EWBG

ElectroWeak BaryoGenesis via Top Transport

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Outline

I. Intro: General 2HDM

Whither 1st Order Phase Trans. / Sufficient CPV?

II. Model

No Z_2 (*ad hoc*) + SM-like flavor org.: FCNH ρ_{ij}

III. **EWBG**

robust w/ large param. space

Bubble Exp. / CPV: ρ_{tt} the Driver; ρ_{tc} the backup

IV. Pheno

$(h \to \mu\tau)$

d_e; $h \to \gamma\gamma$; $t \to ch$; $\tau \to \mu\gamma$; $\delta\lambda_{hhh}$; $H^0, A^0, H^\pm$ @ sub-TeV

ρ_{ee} (ρ_{ij}) consideration; Alignment Limit

V. Conclusion

K. Fuyoto, WSH, E. Senaha, 1705.05034

I. Intro: General 2HDM

Two Higgs Doublet Model

Whither 1st Order Phase Trans. / *Sufficient* CPV?

SM: Weak Int. too Weak / Jarlskog Invariant *way too small!*
All 3 gens. ⇒ Mass and CKM suppressed

2HDM: $\mathcal{O}(1)$ Higgs Couplings OK / CPV in $V(\Phi_1, \Phi_2)$ problematic w/ d_n
Wise to keep $V(\Phi_1, \Phi_2)$ CP Conserving

Comment: Known CPV in CKM, i.e. Yukawa's. Extra Yukawa's?

Killed by Z_2 (Glashow-Weinberg 1977)
for Flavor Conservation.

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General 2HDM: $\mathcal{O}(1)$ Higgs Couplings OK / Extra Yukawa's w/o Z_2 *ad hoc*

$\mathcal{O}(1)$ ρ_{tt} the driver; ρ_{tc} the backup

N.B. Data-driven ρ_{ij}: $B \to D^{(*)}\tau\nu$ Anomaly; $t \to ch$; $h \to \mu\tau$ ...

II. Model

General ~~2HDM~~ w/o Z_2

General Yukawa interaction for up-type quarks

$$-\mathcal{L}_Y = \bar{q}_{iL}(Y^u_{1ij}\tilde{\Phi}_1 + Y^u_{2ij}\tilde{\Phi}_2)u_{jR} + \text{h.c.}$$

$\upsilon_1 = \upsilon\, c_\beta \qquad \upsilon_2 = \upsilon\, s_\beta$

$$\boxed{Y^{\rm SM} = Y_1\, c_\beta + Y_2\, s_\beta}$$

$m_f = y_f\, v/\sqrt{2}$

$$V_L^{u\dagger} Y^{\rm SM} V_R^u = \text{diag}(y_u,\ y_c,\ y_t) \equiv Y_D$$ diagnonal

$$\boxed{\rho = V_L^{u\dagger}\left(-Y_1\, s_\beta + Y_2\, c_\beta\right) V_R^u}$$ FCNH (flavor changing neural H)

Neutral up-type Yukawa interaction

$$\begin{aligned}-\mathcal{L}_Y = {} & \bar{u}_{iL}\left[\frac{y_i\delta_{ij}}{\sqrt{2}}s_{\beta-\alpha} + \frac{\rho_{ij}}{\sqrt{2}}\,c_{\beta-\alpha}\right]u_{jR}h \\ & + \bar{u}_{iL}\left[\frac{y_i\delta_{ij}}{\sqrt{2}}\,c_{\beta-\alpha} - \frac{\rho_{ij}}{\sqrt{2}}\,s_{\beta-\alpha}\right]u_{jR}H \\ & - \frac{i}{\sqrt{2}}\,\bar{u}_{iL}\rho_{ij}u_{jR}\,A + \text{h.c.},\end{aligned}$$

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Neutral up-type Yukawa interaction

$c_{\beta-\alpha} \to 0$ alignment limit!

$$-\mathcal{L}_Y = \bar{u}_{iL}\left[\frac{y_i\delta_{ij}}{\sqrt{2}} s_{\beta-\alpha} + \frac{\rho_{ij}}{\sqrt{2}}\, c_{\beta-\alpha}\right] u_{jR} h \quad \to \text{diag.}$$

$$+ \bar{u}_{iL}\left[\frac{y_i\delta_{ij}}{\sqrt{2}}\, c_{\beta-\alpha} - \frac{\rho_{ij}}{\sqrt{2}}\, s_{\beta-\alpha}\right] u_{jR} H$$

$$- \frac{i}{\sqrt{2}}\, \bar{u}_{iL}\rho_{ij} u_{jR}\, A + \text{h.c.},$$

$\to$ FCNH ρ_{ij}

$|\rho_{ij}|e^{i\phi_{ij}}$

III. EWBG

strongly 1st order EW phase transition (EWPT)

Expanding Bubble of Broken Phase

Extra Higgs Thermal Loops
w/ **O(1) Higgs Couplings**

2HDM OK

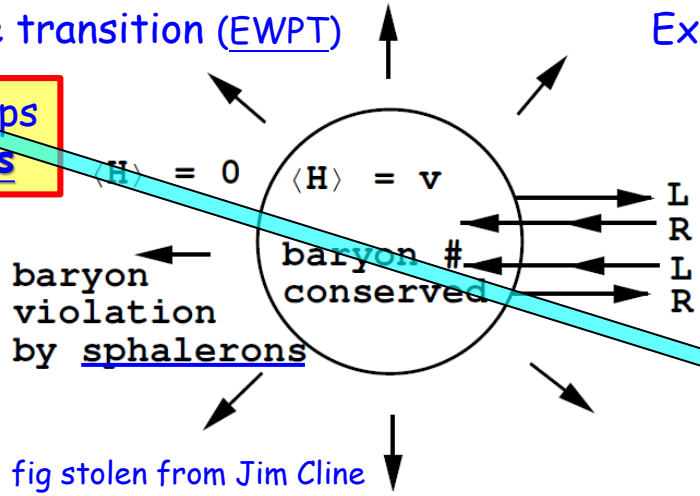

fig stolen from Jim Cline

To avoid n_B washout:

Hubble const.

$$\Gamma_B^{(\mathrm{br})}(T_C) < H(T_C)$$

n_B changing rate (br)

$$v_C/T_C > \zeta_{\mathrm{sph}}(T_C) \sim \mathcal{O}(1)$$

vev @ T_C

$$\sqrt{v_1^2(T_C) + v_2^2(T_C)}$$

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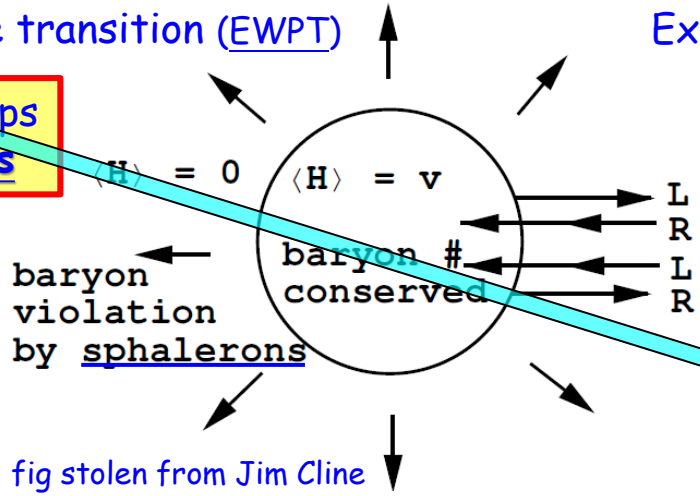

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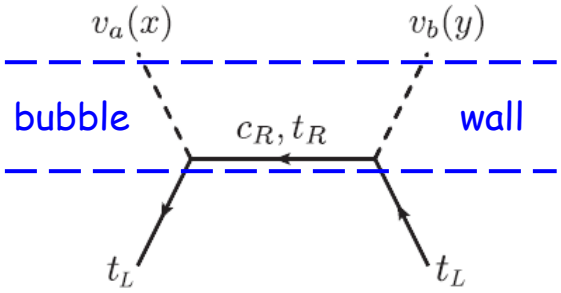
Baryon Asymm. of Universe (BAU) n_B/s

$$Y_B = \frac{-3\Gamma_B^{(\mathrm{sym})}}{2D_q\lambda_+ s}\int_{-\infty}^{0} dz'\; n_L(z')e^{-\lambda_- z'}$$

Planck 2014

$$Y_B^{\mathrm{obs}} = 8.59\times 10^{-11}$$



$\Gamma_B^{(\mathrm{sym})} = 120\alpha_W^5 T$ n_B changing rate (sym)

$D_q \simeq 8.9/T$ quark diffusion const

s entropy density

$\lambda_\pm \simeq v_w$ bubble wall velocity

n_L l.h. fermion density (l.h. top density)

z' coord. oppo. bubble exp. dir.

CPV Top interactions

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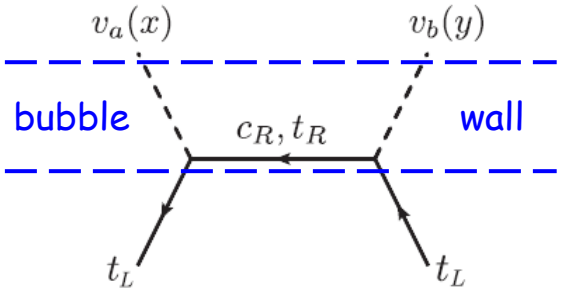

BAU ⇐ CPV Top interactions at Bubble Wall

left-handed Top density

n_L

skip detail (Transport)

z' coord. oppo. bubble exp. dir.

CPV Top interactions

CPV source term

$$S_{i_L j_R}(Z) = N_C F \left[\mathrm{Im}\left[(Y_1)_{ij} (Y_2)^*_{ij} \right] \right] v^2(Z)\, \partial_{t_Z} \beta(Z)$$

$Z = (t_Z, \boldsymbol{Z})$	position in heat bath (Very Early Univ.)
$N_C = 3$	# of color
F	function of complex energies for i_L, j_R
$\partial_{t_Z} \beta(Z)$	physical variation ($\Delta\beta = 0.015$)

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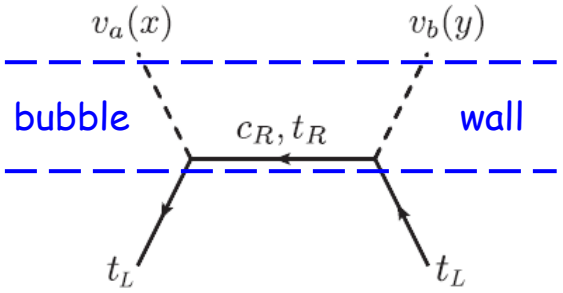

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$$\mathrm{Im}\left[(Y_1)_{ij}(Y_2)^*_{ij}\right] = \mathrm{Im}\left[(V_L^u Y_D V_R^{u\dagger})_{ij}(V_L^u \rho V_R^{u\dagger})^*_{ij}\right]$$

To understand the plot to follow, suppose

$(Y_1)_{tc} \neq 0, (Y_2)_{tc} \neq 0, (Y_1)_{tt} = (Y_2)_{tt} \neq 0$ (3 params.)

all else vanish, and take $t_\beta = 1$ for convenience

then $\sqrt{2} Y^{\rm SM} = Y_1 + Y_2$ diag. by just V_R^u (solve)

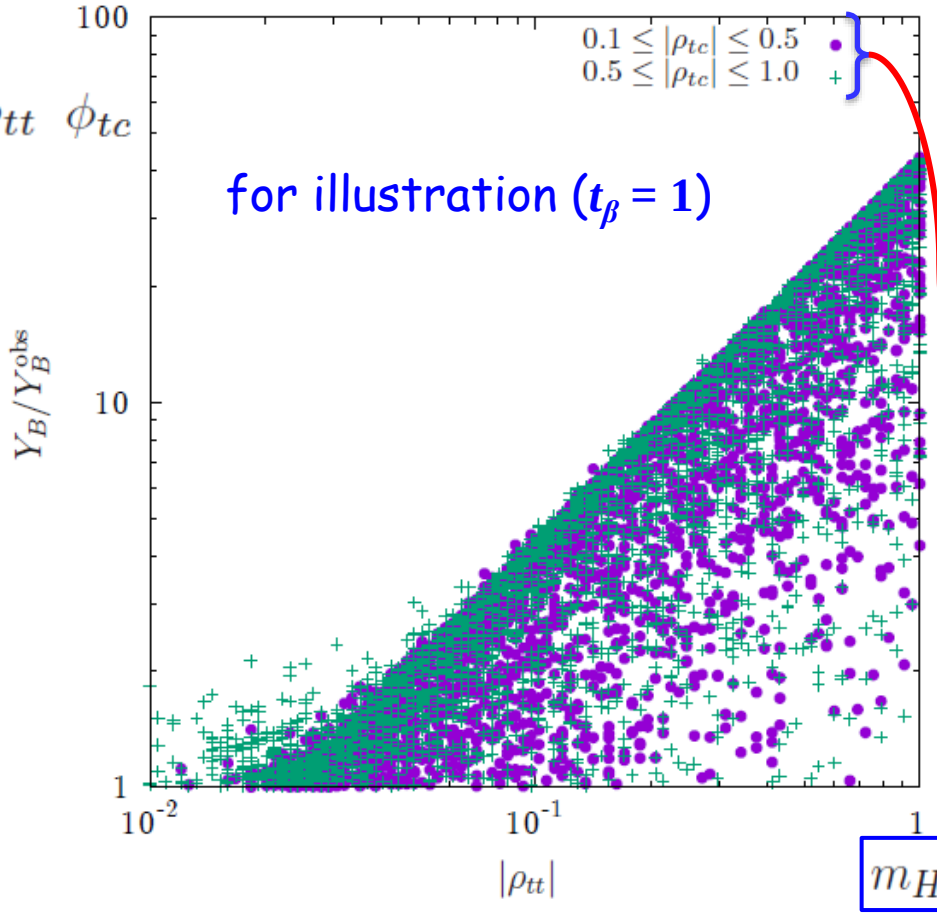
but $-Y_1 + Y_2$ not diag.

$$\Rightarrow \quad \mathrm{Im}\left[(Y_1)_{tc}(Y_2)^*_{tc}\right] = -y_t \mathrm{Im}(\rho_{tt}), \quad \rho_{ct} = 0$$

ρ_{tc} still basically free param.

Robust: Large Parameter Space for EWBG

scan over $|\rho_{tc}|$ ϕ_{tt} ϕ_{tc}



ρ_{tc}, ρ_{tt} satisfy $B_{d,s}$ mixing, $b \to s\gamma$

no obvious diff.

$\Rightarrow \rho_{tt}$ driven !

the charm of EWBG

$$m_H = m_A = m_{H^\pm} = 500 \text{ GeV}$$

$v_C/T_C > \mathcal{O}(1)$

$T_C = 119.2$ GeV	$v_C = 176.7$ GeV	$v_w = 0.4$	$\Delta\beta = 0.015$	$D_q = 8.9/T$	$D_H = 101.9/T$
$m_{t_L} = 0.59T$	$m_{t_R} = 0.62T$	$m_{c_R} = 0.50T$	$\Gamma_{q_{L,R}} = 0.22T$	$\Gamma_B^{(s)} = 120\alpha_W^5 T$	$\Gamma_{ss} = 16\alpha_s^4 T$

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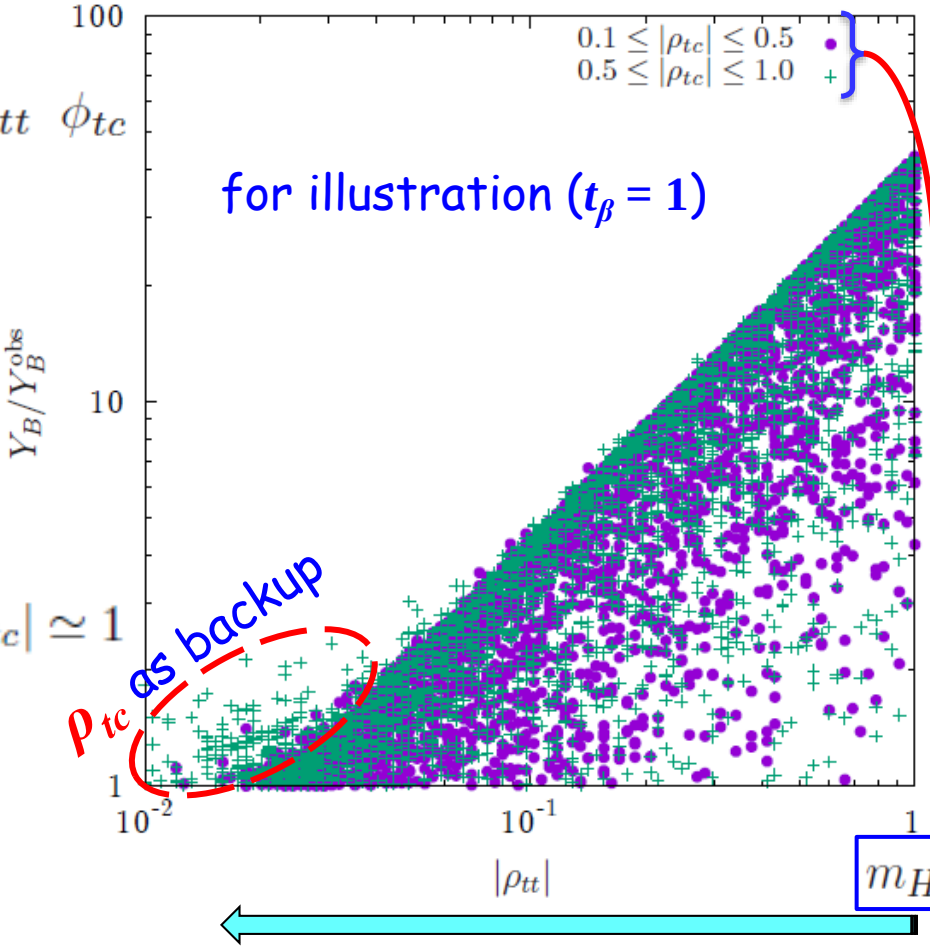
scan over $|\rho_{tc}|$ ϕ_{tt} ϕ_{tc}



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small ρ_{tt}

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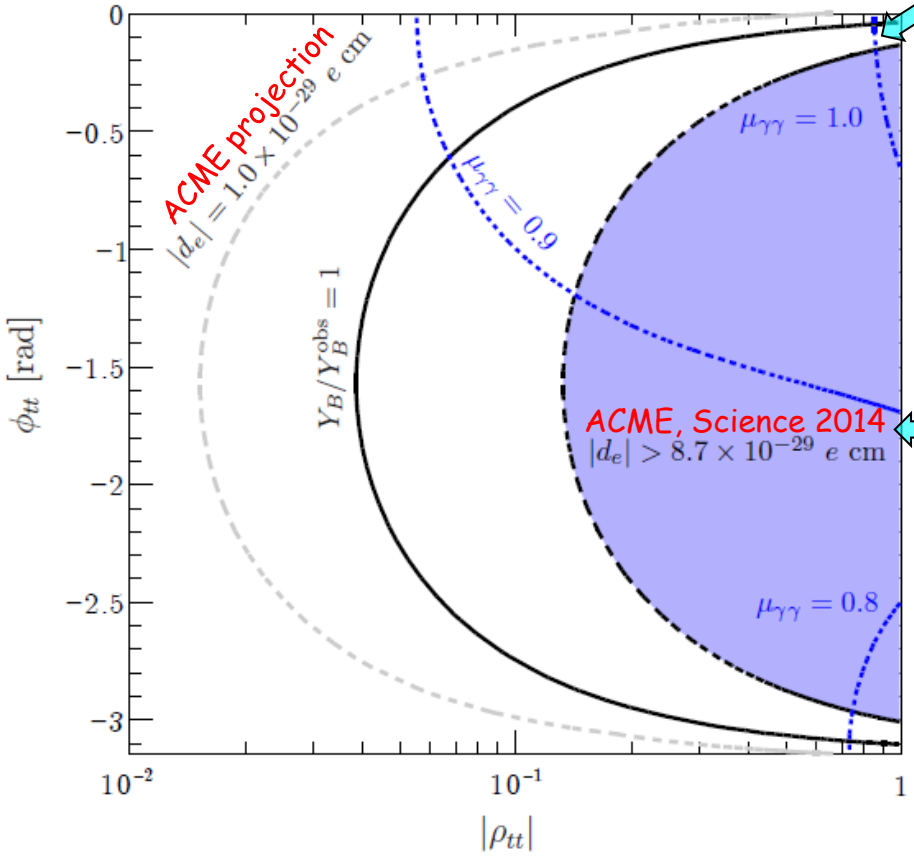
IV. Pheno

for illustration: $t_\beta = 1$, $c_{\beta-\alpha} = 0.1$

$\mathcal{B}(t \to ch) \simeq 0.15\%$ for $|\rho_{tc}| = 1$

vs < 0.46% (0.40%) ATLAS (CMS)



charged Higgs H^+

$h \to \gamma\gamma$ width reduction (ρ_{tt} compensate)

Barr-Zee e-EDM (2-loop)

but: $c_{\beta-\alpha} \to 0$, $|\rho_{ee}| \sim y_e$

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$\mathcal{B}(h \to \mu\tau) < 0.25\%$ CMS 13 TeV (2016)

$\mathcal{B}(t \to ch) \simeq 0.15\%$ for $|\rho_{tc}| = 1$ ⇒ $\mathcal{B}(\tau \to \mu\gamma) \lesssim 10^{-8}$ Belle II

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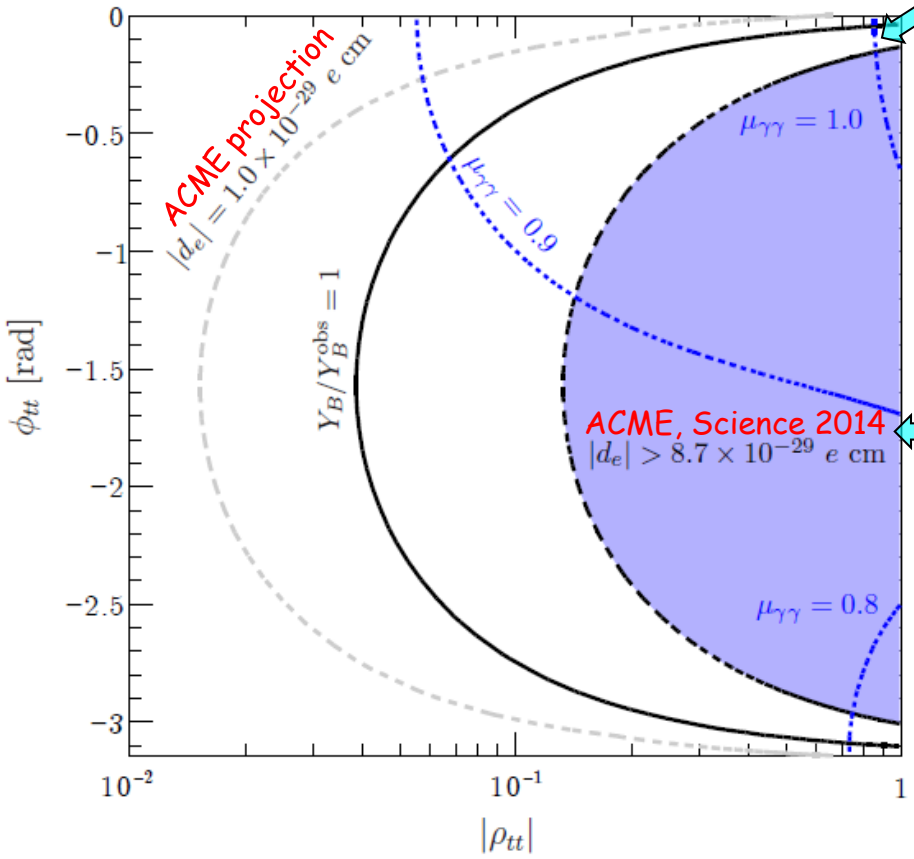

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- EWBG
- $h \to \gamma\gamma$ width reduction
- λ_{hhh} coupling

$$\Delta\lambda_{hhh} \equiv (\lambda_{hhh}^{\rm 2HDM} - \lambda_{hhh}^{\rm SM})/\lambda_{hhh}^{\rm SM} \simeq 60\%$$

- Higgs @ LHC

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probably hidden in tt(bar)

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$c_{\beta-\alpha} \to 0$

Barr-Zee e-EDM (2-loop)

but: $c_{\beta-\alpha} \to 0$ and $|\rho_{ee}| \sim y_e$

V. Conclusion

WSH, E. Senaha, 1705.05034

Conclusion.— We have studied EWBG induced by the top quark in the general 2HDM with FCNH couplings. The leading effect arises from the extra ρ_{tt} coupling, where BAU can be in the right ballpark for $\rho_{tt} \gtrsim 0.01$ with moderate CPV phase. Even if $\rho_{tt} \ll 0.01$, $|\rho_{tc}| \simeq 1$ with large CPV phase can still generate sufficient BAU. These scenarios are testable in the future, with new flavor parameters that have rich implications, and extra Higgs bosons below the TeV scale. Nature may opt for a second Higgs doublet for generating the matter asymmetry of the Universe, through a new CPV phase associated with the top quark.

Extra !!

Alignment Emerges Naturally from General 2HDM!

WSH, M. Kikuchi, 1706.07694

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