top FCNC and axion

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based on JHEP11(2015)057 [arXiv:1507.04354],PhysRevD.97.035015 [arXiv:1711.02993], arxiv:1806.XXXX

at Benasque on 30th May 2018

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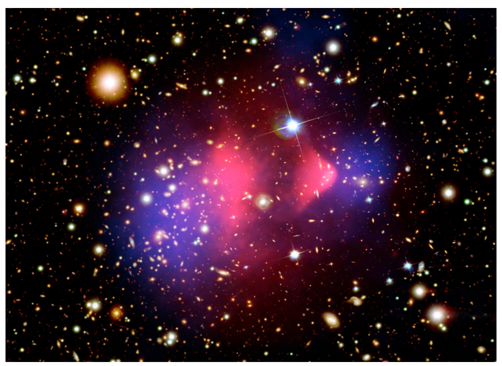
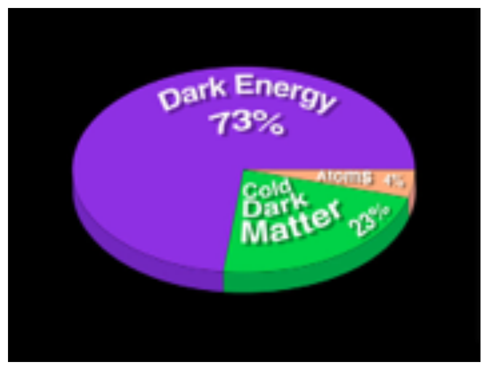
Two big problems in particle physics

Existence of DM (serious problem)

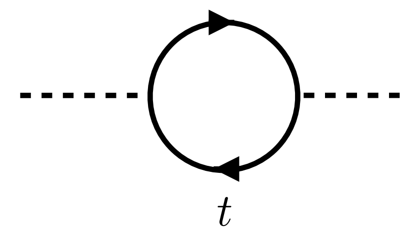




Naturalness (Fine tuning in Higgs sector)

$$m^2_{h,\text{phys}} = m^2_{h,\text{tree}} + \delta m^2_h \sim 125^2\text{GeV}^2 \sim 10^4\text{GeV}^2$$

$\delta m_h^2 \sim$

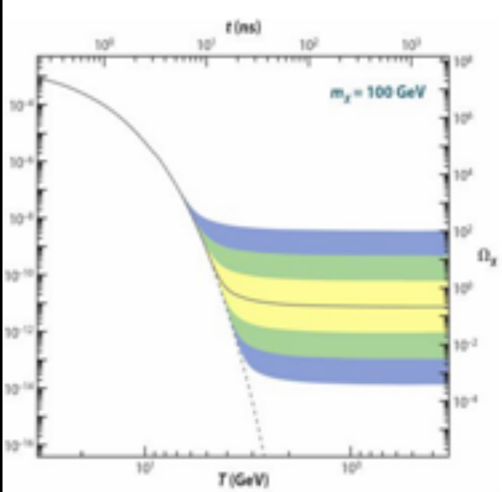


$$\sim -\frac{3}{4\pi} y_t^2 \Lambda_{\text{SM}}^2$$

$$\sim 10^{38}\text{GeV}^2 (\Lambda_{\text{SM}} = M_{\text{Planck}})$$

$$\sim 10^6\text{GeV}^2 (\Lambda_{\text{SM}} = 1\text{TeV})$$

Weak scale SUSY, or TeV scale SUSY elegantly solve both problems



WIMP miracle

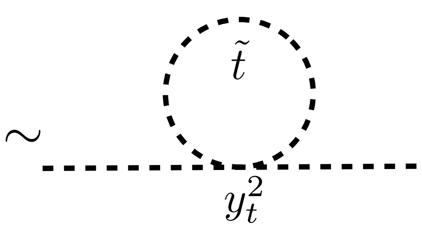
$$\Omega_X \propto \frac{1}{\langle\sigma v\rangle} \sim \frac{m_X^2}{\alpha^2} \sim 10^9\text{GeV}^2$$

neutralino DM

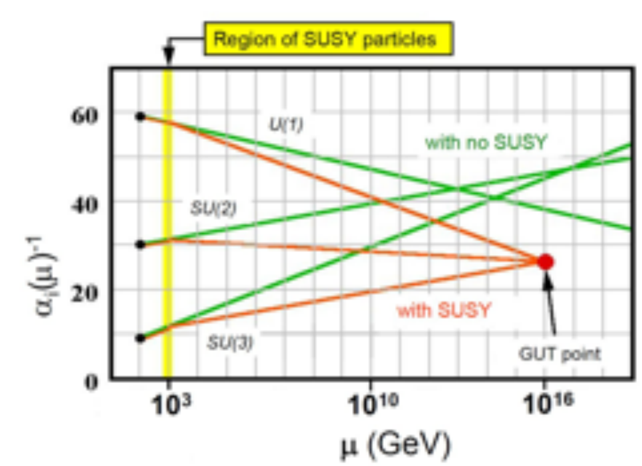
perfect WIMP DM

new partner particle, same coupling by symmetry

$\delta m_h^2 \sim$



$$\sim +\frac{3}{4\pi} y_t^2 \Lambda^2$$



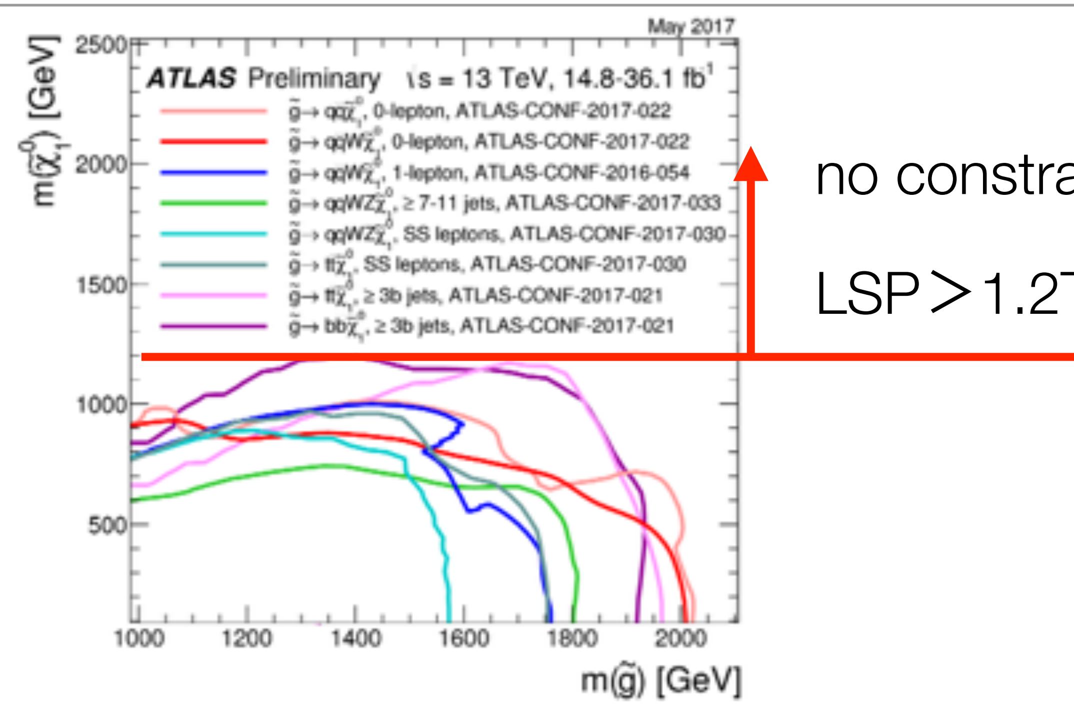
gauge coupling unification also suggests new states at TeV

SUSY would be the most attractive candidate

SUSY search results at LHC 13TeV with ~ 36 fb-1

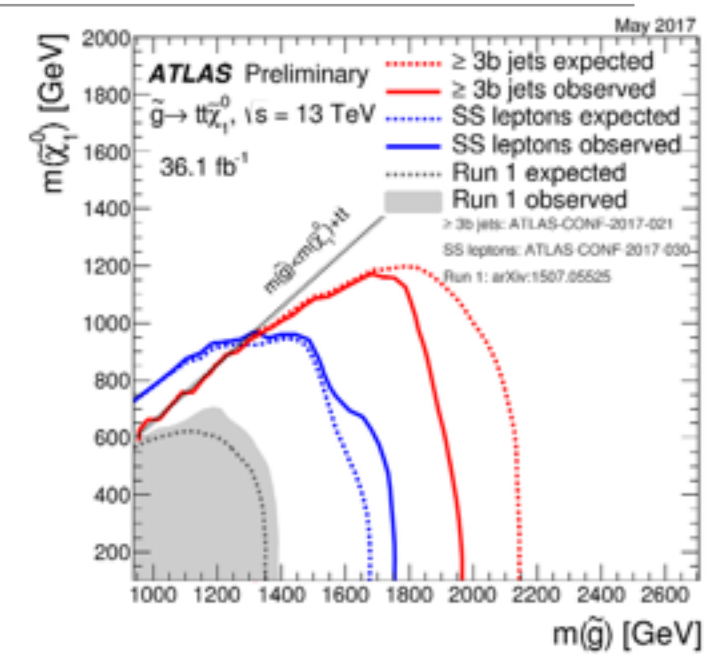
For massless LSP

~2 TeV gluino excluded

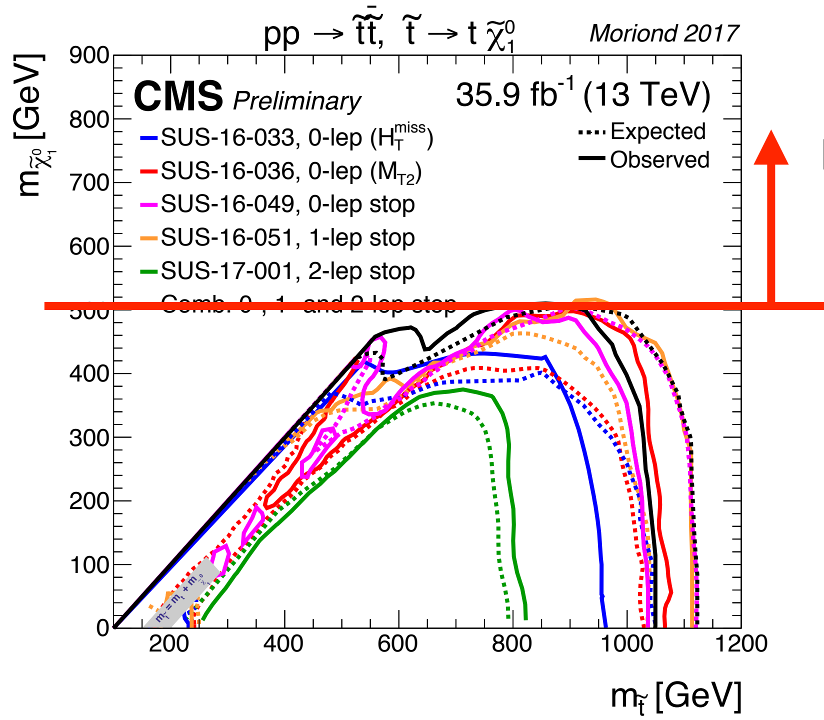


no constraint

LSP＞1.2TeV

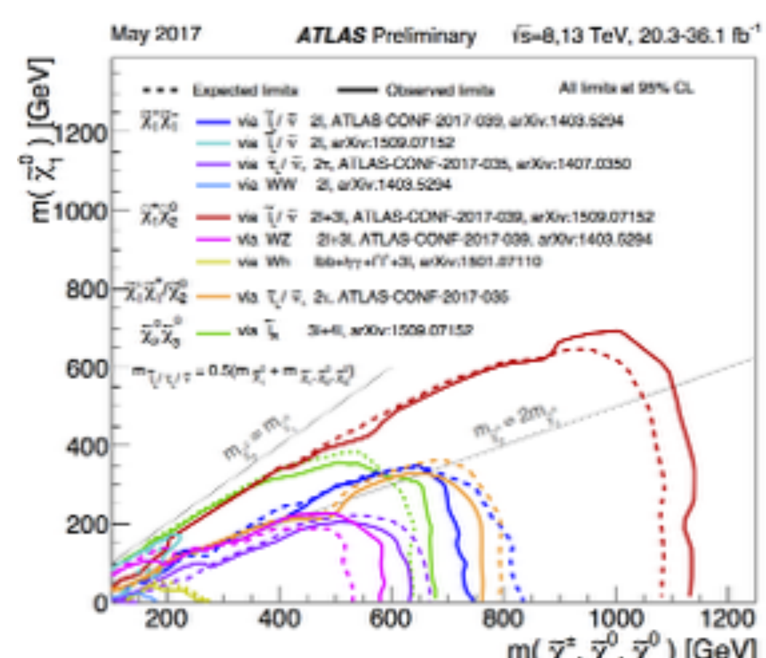


~1 TeV stop excluded



no constraint

LSP>500GeV

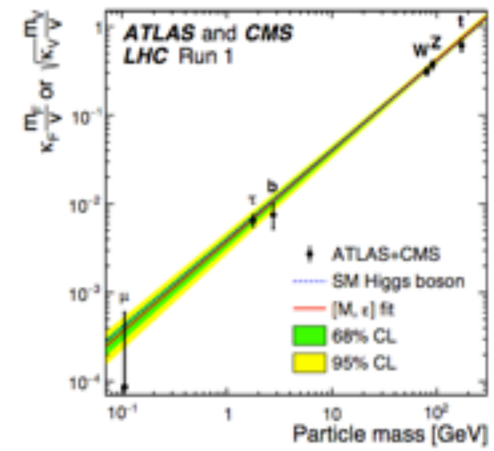


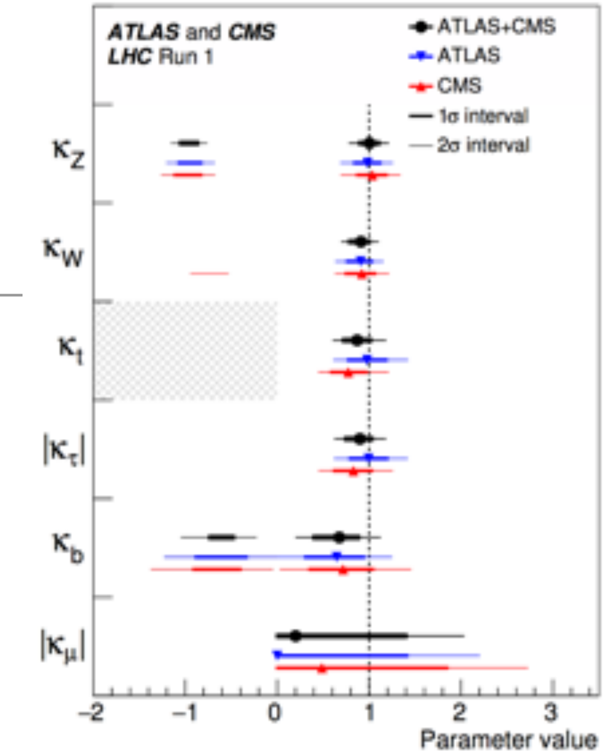
when LSP is heavy enough no constraints we can set.

~600 GeV EWkino (W/Z) excluded
(highly depends on BR)

SM Higgs, no evidence of heavy higgses

Higgs couplings: consistent to SM Higgs at 10-20%

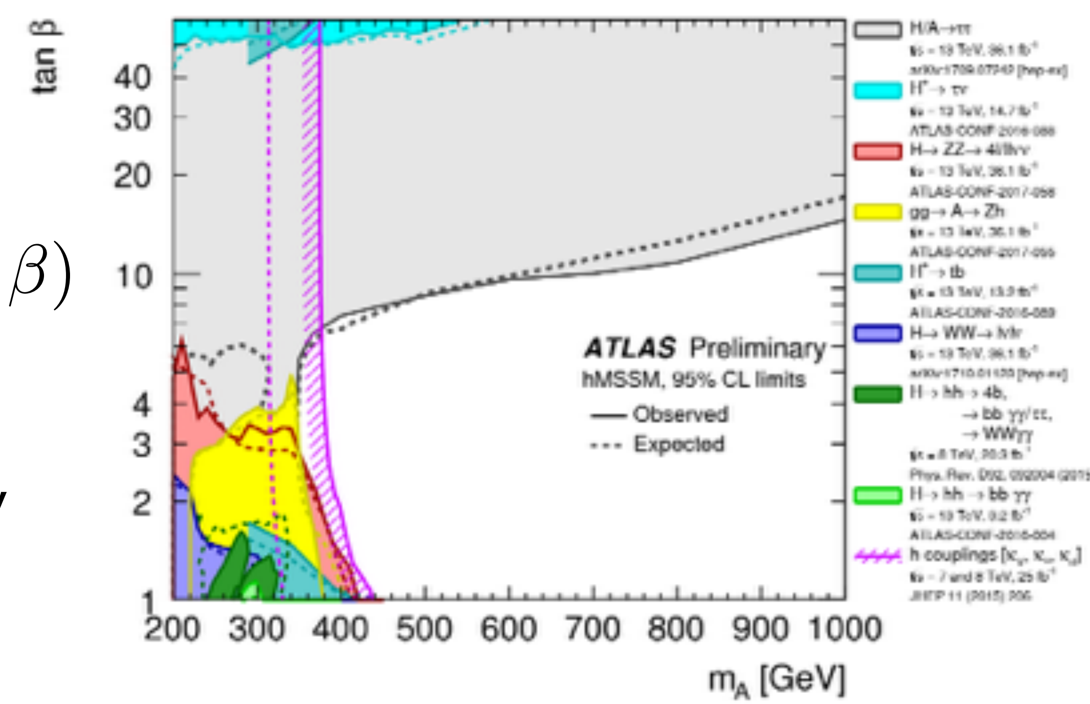




MSSM can realize it in decoupling limit
and enough room for 10-20% deviations

Heavy higgs searches

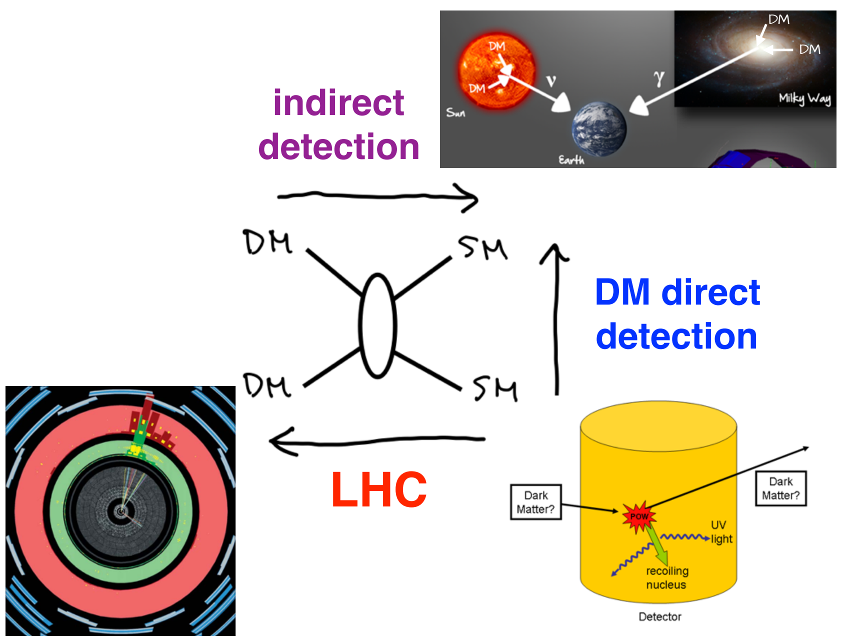
For large tan β, $A \to \tau\tau$ dominates

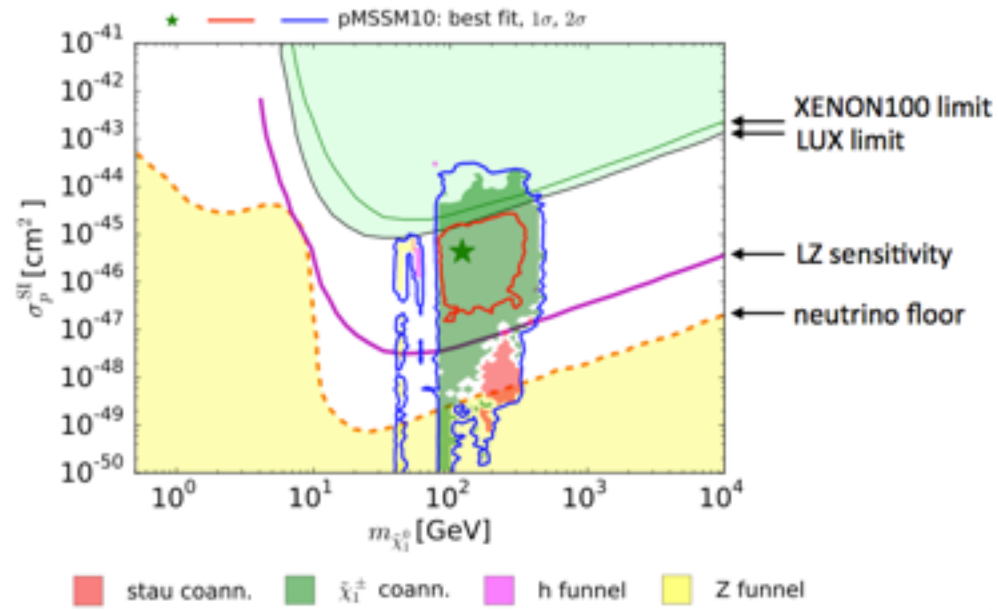


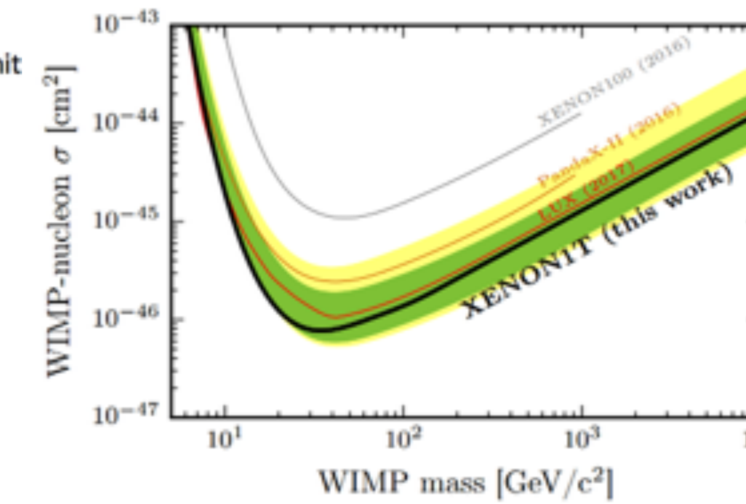
MSSM Higgs sector : parametrized by $(m_A, \tan\beta)$
not like in a general 2HDM

→ Light higgs coupling measurements already constrain $m_A \gtrsim 400\mathrm{GeV}$

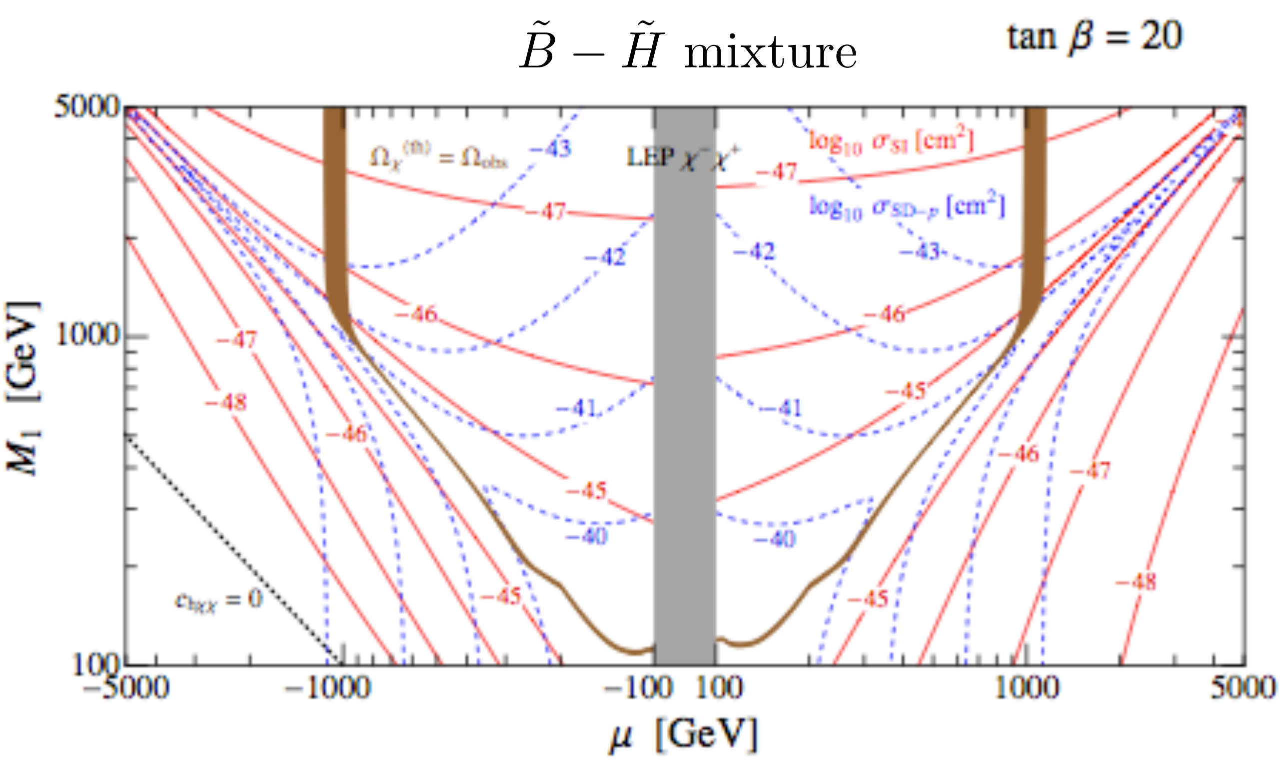
Null results from DM Direct Detection experiments







$$\sigma_{SI} < 10^{-45} \sim 10^{-46} \mathrm{cm}^2$$



Typically, spin independent cross section in MSSM

$$10^{-44} \sim 10^{-47} \mathrm{cm}^2$$

not all excluded, remaining parameter space mainly

pure states, blind spots, co-annihilation

XENON1T starts to find something?

No signature of SUSY anywhere yet

no evidence of SUSY anywhere: Higgs measurement, Direct-Detection…

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

why attractive: can solve DM and the fine tuning problem

Another fine tuning problem: 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 -> 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 $|d_n| = 4.5 \times 10^{-15} \theta_{\rm eff} e{\rm cm}$

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

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

while the origin of θ and arg M is completely different

Fine tuning problem

Peccei-Quinn mechanism

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

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

1. introduce a field a, axion.
2. assuming axial U(1) sym. which is spontaneously broken at η above QCD scale
3. impose appropriate PQ charges into quarks so that there exists $\mathrm{U}(1)_{PQ}$-$\mathrm{SU}(3)$-$\mathrm{SU}(3)$ anomaly

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

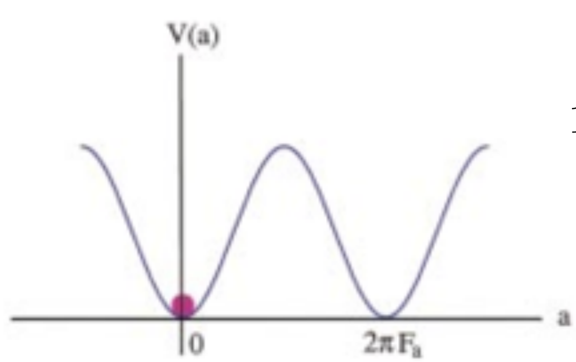
$\frac{a}{\eta} \to \frac{a}{\eta} + \epsilon$ induces $\delta\mathcal{L} = -\frac{g^2}{32\pi^2}\epsilon A G^{a\mu\nu}\tilde{G}^a_{\mu\nu}$, induce the potential in the effective lagrangian

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

$$F_a = \eta / A$$

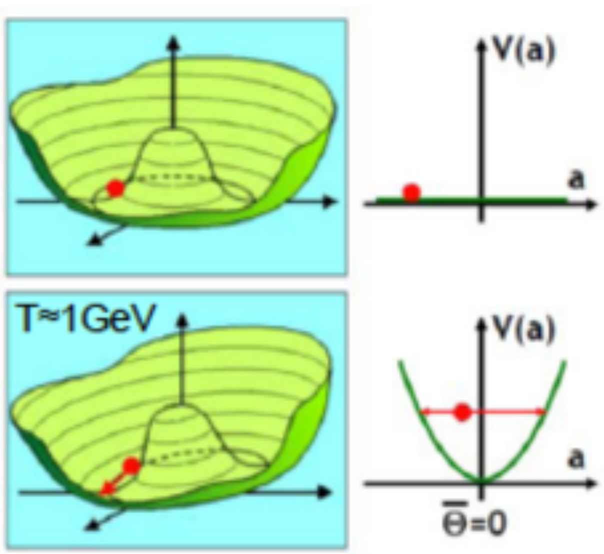
From the effective Lagrangian, effective potential to axion field can be computed.

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



$1 - \cos(\frac{a}{F_a} - \bar{\theta})$

$a + (\theta_{\mathrm{stong}} + \theta_{\mathrm{EM}})F_a$



Invisible Axions

axion mass

$$m_a = \frac{\sqrt{z}}{1+z}\frac{f_\pi m_\pi}{F_a} \simeq 6\mu\text{eV}\frac{10^{12}\text{GeV}}{F_a}$$

photon coupling

$$\mathcal{L} = -\frac{g_{a\gamma\gamma}}{4} a F^{\mu\nu}\tilde{F}_{\mu\nu}$$

$$g_{a\gamma\gamma} = \frac{\alpha}{\pi}\frac{g_\gamma}{F_a}$$

$g_\gamma = 0.97(\text{KSVZ}), -0.36(\text{DFSZ})$

Original axion model soon ruled out as axion is visible $\eta \sim v_{EW}$

people realized, η can be very high scale

$U(1)_{\text{PQ}}$:
$\Phi \to e^{i\epsilon}\Phi.$

$$V(\Phi) = \frac{\lambda}{4}(|\Phi|^2 - \eta^2)^2,$$

currently viable set up is categorized into two types

invisible axion model (KSVZ; Kim 1979, Shifman, Vainshtein, Zakharov 1980)

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

invisible axion model (ZDFS; Zhitnitsky1980, Dine, Fischler, Srednicki 1981)

$$\begin{aligned} V(\Phi_1,\Phi_2,\sigma) = {} & \lambda_1\left(|\Phi_1|^2 - \frac{v_1^2}{2}\right)^2 + \lambda_2\left(|\Phi_2|^2 - \frac{v_2^2}{2}\right)^2 + \lambda\left(|\sigma|^2 - \frac{v^2}{2}\right)^2 \\ & + a\,|\Phi_1|^2|\sigma|^2 + b\,|\Phi_2|^2|\sigma|^2 + \left(m\,\Phi_1^\dagger\Phi_2\sigma + \text{h.c.}\right) \\ & + d\,|\Phi_1^\dagger\Phi_2|^2 + e\,|\Phi_1|^2\,|\Phi_2|^2 . \end{aligned}$$

Here, $\sigma = \Phi$

$U(1)_{\text{PQ}}$:

$$\varphi_1 \to e^{-i\epsilon}\varphi_1, \quad \varphi_2 \to e^{-i\epsilon}\varphi_2,$$
$$u_L \to u_L, \quad u_R \to e^{+i\epsilon}u_R,$$
$$d_L \to d_L, \quad d_R \to e^{+i\epsilon}d_R,$$

light quarks couples to either of φ through Yukawa couplings

No need to introduce new quarks

Axion as dark matter

Historically, axion not considered as a DM candidate

Original model axion is "visible" and soon ruled out

[T. Donnelly, S. Freedman, R. Lytel, R. Peccei and M. Schwartz, Phys.Rev. D18 (1978) 1607.]

invisible axions ~ 1/f_a

[J. E. Kim, Phys.Rev.Lett. 43 (1979) 103.]
[M. A. Shifman, A. Vainshtein and V. I. Zakharov, Nucl.Phys. B166 (1980) 493]
[M. Dine, W. Fischler and M. Srednicki, Phys.Lett. B104 (1981) 199]
[A. Zhitnitsky, Sov.J.Nucl.Phys. 31 (1980) 260]

invisibleness -> DM candidate! (coherent oscillation)

while extremely light, non-thermal production make them non-relativistic

-> Cold DM (consistent to structure formation)

[J. Preskill, M. B. Wise and F. Wilczek, Phys.Lett. B120 (1983) 127–132.]
[L. Abbott and P. Sikivie, Phys.Lett. B120 (1983) 133–136.]
[M. Dine and W. Fischler, Phys.Lett. B120 (1983) 137–141.]

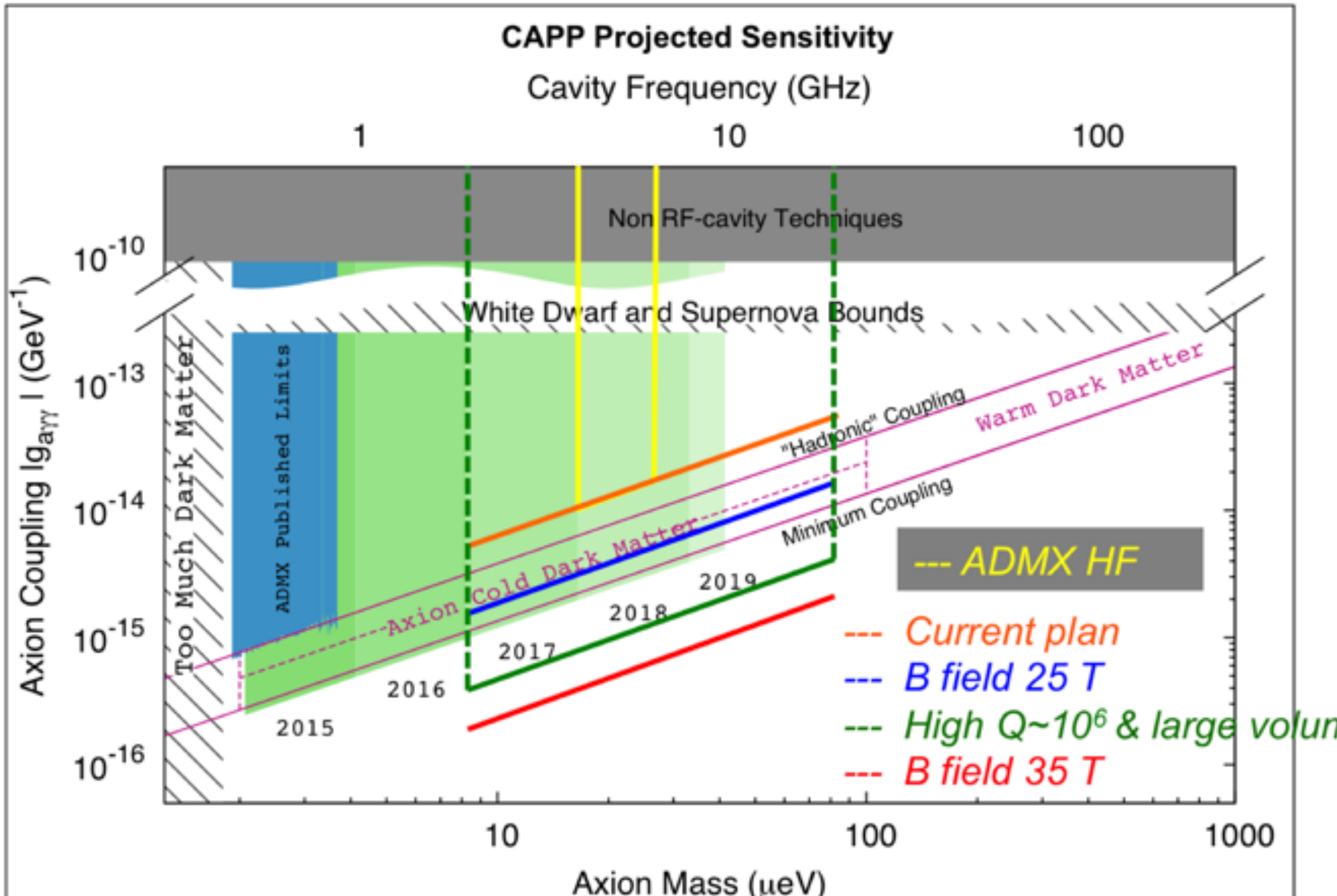
$$\Omega_{a,0}h^2 = 0.095 \times (\bar{\theta}^{\rm ini})^2 \left(\frac{g_{*,1}}{70}\right)^{-(n+2)/2(n+4)} \left(\frac{F_a}{10^{12}{\rm GeV}}\right)^{(n+6)/(n+4)} \left(\frac{\Lambda_{\rm QCD}}{400{\rm MeV}}\right).$$

$F_a < 10^{12}{\rm GeV}$ ⟷ $m_a > 1\mu{\rm eV}$

Current Axion DM searches

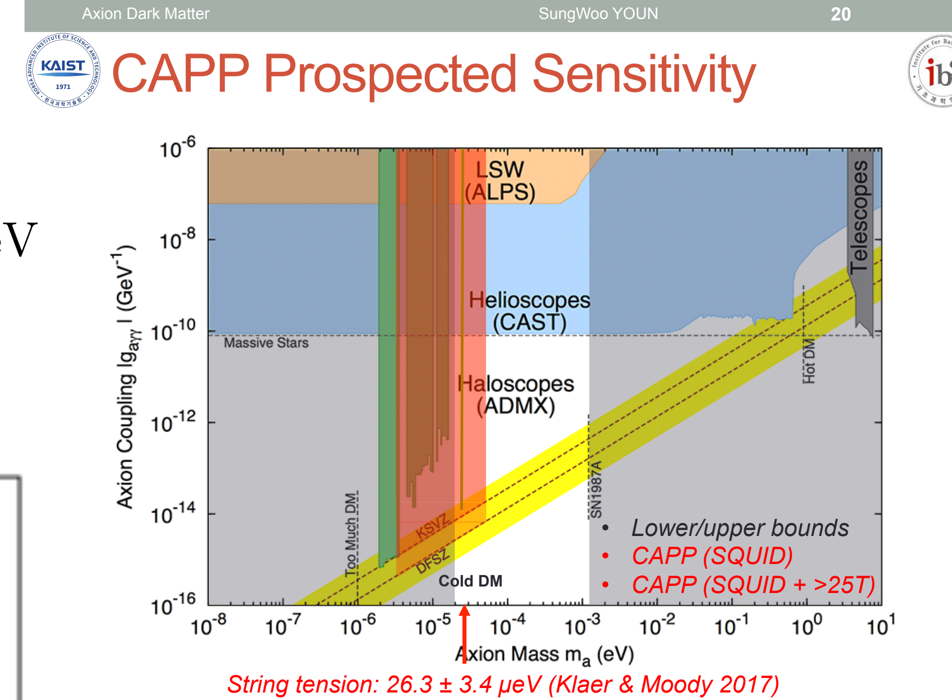
Axion DM abondance $F_a < 10^{12}\mathrm{GeV} \leftrightarrow m_a > 1\mu\mathrm{eV}$

$$\Omega_{a,0}h^2 = 0.095 \times (\bar{\theta}^{\rm ini})^2 \left(\frac{g_{*,1}}{70}\right)^{-(n+2)/2(n+4)} \left(\frac{F_a}{10^{12}\mathrm{GeV}}\right)^{(n+6)/(n+4)} \left(\frac{\Lambda_{\rm QCD}}{400\mathrm{MeV}}\right).$$



Int.J.Mod.Phys.Conf.Ser. 43 (2016) 1660193

Fig. 4. Projected sensitivities by CAPP/IBS for the axion coupling versus its mass (frequency) for different scenarios represented by lines in different colors. The blue area corresponds to the published exclusion region by ADMX,[12] while the green areas with different contrasts are the projected sensitivities by ADMX for the next 5 years. The yellow lines represent the limits expected by the ADMX-HF.



Scanning rate:

$$\frac{df}{dt} = \frac{f}{Q}\frac{1}{t} \sim \frac{1\,\mathrm{GHz}}{\mathrm{year}}\left(g_{a\gamma\gamma}10^{15}\mathrm{GeV}\right)^4\left(\frac{5\,\mathrm{GHz}}{f}\right)^2\left(\frac{4}{SNR}\right)^2\left(\frac{0.25\,\mathrm{K}}{T}\right)^2\left(\frac{B}{25\,T}\right)^4\left(\frac{c}{0.6}\right)^2\left(\frac{V}{5\,l}\right)^2\left(\frac{Q}{10^5}\right)$$

CAPP/IBS axion target plan

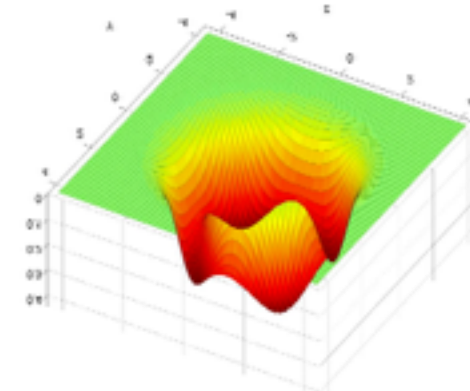
- Major improvement elements:
  - High field solenoid magnets, B: 9T→25T→40T
  - High volume magnets/cavities, V: 5*l*→50*l*
  - High quality factor of cavity, Q: $10^5 \rightarrow 10^6$
  - Low noise amplifiers, T_N: 2K→0.25K
  - Low physical temperature, T_{ph}: 1K→0.1K

Scanning rate improvement: 25×10^6
Improvement in coupling constant: 70

ibs CAPP director:
Prof. Yannis Semertzidis's talk

interesting region for DM covered in 5 years

Domain wall problem



$$U(1)_{PQ} \to Z_N, \quad N = |\sum_i^{N_g}(2q_i + u_i + d_i)|$$ number of PQ charged quarks

QCD instanton effects give an axion a potential of the form $1 - \cos(aN/\eta)$ and minimizing it gives $< a >= \theta_{\text{eff}} = 0$.

So as $< a >= \frac{2\pi n}{N}\eta \ (n = 0, \ldots, N-1)$

for invisible axion model (KSVZ model) $N_{DM} = 1$

a periodic in 2πη ⇔ θ periodic in 2πη/N

for invisible axion model (ZDFS model)

$$V(\Phi_1, \Phi_2, \sigma) = \lambda_1 \left(|\Phi_1|^2 - \frac{v_1^2}{2}\right)^2 + \lambda_2 \left(|\Phi_2|^2 - \frac{v_2^2}{2}\right)^2 + \lambda \left(|\sigma|^2 - \frac{v^2}{2}\right)^2$$
$$+a\,|\Phi_1|^2|\sigma|^2 + b\,|\Phi_2|^2|\sigma|^2 + \left(m\,\Phi_1^\dagger\Phi_2\sigma + \text{h.c.}\right)$$
$$+d\,|\Phi_1^\dagger\Phi_2|^2 + e\,|\Phi_1|^2\,|\Phi_2|^2\,.$$

$$N_{DW} = \left|\frac{N}{h_1 + h_2}\right| = N_g$$

[C.Q. Geng, J. N. Ng, PhysRevD.41.3848]

$N_g = 1$ is free from domain wall problem.

only 1 quark couples with PQ-charged Higgs solves the domain wall problem

Variant Axion model PQ charges: $u_3 = -1, h_2 = -1, \sigma = 1$

[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

rapid progress in axion DM searches

↓

invisible axion models

KSVZ $N_{DM} = 1$

heavy Q introduced
no problem but no low energy phenomenology
(not interesting)

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

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

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

but suffer from Domain wall problem

↓

$N_{DM} = 1$

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

top-specific Variant Axion model

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

$$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right)$$

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

Φ_2 only couple with u_{R3}

other quarks only couples with Φ_1

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

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

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

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

when we take top as the special one,

top FCNC is the prediction

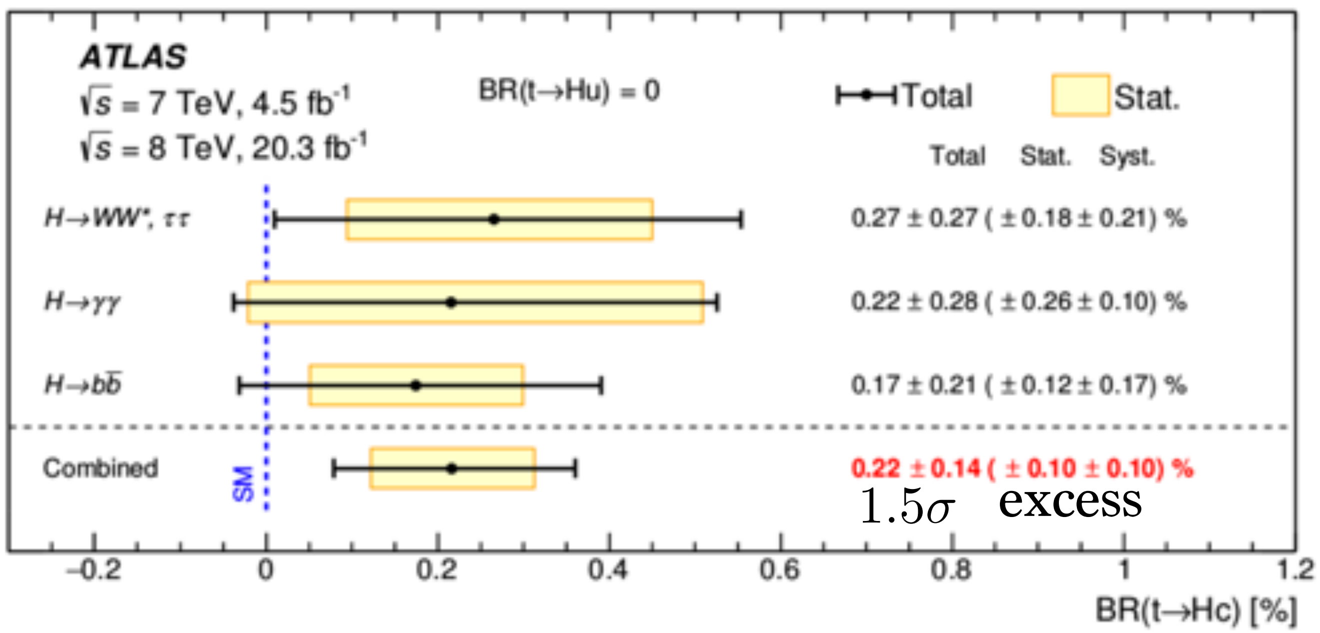
third gen. is identical to type II

top-specific Variant Axion model

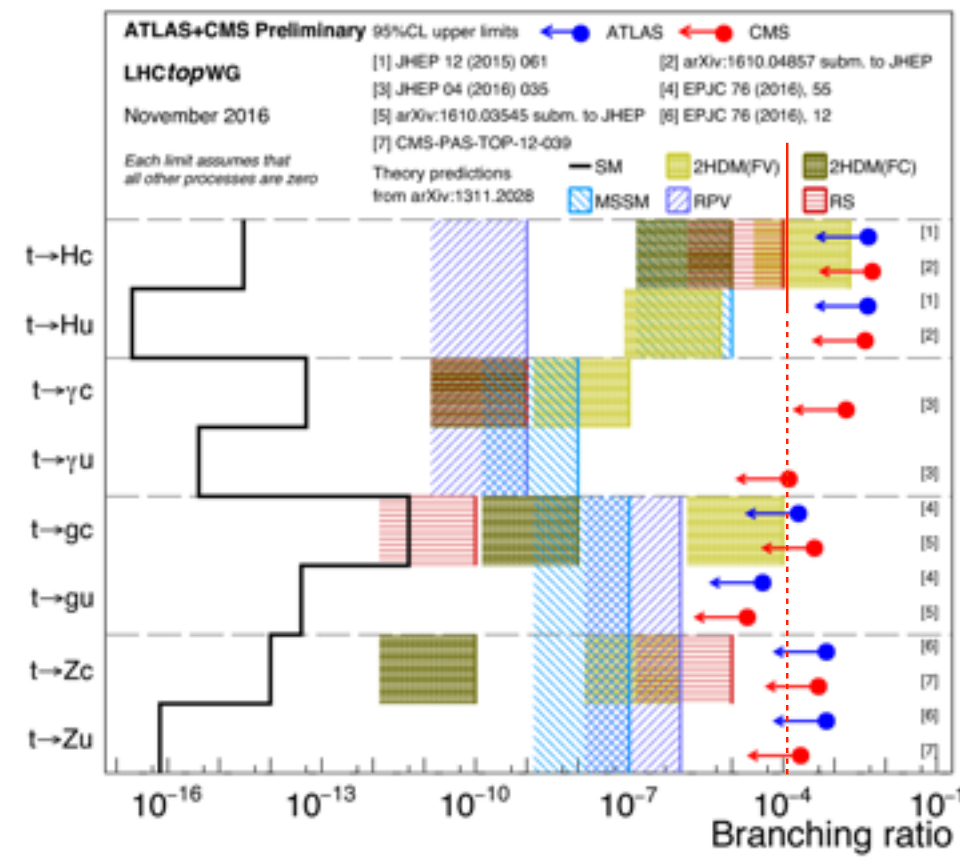
top FCNC is the prediction

$$BR(t \to ch) = 0.22 \pm 0.14\%$$

ATLAS 8TeV [JHEP 1512, 061 (2015)]



13 TeV ATLAS result set BR<0.22%



no hope for MSSM, FC 2HDM

Experimentalists can cite our model
as a well motivated model to predict t → ch

	Φ_1	Φ_2	t_R	c_R	u_R	d_R	ℓ_R	Q_L	L_L	top FCNC is the prediction
top-specific VA Model	$+$	$-$	$-$	$+$	$+$	$+$	$+$	$+$	$+$	third gen. is identical to type II

top-specific Variant Axion model

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

Φ_2 only couple with u_{R3}

other quarks only couples with Φ_1

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

in the Higgs basis

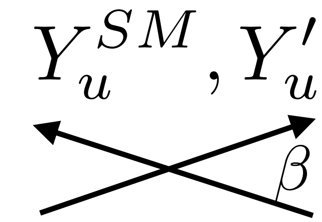
$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} = R_\beta \begin{pmatrix} \Phi^{\rm SM} \\ \Phi' \end{pmatrix} \ , \text{ with } R_\theta = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \ , \quad (1)$$

$$\text{with } \ \Phi^{\rm SM} = \begin{pmatrix} G^+ \\ (v_{\rm SM} + h^{\rm SM} + iG^0)/\sqrt{2} \end{pmatrix} \ , \ \Phi' = \begin{pmatrix} H^+ \\ (h' + iA^0)/\sqrt{2} \end{pmatrix} \ , \quad (2)$$

$$\begin{pmatrix} H \\ h \end{pmatrix} = R_{\beta-\alpha} \begin{pmatrix} h^{\rm SM} \\ h' \end{pmatrix}$$

$$Y_u^{\rm SM} = \cos\beta Y_{u1} + \sin\beta Y_{u2} \ , \quad Y_u' = -\sin\beta Y_{u1} + \cos\beta Y_{u2} = \begin{pmatrix} -\tan\beta & & \\ & -\tan\beta & \\ & & \cot\beta \end{pmatrix} Y_u^{SM} \ .$$

top-specific 2HDM



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

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

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

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

using $\begin{pmatrix} H \\ h \end{pmatrix} = R_{\beta-\alpha} \begin{pmatrix} h^{\text{SM}} \\ h' \end{pmatrix}$

$$\xi_f \equiv \begin{cases} \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha) & (\text{for } f = t) \\ \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha) & (\text{for } f \neq t) \end{cases}$$

as usual in 2HDM

$$\mathcal{L}_Y \equiv - \sum_{f=e,\cdots,u,\cdots,d,\cdots} \xi_f \frac{m_f}{v_{\text{SM}}} h \overline{f} f + \mathcal{L}_{\text{FCNC}}$$

with $\mathcal{L}_{\text{FCNC}} = -a \sum_{f,f'=u,c,t} (H_u)_{ff'} \frac{m_{f'}}{v_{\text{SM}}} h \overline{f}_R f'_L + \text{h.c.}$

$$a \equiv (\tan\beta + \cot\beta)\cos(\beta - \alpha) \ .$$

FC effect proportional to a and m_{f_L}

prediction in VA

Large

$$\mathcal{L}_{tc} = -\frac{a}{2v_{\text{SM}}} h \begin{pmatrix} \bar{c}_R & \bar{t}_R \end{pmatrix} \begin{pmatrix} m_c(1-\cos\rho) & m_t \sin\rho \\ m_c \sin\rho & m_t(\cos\rho - 1) \end{pmatrix} \begin{pmatrix} c_L \\ t_L \end{pmatrix} + \text{h.c.}$$

Small

top FC decay $t \to ch$

Large

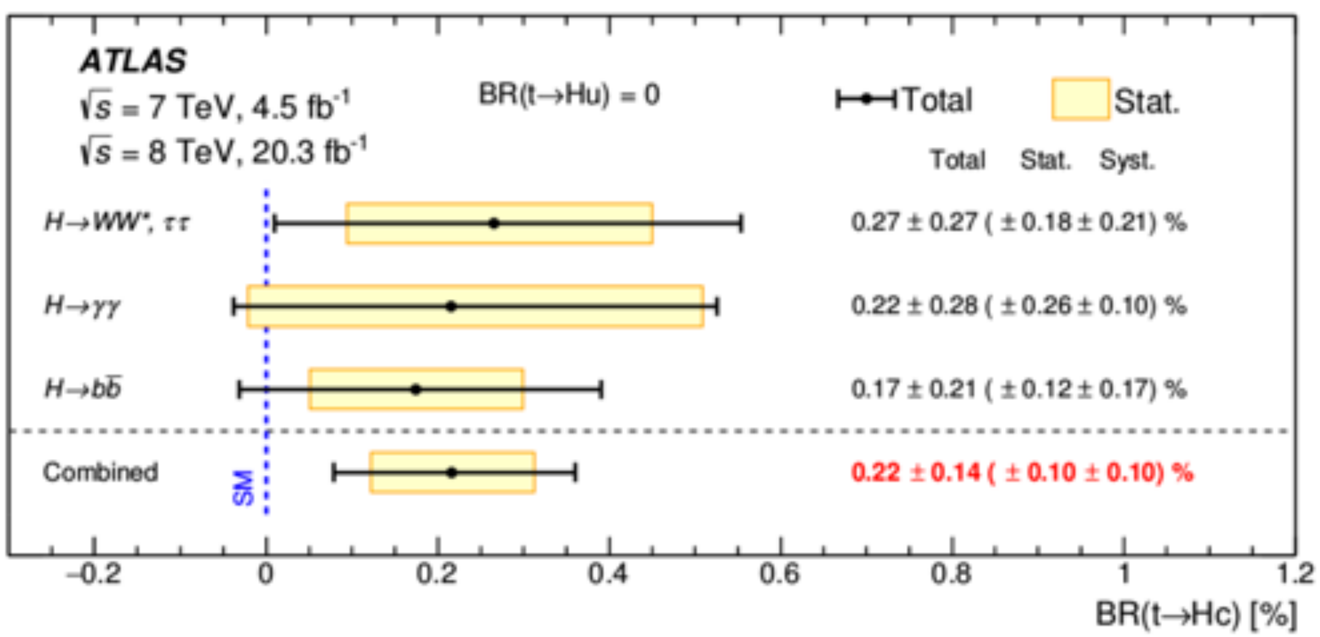
$$\mathcal{L}_{tc} = -\frac{a}{2v_{\rm SM}} h \left(\bar{c}_R \quad \bar{t}_R\right) \begin{pmatrix} m_c(1-\cos\rho) & m_t \sin\rho \\ m_c \sin\rho & m_t(\cos\rho - 1) \end{pmatrix} \begin{pmatrix} c_L \\ t_L \end{pmatrix} + \text{h.c.}$$

$\rho = 0 \to$ no FCNC

Small

$$\mathrm{BR}(t \to ch) = \frac{(1-r_h^2)^2}{8(1-r_W^2)^2(1+2r_W^2)|V_{tb}|^2} a^2 \sin^2\rho \simeq (3.24 \times 10^{-2}) a^2 \sin^2\rho \ .$$

$BR(t \to ch) = 0.22 \pm 0.14\%$ ATLAS 8TeV [JHEP 1512, 061 (2015)] 1.5σ excess



13 TeV ATLAS BR<0.22% merginal

$$a^2 \sin^2\rho = 0.068$$

future exp. 2×10^{-4} (3000 fb^{-1} at 14 TeV) with $h \to \gamma\gamma$

can be improved compared with N(top) ~10^10 for a whole LHC lifetime?

Higgs global fit (with latest data)

model parameter: tanβ, cos(β-α), ρ

	$\gamma\gamma$	ZZ	WW	$\tau\tau$	bb
$\mathrm{ggF}^{7,8\mathrm{TeV}}$	$1.10^{+0.23}_{-0.22}$	$1.13^{+0.34}_{-0.31}$	0.84 ± 0.17	1.0 ± 0.6	–
$\mathrm{ggF}^{13\mathrm{TeV}}_{\mathrm{ATLAS}}$	$0.8^{+0.19}_{-0.18}$ [54]	1.11 ± 0.245 [53]	–	–	–
$\mathrm{ggF}^{13\mathrm{TeV}}_{\mathrm{CMS}}$	$1.11^{+0.19}_{-0.18}$ [51]	$1.20^{+0.22}_{-0.21}$ [49]	$0.9^{+0.4}_{-0.3}$ [65]	$1.17^{+0.47}_{-0.40}$ [66]	$2.3^{+1.8}_{-1.6}$ [68]
$\mathrm{VBF}^{7,8\mathrm{TeV}}$	1.3 ± 0.5	$0.1^{+1.1}_{-0.6}$	1.2 ± 0.4	1.3 ± 0.4	–
$\mathrm{VBF}^{13\mathrm{TeV}}_{\mathrm{ATLAS}}$	2.1 ± 0.6 [54]	4.0 ± 1.77 [53]	$3.2^{+4.4}_{-4.2}$ [59]	–	$-3.9^{+2.8}_{-2.7}$ [61]
$\mathrm{VBF}^{13\mathrm{TeV}}_{\mathrm{CMS}}$	$0.54^{+0.6}_{-0.5}$ [51]	$0.06^{+1.03}_{-0.06}$ [49]	1.4 ± 0.8 [65]	$1.11^{+0.34}_{-0.35}$ [66]	$-3.7^{+2.4}_{-2.5}$ [62]
$\mathrm{VH}^{7,8\mathrm{TeV}}$	0.5 ± 1.1	–	2.3 ± 1.0	-0.2 ± 1.1	0.63 ± 0.3
$\mathrm{VH}^{13\mathrm{TeV}}_{\mathrm{ATLAS}}$	$0.7^{+0.9}_{-0.8}$ [54]	< 3.8 [53]	$1.7^{+1.1}_{-0.9}$ [59]	–	$1.20^{+0.42}_{-0.36}$ [55]
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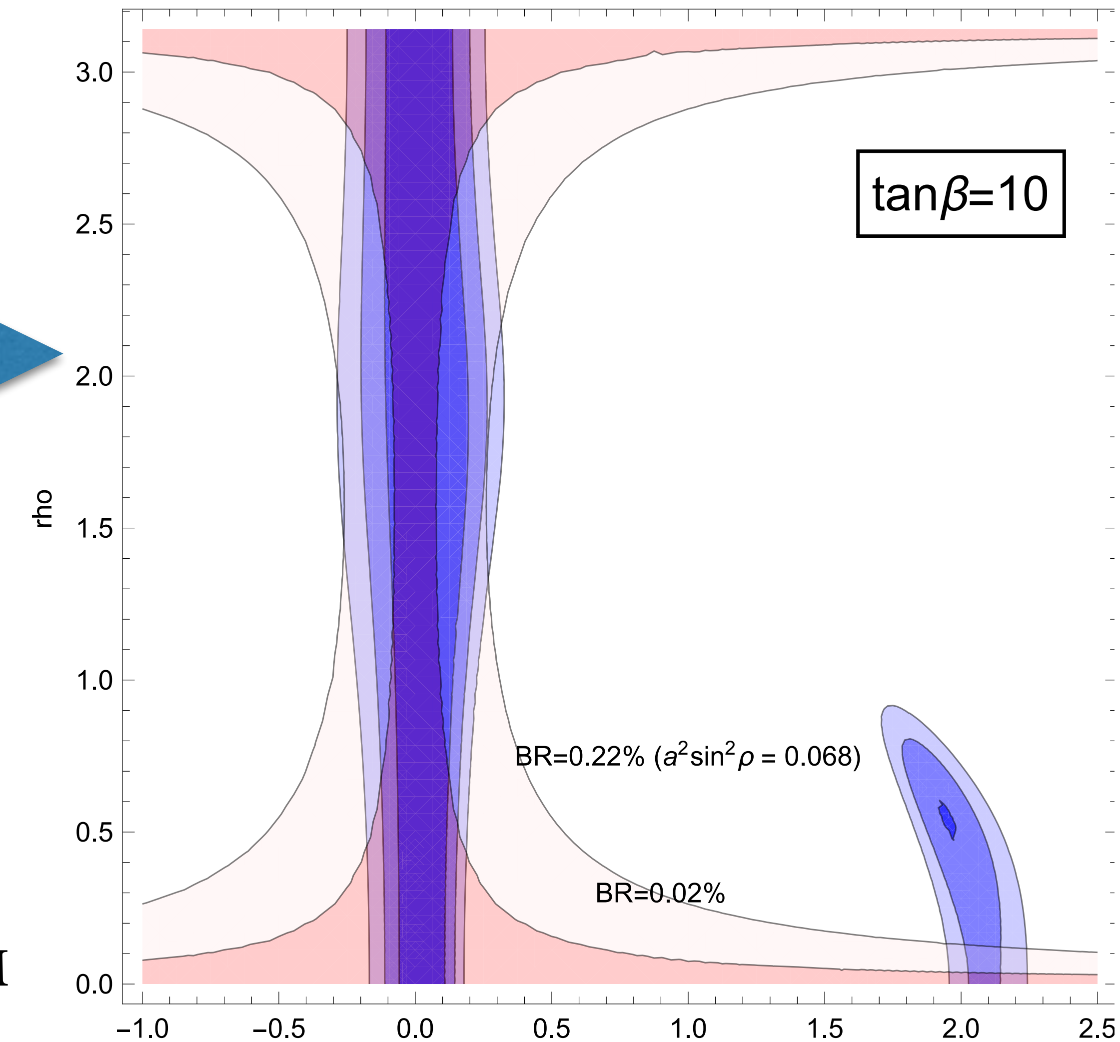
$ttH^{7,8\mathrm{TeV}}$	$2.2^{+1.6}_{-1.3}$	–	$5.0^{+1.8}_{-1.7}$	$-1.9^{+3.7}_{-3.3}$	1.1 ± 1.0
$ttH^{13\mathrm{TeV}}_{\mathrm{ATLAS}}$	0.5 ± 0.6 [54]	(WW)	$2.5^{+1.3}_{-1.1}$ [56]	(WW)	$2.1^{+1.0}_{-0.9}$ [56]
$ttH^{13\mathrm{TeV}}_{\mathrm{CMS}}$	$2.22^{+0.9}_{-0.8}$ [51]	(WW)	1.5 ± 0.5 [67]	$0.72^{+0.62}_{-0.53}$ [64]	-0.19 ± 0.80 [63]

blue：Higgs data, red: t → ch



$a \equiv (\tan\beta + \cot\beta)\cos(\beta - \alpha)$.

for ρ=0, 3rd gen is identical to type2 THDM

$$\xi_f = \begin{cases} \sin(\beta-\alpha) + \left(\cot\beta - \frac{1-\cos\rho}{2}(\tan\beta+\cot\beta)\right)\cos(\beta-\alpha) & (\text{for } f=t)\ , \\ \sin(\beta-\alpha) - \left(\tan\beta - \frac{1-\cos\rho}{2}(\tan\beta+\cot\beta)\right)\cos(\beta-\alpha) & (\text{for } f=c)\ , \\ \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha) & (\text{for the others})\ . \end{cases}$$

$$\mathcal{L}_{tc} = -\frac{a}{2v_{\mathrm{SM}}} h \begin{pmatrix} \bar{c}_R & \bar{t}_R \end{pmatrix} \begin{pmatrix} m_c(1-\cos\rho) & m_t\sin\rho \\ m_c\sin\rho & m_t(\cos\rho - 1) \end{pmatrix} \begin{pmatrix} c_L \\ t_L \end{pmatrix} + \mathrm{h.c.}$$

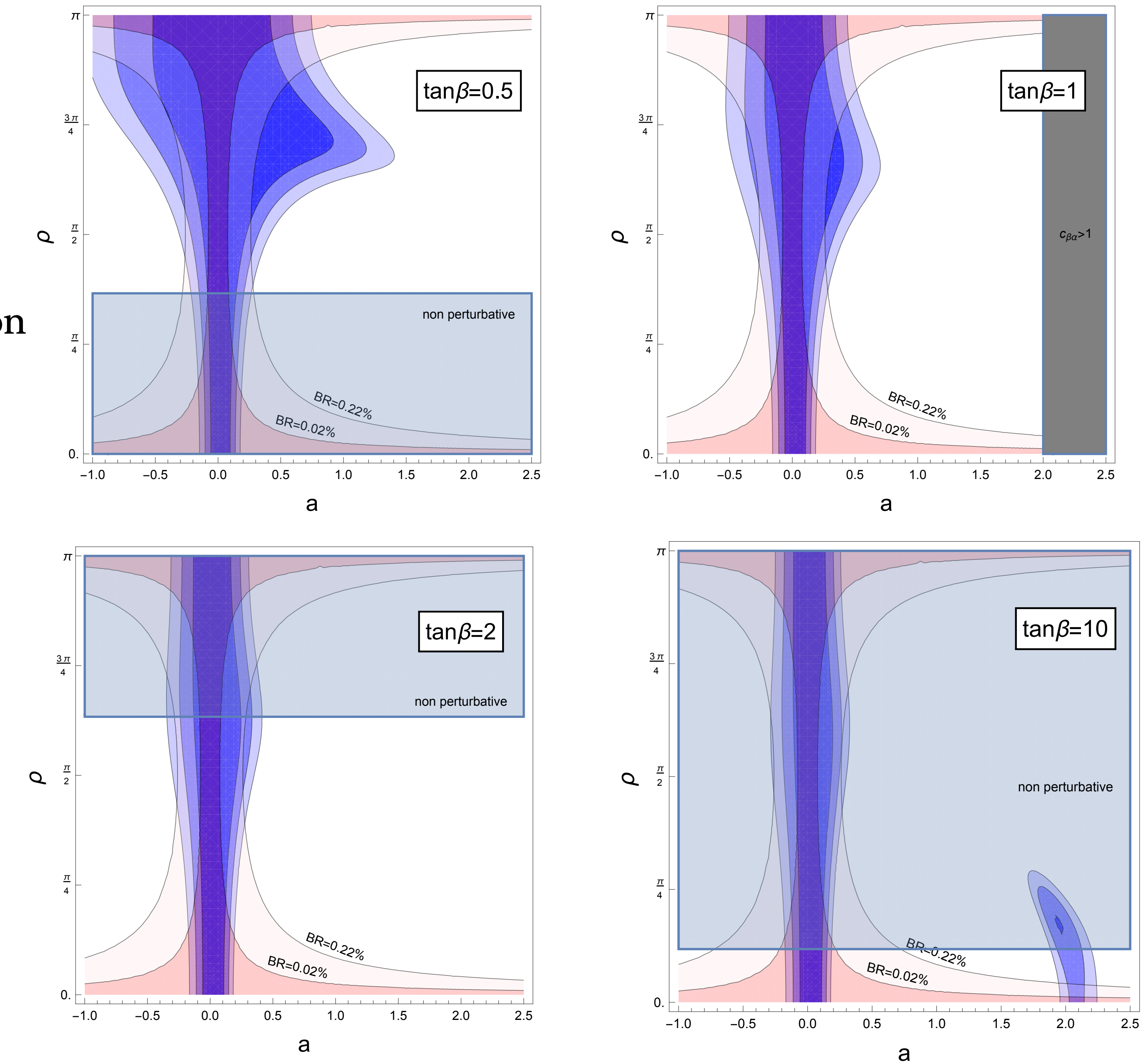
tan beta dependence

$$a \equiv (\tan\beta + \cot\beta)\cos(\beta - \alpha)\ .$$

low tan beta provide broader parameter region consistent with Higgs data

mainly by the condition $\xi_t/\xi_b = 1$

upper bound on tan beta
assuming BR=0.22%
and consistent with Higgs data



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helicity structure in top FC decay

$t \to ch$

Large

$$\mathcal{L}_{tc} = -\frac{a}{2v_{\rm SM}} h \begin{pmatrix} \bar{c}_R & \bar{t}_R \end{pmatrix} \begin{pmatrix} m_c(1-\cos\rho) & m_t \sin\rho \\ m_c \sin\rho & m_t(\cos\rho - 1) \end{pmatrix} \begin{pmatrix} c_L \\ t_L \end{pmatrix} + \text{h.c.}$$

Small

$h\bar{c}_R t_L$: always c_R observed $(m_c \ll m_t)$ in $t \to ch$

from spin conservation, top helicity and direction of c_R is alined.

Spin analyzing power: $$\frac{1}{\Gamma_i}\frac{d\Gamma_i}{d\cos\theta_i} = \frac{1}{2}(1 + \kappa_i P \cos\theta_i)$$

$\kappa_{\ell+}$	$\kappa_{\bar{d}}$	κ_u	κ_b	κ_c	κ_h
$+1$	$+1$	-0.32	-0.39	$+1$	-1

(LO) $\kappa_f = -\bar{\kappa}_{\bar{f}}$

Using spin correlation, we can check it.

at LHC, helicity basis is known to be a reasonably good spin axis

$$A_{\rm hel} = \frac{N(t_\uparrow \bar{t}_\uparrow) + N(t_\downarrow \bar{t}_\downarrow) - N(t_\uparrow \bar{t}_\downarrow) - N(t_\downarrow \bar{t}_\uparrow)}{N(t_\uparrow \bar{t}_\uparrow) + N(t_\downarrow \bar{t}_\downarrow) + N(t_\uparrow \bar{t}_\downarrow) + N(t_\downarrow \bar{t}_\uparrow)} \sim 0.35 \quad (14\text{TeV})$$

helicity structure in top FC decay $t \to ch$

$$\frac{1}{\Gamma_i}\frac{d\Gamma_i}{d\cos\theta_i} = \frac{1}{2}(1 + \kappa_i P \cos\theta_i)$$

$\kappa_{\ell+}$	$\kappa_{\bar{d}}$	κ_u	κ_b	κ_c	κ_h
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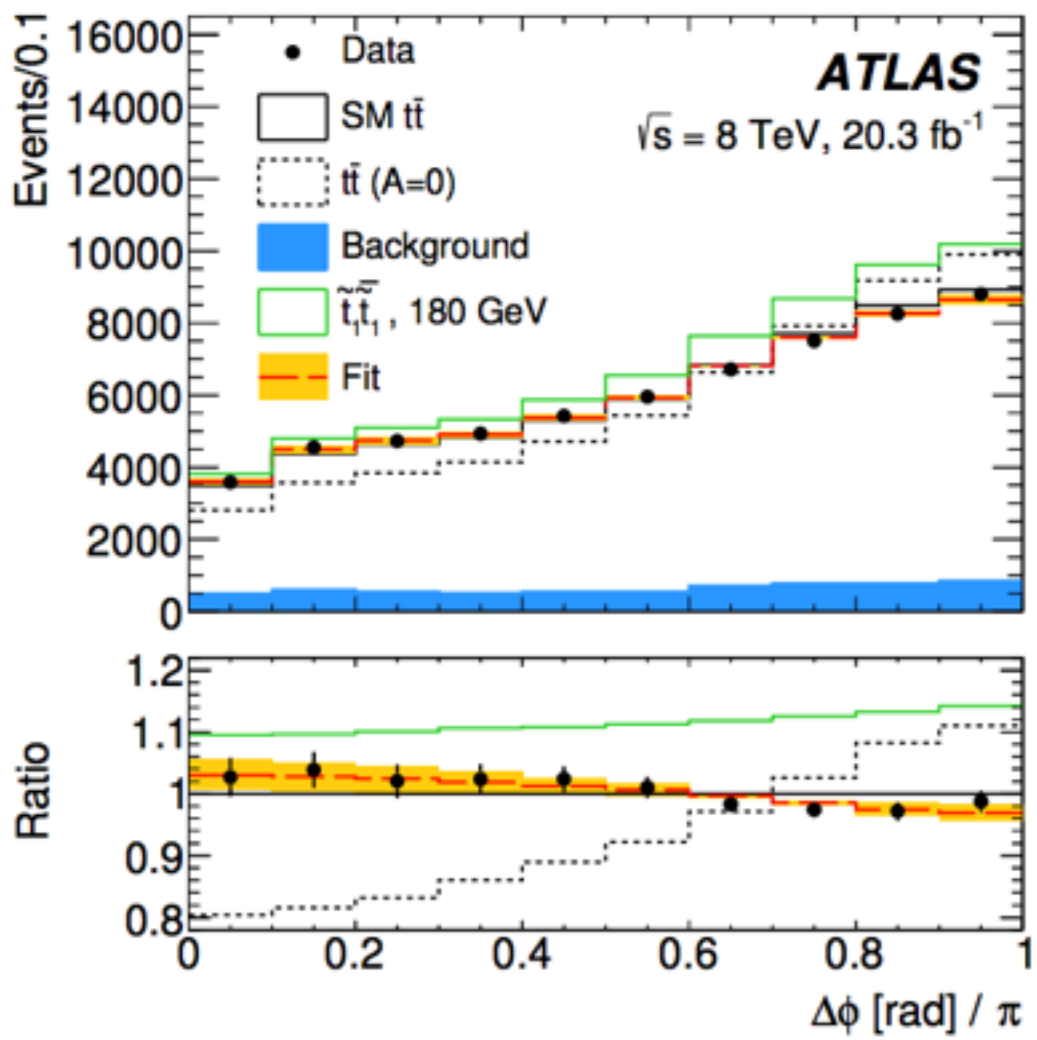


Already measured by ATLAS, CMS

arXiv:1412.4742 CMS-PAS-TOP-13-015

$$A_{\rm hel}^{{\rm SM},8TeV} = 0.318 \pm 0.005$$

$$A_{\rm hel}^{{\rm ATLAS},8TeV} = 0.38 \pm 0.04$$

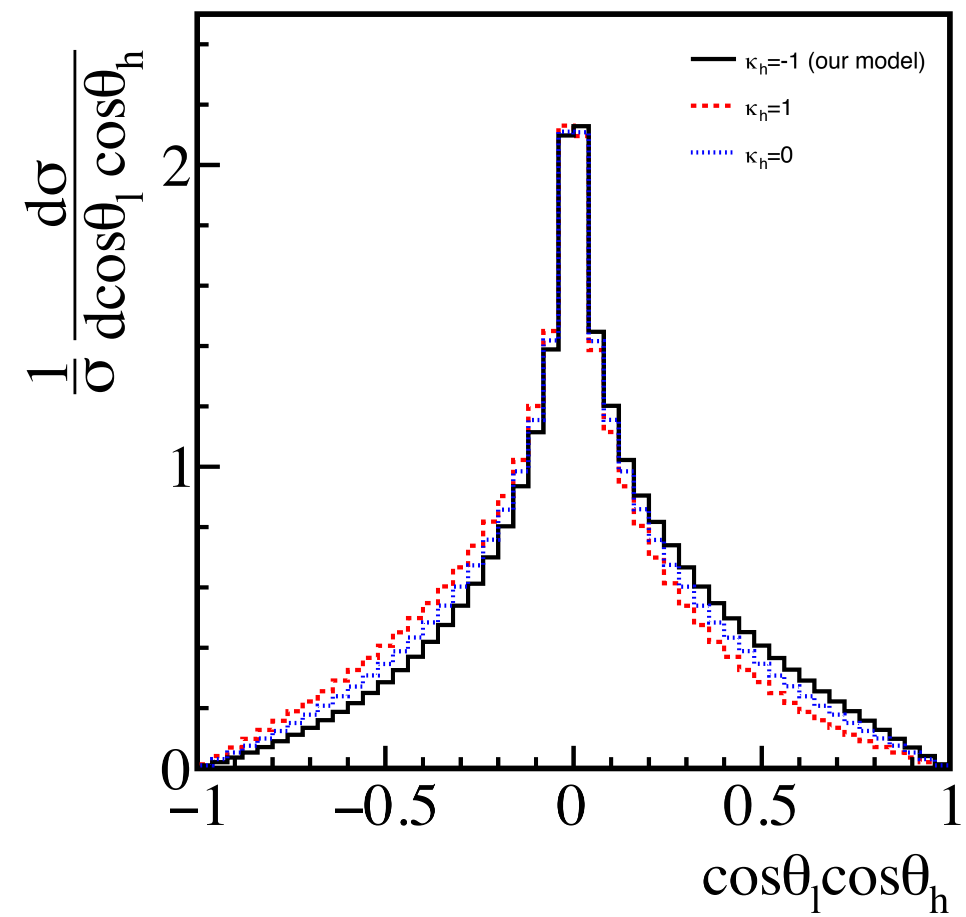
$$A_{\rm hel} = \frac{N(t_\uparrow\bar{t}_\uparrow) + N(t_\downarrow\bar{t}_\downarrow) - N(t_\uparrow\bar{t}_\downarrow) - N(t_\downarrow\bar{t}_\uparrow)}{N(t_\uparrow\bar{t}_\uparrow) + N(t_\downarrow\bar{t}_\downarrow) + N(t_\uparrow\bar{t}_\downarrow) + N(t_\downarrow\bar{t}_\uparrow)} \sim 0.35 \quad (14{\rm TeV})$$

helicity structure in top FC decay $t \to ch$

always c_R observed $(m_c \ll m_t)$

$$A_{\rm hel} = \frac{N(t_\uparrow \bar{t}_\uparrow) + N(t_\downarrow \bar{t}_\downarrow) - N(t_\uparrow \bar{t}_\downarrow) - N(t_\downarrow \bar{t}_\uparrow)}{N(t_\uparrow \bar{t}_\uparrow) + N(t_\downarrow \bar{t}_\downarrow) + N(t_\uparrow \bar{t}_\downarrow) + N(t_\downarrow \bar{t}_\uparrow)} \sim 0.35$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_i d\cos\theta_j} = \frac{1}{4}(1 + A_{\rm hel}\,\kappa_i \bar{\kappa}_j \cos\theta_i \cos\theta_j)$$



rough estimate of the sensitivity:

$$A_{\ell h} = \frac{N(\cos\theta_\ell \cos\theta_h > 0) - N(\cos\theta_\ell \cos\theta_h < 0)}{N(\cos\theta_\ell \cos\theta_h > 0) + N(\cos\theta_\ell \cos\theta_h < 0)} = \frac{A_{\rm hel}\kappa_{\ell+}\bar{\kappa}_h}{4} \sim 0.088\bar{\kappa}_h.$$

$\Delta A_{\ell h} \simeq \Delta N/N \simeq 1/\sqrt{N} > 0.088$ → at least 130 signal events needed.

with $\sigma(t\bar{t}) \sim 1$ nb for 3 ab^{-1}, 3×10^9 top pair expecetd

even for $BR(t \to ch) BR(h \to \gamma\gamma) = 2.2 \times 10^{-3} \times 2.3 \times 10^{-3}$,

~ 5000 of $t \to ch_{\to\gamma\gamma}$ events expected   not so difficult

using h→bb would improve the sensitivity

Summary

We consider top specific 2HDM, which predicts FCNC $t \to ch$

Strong CP problem

PQ solution with axion

promising axion DM searches near future

top-specific invisible axion model (ZDFS) $N_{DM} = 1$

a well motivated model for FV 2HDM

Central value of the current excess BR=0.22% and Higgs data is compatible to our model

We predict in general distinct helicity structure in FC higgs couplings.

As top pairs are produced copiously at LHC, we should be able to test it using the spin correlation for a reasonable $BR(t \to ch)$.

improving the analysis on this mode would be very important [LHC: top factory]

more detail: JHEP11(2015)057 [arXiv:1507.04354], PhysRevD.97.035015 [arXiv:1711.02993], arxiv:1806.XXXX

Backup

Up sector FCNC constraints

	$\lvert Y_{ut}Y_{ct}\rvert$, $\lvert Y_{tu}Y_{tc}\rvert$	$< 7.6 \times 10^{-3}$
D^0 oscillations [49]	$\lvert Y_{tu}Y_{ct}\rvert$, $\lvert Y_{ut}Y_{tc}\rvert$	$< 2.2 \times 10^{-3}$
	$\lvert Y_{ut}Y_{tu}Y_{ct}Y_{tc}\rvert^{1/2}$	$< 0.9 \times 10^{-3}$

t -> ch constraints $|\lambda ct| < 0.09$ (BR<0.22%)

the most stringent bound is

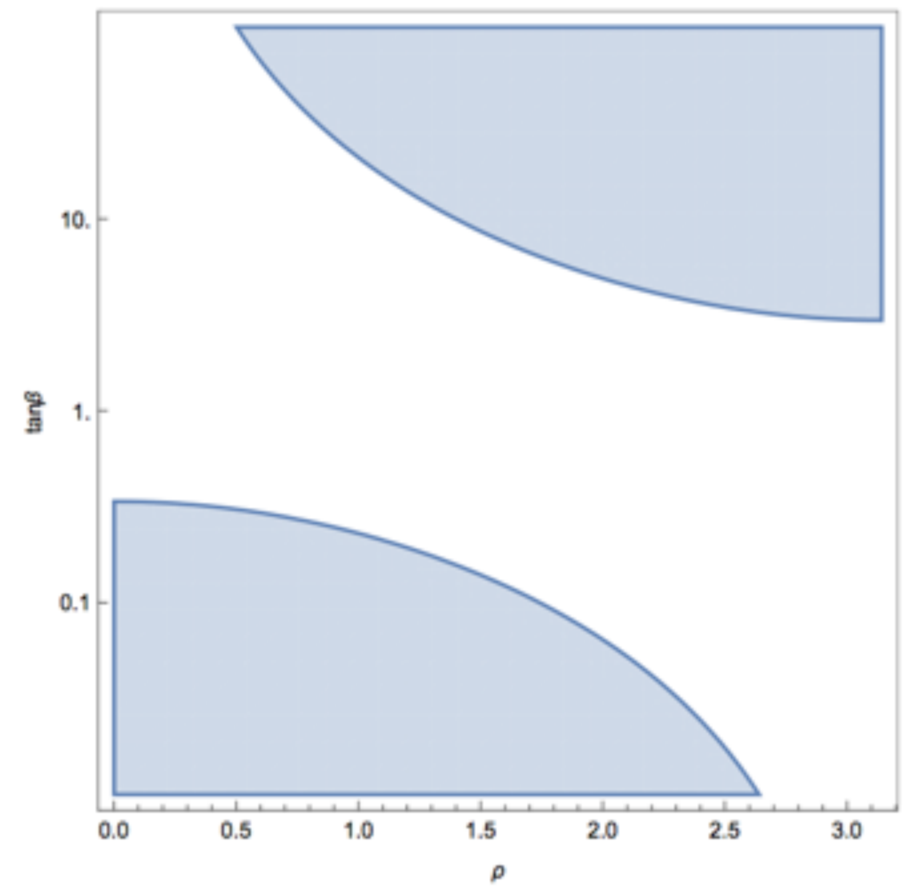
$$|\lambda_{ut}\lambda_{ct}| = |\lambda_{ct}|^2|\lambda_{ut}/\lambda_{ct}| = 0.008|\lambda_{ut}/\lambda_{ct}| < 7.6 \cdot 10^{-3}$$

$|\lambda_{ut}/\lambda_{ct}| \lesssim \mathcal{O}(1)$ is enough to avoid D-D mixing constraints

perturbativity

$$Y'^{,\mathrm{diag}}_{u\ ct} = (\tan\beta + \cot\beta)\frac{\sin\rho}{\sqrt{2}}\frac{m_t}{v}.$$

$$\begin{aligned}
\mathcal{D}Y^d_j &= a_d Y^d_j + \sum_{k=1}^{n_H} T_{jk} Y^d_k \\
&+ \sum_{k=1}^{n_H}\left(-2\,Y^u_k Y^{u\dagger}_j Y^d_k + \frac{1}{2}\,Y^u_k Y^{u\dagger}_k Y^d_j + Y^d_j Y^{d\dagger}_k Y^d_k + \frac{1}{2}\,Y^d_k Y^{d\dagger}_k Y^d_j\right), \\
\mathcal{D}Y^u_j &= a_u Y^u_j + \sum_{k=1}^{n_H} T^*_{jk} Y^u_k \\
&+ \sum_{k=1}^{n_H}\left(-2\,Y^d_k Y^{d\dagger}_j Y^u_k + \frac{1}{2}\,Y^d_k Y^{d\dagger}_k Y^u_j + Y^u_j Y^{u\dagger}_k Y^u_k + \frac{1}{2}\,Y^u_k Y^{u\dagger}_k Y^u_j\right), \\
\mathcal{D}Y^e_j &= a_e Y^e_j + \sum_{k=1}^{n_H} T_{jk} Y^e_k + \sum_{k=1}^{n_H}\left(Y^e_j Y^{e\dagger}_k Y^e_k + \frac{1}{2}\,Y^e_k Y^{e\dagger}_k Y^e_j\right),
\end{aligned}$$



$\tan\beta \sim 1$ is theoretically preferred

$$\xi_f = \begin{cases} \sin(\beta-\alpha) + \left(\cot\beta - \frac{1-\cos\rho}{2}(\tan\beta+\cot\beta)\right)\cos(\beta-\alpha) & (\text{for } f = t)\ , \\ \sin(\beta-\alpha) - \left(\tan\beta - \frac{1-\cos\rho}{2}(\tan\beta+\cot\beta)\right)\cos(\beta-\alpha) & (\text{for } f = c)\ , \\ \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha) & (\text{for the others})\ . \end{cases}$$

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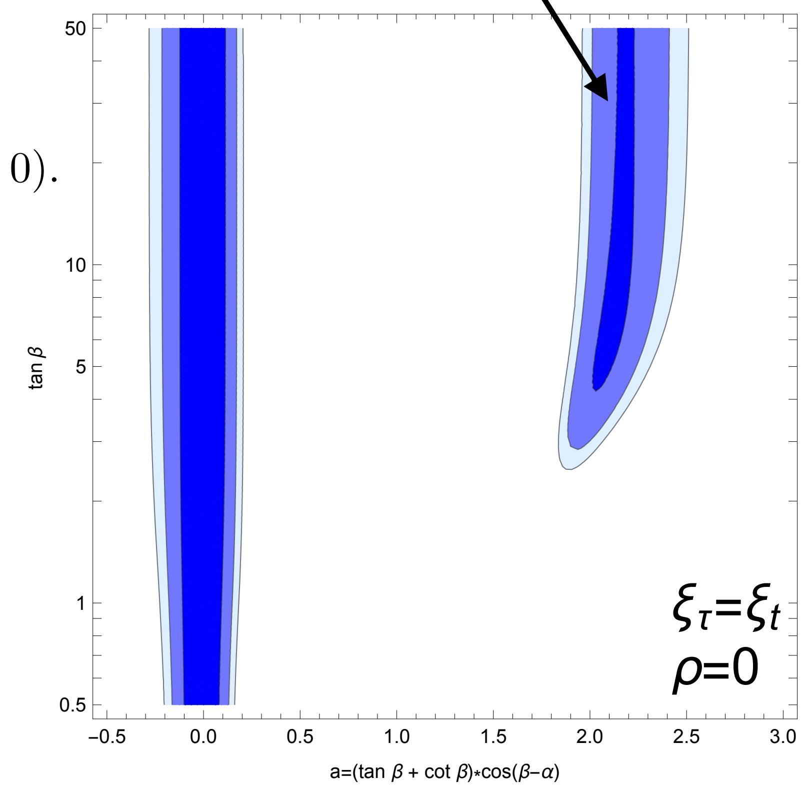
Higgs global fit

Observable	ATLAS [16]	CMS [17]
$\mu_{ZZ}^{\rm GGF}$	$1.7^{+0.5}_{-0.4}$	$0.883^{+0.336}_{-0.272}$
$\mu_{WW}^{\rm GGF}$	$0.98^{+0.29}_{-0.26}$	$0.766^{+0.228}_{-0.205}$
$\mu_{WW}^{\rm VBF}$	$1.28^{+0.55}_{-0.47}$	$0.623^{+0.593}_{-0.479}$
$\mu_{\gamma\gamma}^{\rm GGF}$	1.32 ± 0.38	$1.007^{+0.293}_{-0.259}$
$\mu_{bb}^{\rm VH}$	0.52 ± 0.40	$1.008^{+0.527}_{-0.499}$
$\mu_{\tau\tau}^{\rm GGF}$	$2.0^{+1.5}_{-1.2}$	$0.843^{+0.423}_{-0.382}$
$\mu_{\tau\tau}^{\rm VBF}$	$1.24^{+0.59}_{-0.54}$	$0.948^{+0.431}_{-0.379}$

when FC effects switched off ($\rho = 0$).

wrong-sign Yukawa region

$\xi_f \sim -1$ other than top



not sensitive to $\tan\beta$ (for > 5)

$a \sim \tan\beta\cos(\beta-\alpha)$

for large $\tan\beta$

$$\xi_f = \begin{cases} \sin(\beta-\alpha) + \left(\cot\beta - \frac{1-\cos\rho}{2}(\tan\beta+\cot\beta)\right)\cos(\beta-\alpha) & (\text{for } f = t)\ , \\ \sin(\beta-\alpha) - \left(\tan\beta - \frac{1-\cos\rho}{2}(\tan\beta+\cot\beta)\right)\cos(\beta-\alpha) & (\text{for } f = c)\ , \\ \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha) & (\text{for the others})\ . \end{cases}$$

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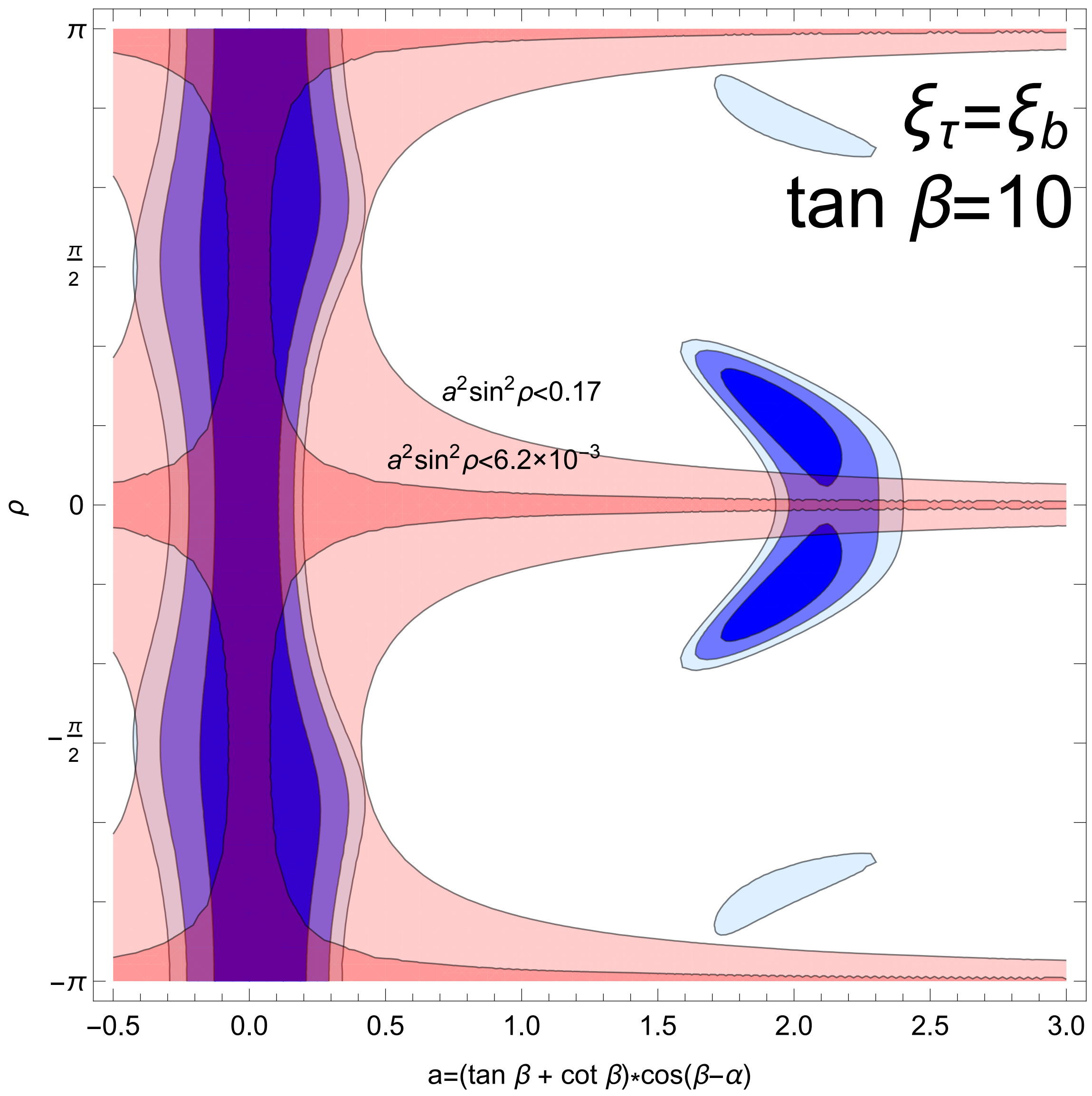

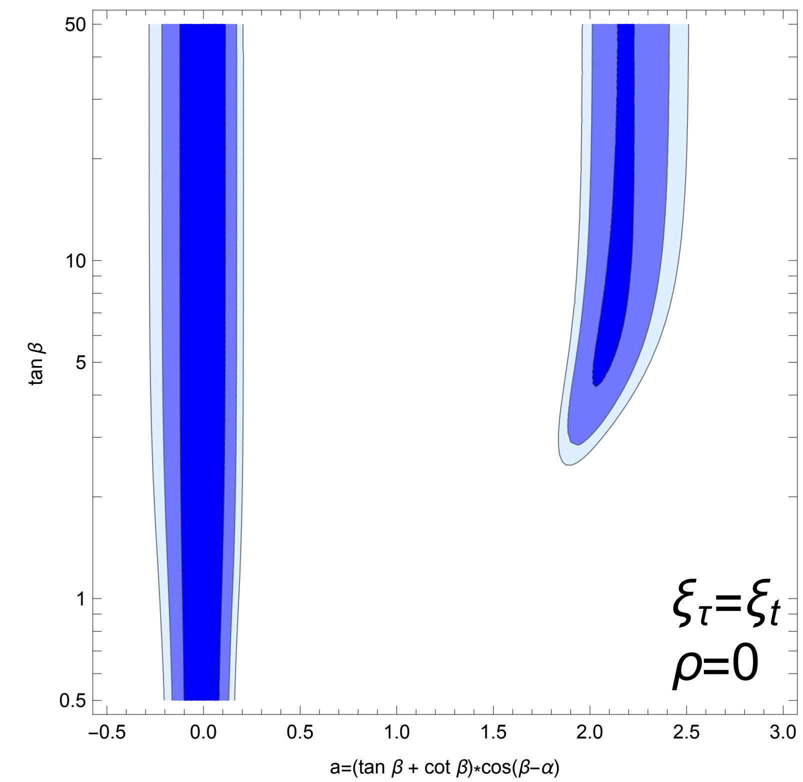

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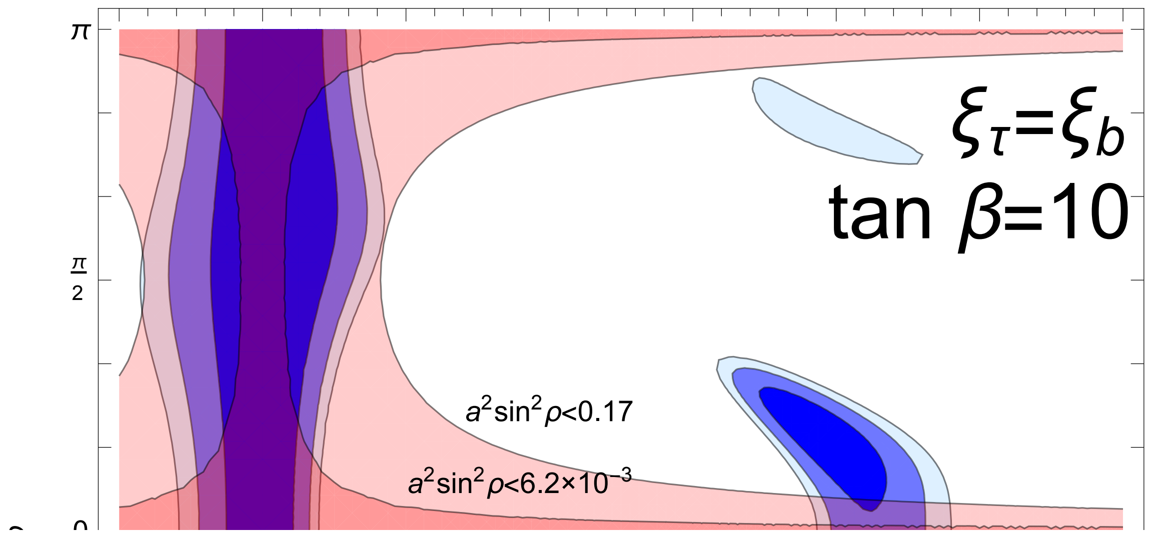
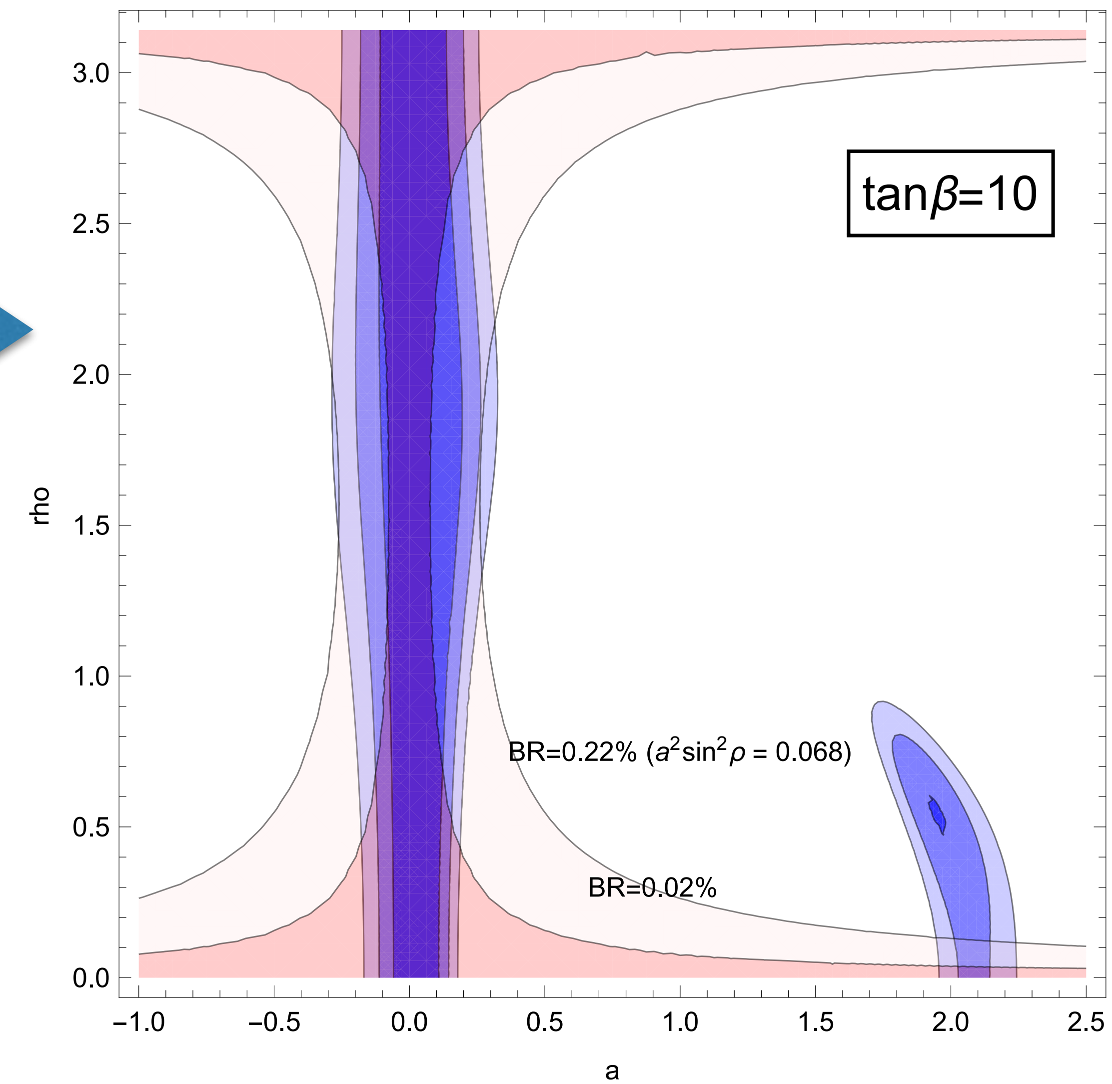
Higgs global fit (with latest data)





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$ttH^{13\mathrm{TeV}}_{\mathrm{CMS}}$	$2.22^{+0.9}_{-0.8}$ [51]	(WW)	1.5 ± 0.5 [67]	$0.72^{+0.62}_{-0.53}$ [64]	-0.19 ± 0.80 [63]

$$\xi_f = \begin{cases} \sin(\beta-\alpha) + \left(\cot\beta - \frac{1-\cos\rho}{2}(\tan\beta+\cot\beta)\right)\cos(\beta-\alpha) & (\text{for } f=t)\ , \\ \sin(\beta-\alpha) - \left(\tan\beta - \frac{1-\cos\rho}{2}(\tan\beta+\cot\beta)\right)\cos(\beta-\alpha) & (\text{for } f=c)\ , \\ \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha) & (\text{for the others})\ . \end{cases}$$

$$\mathcal{L}_{tc} = -\frac{a}{2v_{\mathrm{SM}}} h \begin{pmatrix} \bar{c}_R & \bar{t}_R \end{pmatrix} \begin{pmatrix} m_c(1-\cos\rho) & m_t \sin\rho \\ m_c \sin\rho & m_t(\cos\rho - 1) \end{pmatrix} \begin{pmatrix} c_L \\ t_L \end{pmatrix} + \mathrm{h.c.}$$