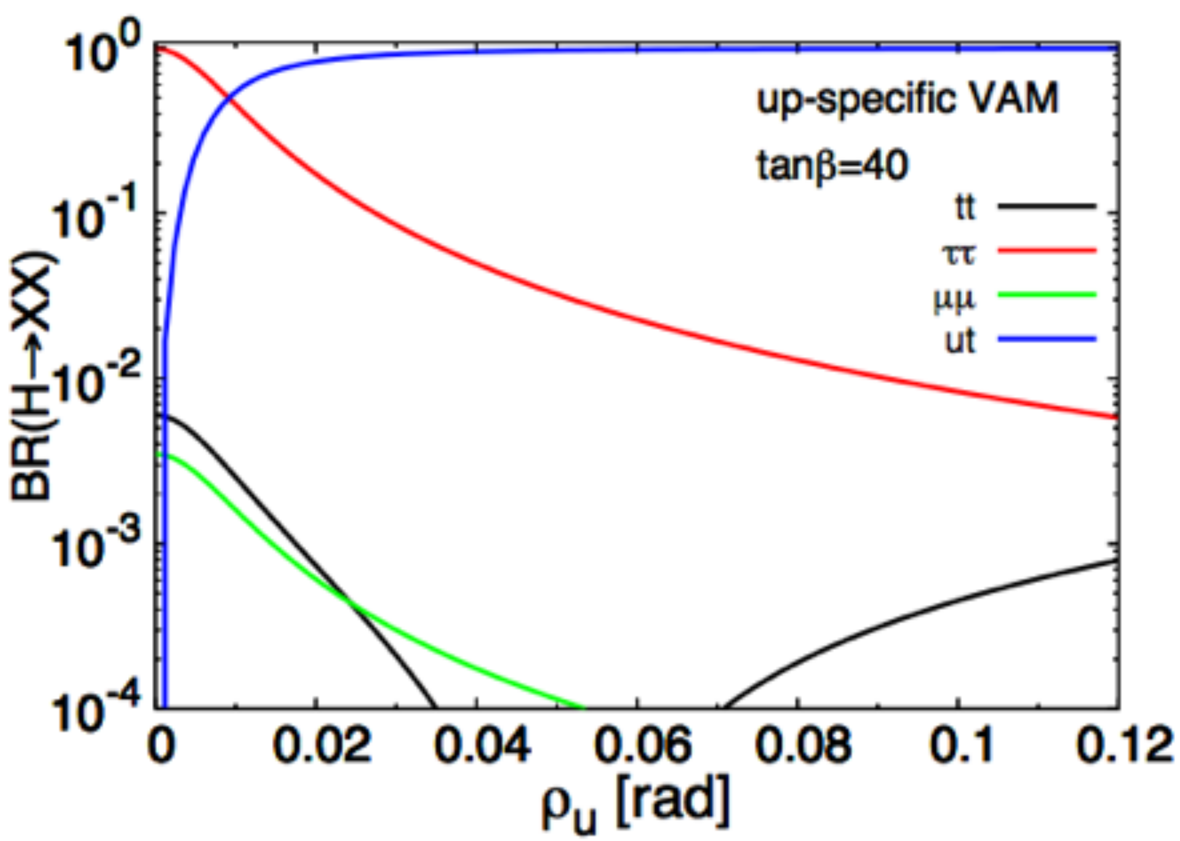
Flavor violating Heavy higgs decays

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 $\rho_u \gtrsim 1/120$.



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

$$\xi^h_{ff'} \equiv s_{\beta-\alpha}\delta_{ff'} + c_{\beta-\alpha}\zeta_{ff'}\,,$$
$$\xi^H_{ff'} \equiv c_{\beta-\alpha}\delta_{ff'} - s_{\beta-\alpha}\zeta_{ff'}\,,$$
$$\xi^A_{ff'} \equiv (2T_3^f)\zeta_{ff'}\,,$$

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

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

very striking signature of the model

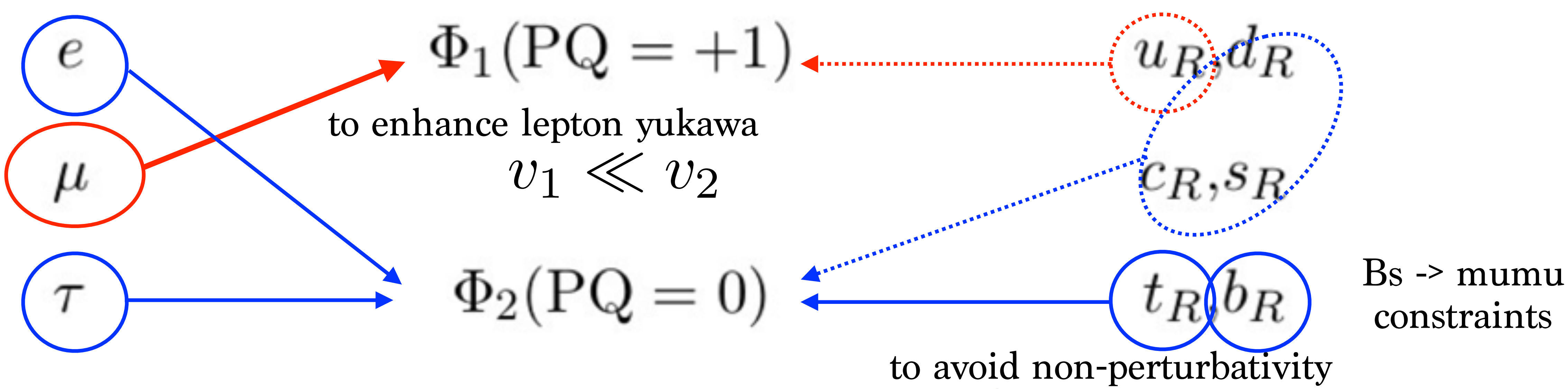
u-specific VAM with muon-specific lepton sector

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%)

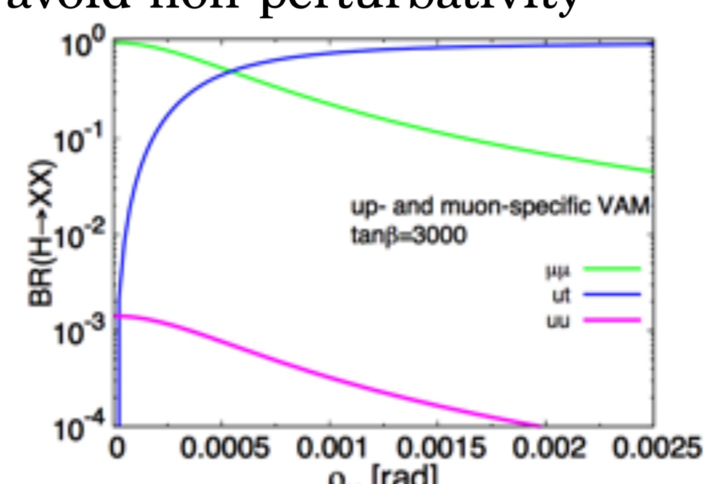
VAM is essentially just a 2HDM with various PQ charge assignments (only one q_R PQ charged)

- 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

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 $m_A \sim 15\text{GeV}$, $\tan\beta \sim 40$

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 the signatures of this model.