Two Top Utilities of 2HDMs: Electroweak Baryogenesis and Alignment

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Outline

I. Intro: General 2HDM for BAU

II. General 2HDM (w/o Z_2): FCNH Yukawa ρ_{ij}

III. EWBG from ρ_{tt}

— Back on Earth —

IV. Bonus: Natural Alignment, w/ ρ_{tt} Protection

V. Pheno & Discussion

VI. Conclusion: H^0, A^0, $H^\pm$ in Our Time

Fuyoto, WSH, Senaha, 1705.05034
WSH & Kikuchi, 1706.07694

I. Intro: General 2HDM for BAU

baryon symm. universe

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 ➔ Yukawa's. Extra Yukawa's?

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

ad hoc

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

Natural: $\mathcal{O}(1)$

ρ_{tt} the driver; ρ_{tc} the backup

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

II. General 2HDM (w/o Z_2): FCNH ρ_{ij}

General Yukawa interaction for up-type quarks

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

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

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

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

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

diagnonal

$$\rho = V_L^{u\dagger}\left(-Y_1\, s_\beta + Y_2\, c_\beta\right) V_R^u$$

FCNH (flavor changing neural H)

Neutral up-type Yukawa interaction

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

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

→ diag. (SM-H)

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

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

→ FCNH ρ_{ij}

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

N.B. $\tan\beta$ unphysical

III. EWBG from ρ_{tt}

strongly 1st order EW phase transition (EWPT)

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

2HDM OK

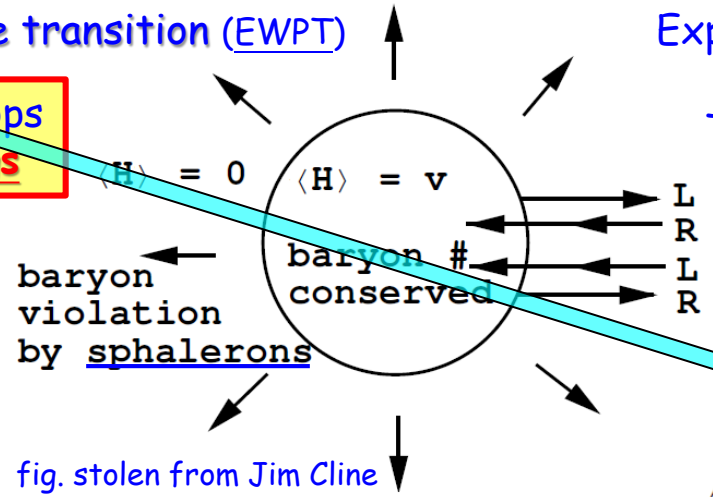


fig. stolen from Jim Cline

Expanding Bubble of Broken Phase

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

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

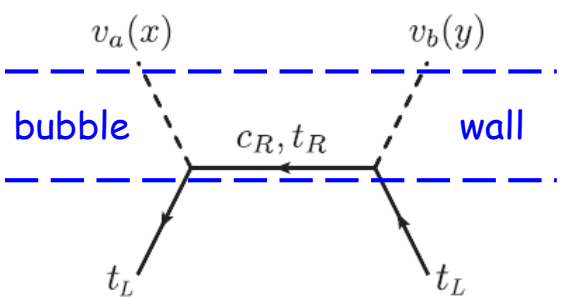
(keep υ_1, υ_2)

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

CPV source term

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

$Z = (t_Z, \boldsymbol{Z})$	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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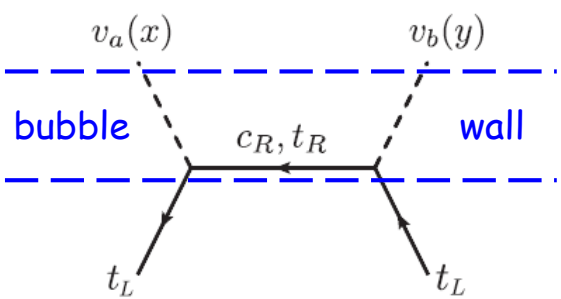


BAU ⇐ CPV Top Interactions at Bubble Wall

left-handed Top density

$\boxed{n_L}$ } skip detail (Transport)

z' coord. oppo. bubble exp. dir.

CPV Top Interactions

CPV source term

"Jarlskog": both doublets participate

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

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

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 $\sqrt{2}Y^{\mathrm{SM}} = Y_1 + Y_2$ diag. by just V^u_R

but $-Y_1 + Y_2$ not diag.

solve

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

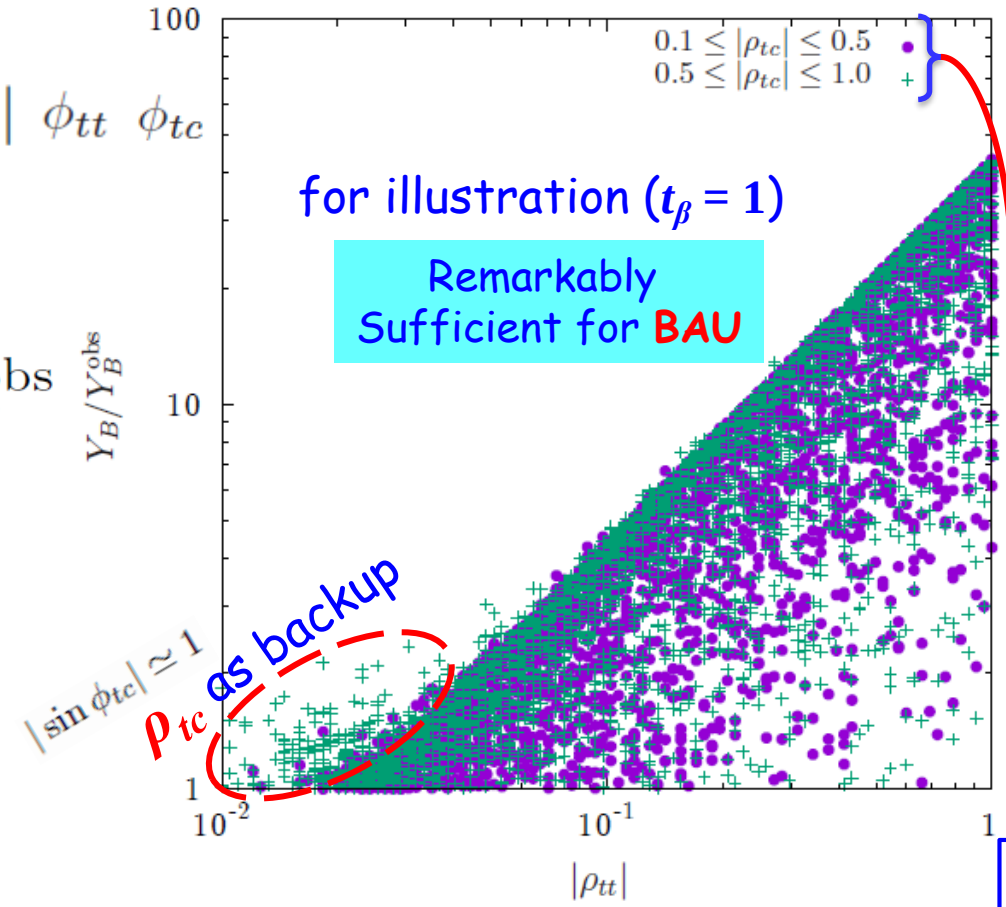
CPV Source

ρ_{tc} still basically free param.

Robust: Large Parameter Space for EWBG

scan over $|\rho_{tc}|$ ϕ_{tt} ϕ_{tc}

$Y_B/Y_B^{\rm obs}$



for illustration ($t_\beta = 1$)

Remarkably Sufficient for **BAU**

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

Altunkaynak et al., 1506.00651

no obvious diff.

$\Rightarrow$ ρ_{tt} driven!

the charm of EWBG

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

sub-TeV

small ρ_{tt}

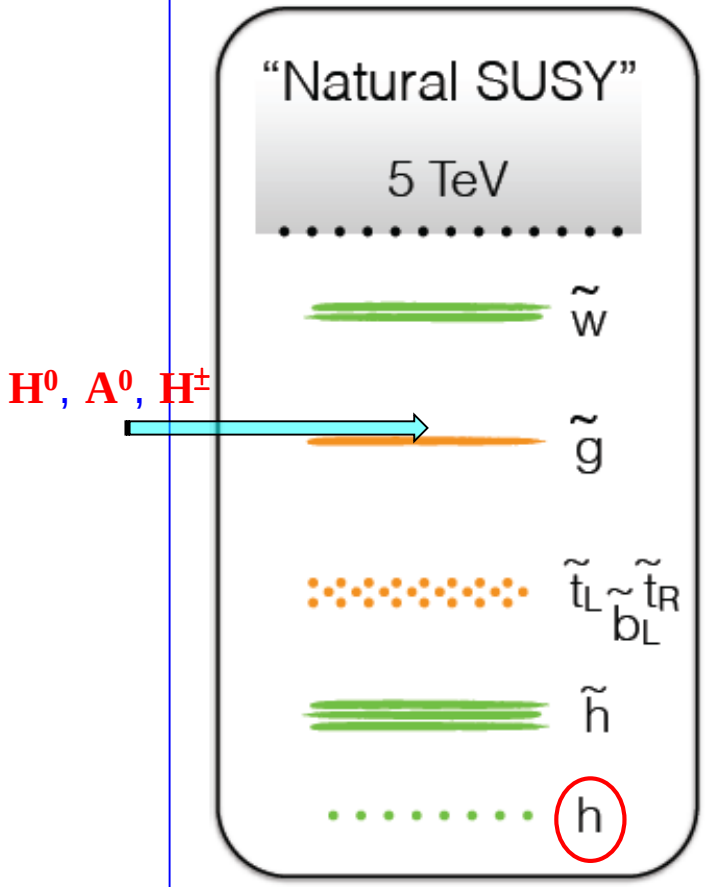
$v_C/T_C > \mathcal{O}(1)$

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

Back on Earth

Where are we?

Where are They?



Best case scenario given null results:
partner mass hierarchy inversely
proportional to contribution to Higgs mass

Supersymmetry

Me: In SUSY there is 2nd Higgs Doublet, where do you place them ?

Craig: ... they are at e.g. 3 TeV ...

Me: OK, you take decoupling limit.

7

Back on Earth

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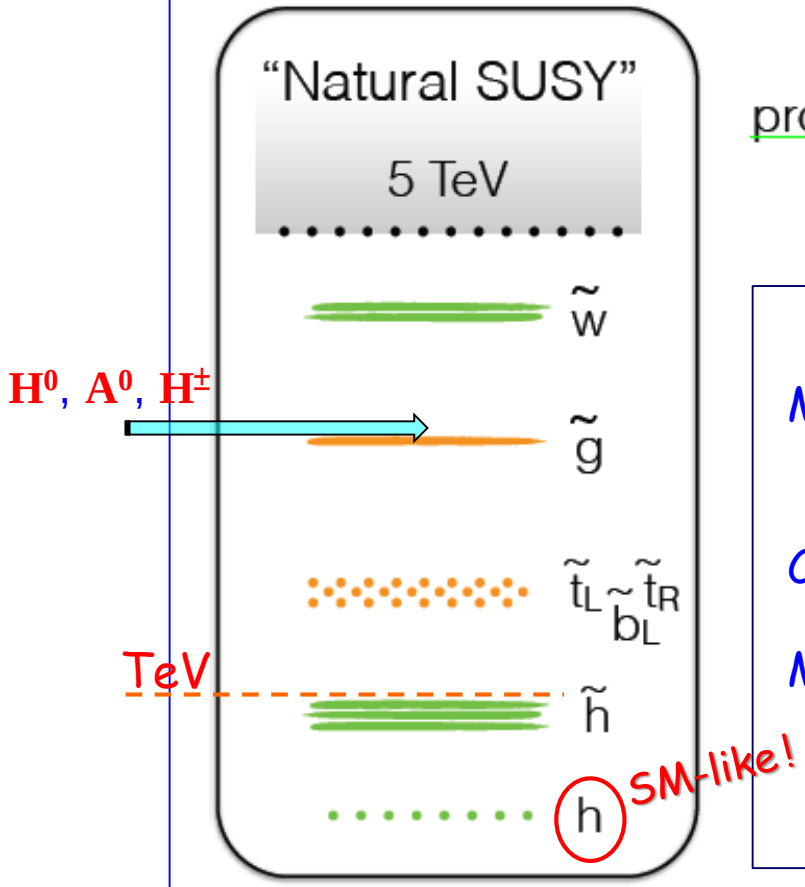

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[backdrop: Alignment by Decoupling]

2HDM-II

fine tuned

N.B. $(3000/125)^2 \approx 600$!!

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The Alignment Enigma: $\cos(\beta-\alpha) \approx 0$

2HDM-II

Impersonating the Standard Model Higgs boson: alignment without decoupling

JHEP 2014

Marcela Carena,[a,b,c] Ian Low,[d,e,f] Nausheen R. Shah,[g] and Carlos E.M. Wagner[b,c,e]

... a new solution also appears

$m_h^2/v^2 \simeq 0.26$

combo of quartics

$$\tan\beta = \frac{\lambda_{\rm SM} - \tilde{\lambda}}{\lambda_7} + \text{small terms}$$

quartic forbidden by Z_2

$\Rightarrow$ generated by soft breaking, hence "small"

r.h.s. large √

l.h.s. large √

My Question: Why should l.h.s. = r.h.s. !?

what Howie Haber calls "accidental cancellation"

fine tuned

The Alignment Enigma: $\cos(\beta-\alpha) \approx 0$

based on Bechtle et al., EPJC'17

The squared-mass matrix is given with respect to the Higgs basis states, $\{\sqrt{2}\,\mathrm{Re}\,H_1^0 - v\,, \sqrt{2}\,\mathrm{Re}\,H_2^0\}$,

$$\mathcal{M}^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & m_A^2 + Z_5 v^2 \end{pmatrix}.$$

The CP-even Higgs mass eigenstates h and H (with $m_h < m_H$) are given by,

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} c_{\beta-\alpha} & -s_{\beta-\alpha} \\ s_{\beta-\alpha} & c_{\beta-\alpha} \end{pmatrix} \begin{pmatrix} \sqrt{2}\,\mathrm{Re}\,H_1^0 - v \\ \sqrt{2}\,\mathrm{Re}\,H_2^0 \end{pmatrix},$$

where α is the diagonalizing angle of the squared-mass matrix with respect to the Φ_1^0–Φ_2^0 basis of scalar fields and $\tan\beta \equiv \langle\Phi_2^0\rangle/\langle\Phi_1^0\rangle$. In the approximate alignment limit where $m_h^2 \simeq Z_1 v^2$, we have

$$\boxed{|c_{\beta-\alpha}| \simeq \frac{|Z_6| v^2}{m_H^2 - m_h^2} \ll 1},$$

which can be achieved in two different ways:

1. $m_A \gg v$, corresponding to the decoupling limit.
2. $\boxed{|Z_6| \ll 1}$, allowing for approximate alignment without decoupling.

< 0.05

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< 0.05

shake off the MSSM mindset!

WSH & Kikuchi, 1706.07694

IV. Bonus: Natural Alignment, w/ ρ_{tt} Protection

General 2HDM w/o Z_2

$$V(\Phi,\Phi') = \mu_{11}^2|\Phi|^2 + \mu_{22}^2|\Phi'|^2 - (\mu_{12}^2\Phi^\dagger\Phi' + \text{h.c.})$$
$$+ \frac{\eta_1}{2}|\Phi|^4 + \frac{\eta_2}{2}|\Phi'|^4 + \eta_3|\Phi|^2|\Phi'|^2 + \eta_4|\Phi^\dagger\Phi'|^2$$
$$+ \left\{\frac{\eta_5}{2}(\Phi^\dagger\Phi')^2 + \left[\eta_6|\Phi|^2 + \eta_7|\Phi'|^2\right]\Phi^\dagger\Phi' + \text{h.c.}\right\}$$

assume CP-Inv.

EWSB

minimization

$$\mu_{11}^2 = -\frac{1}{2}\eta_1 v^2, \quad \underbrace{\mu_{12}^2 = \frac{1}{2}\eta_6 v^2,}_{\text{“soft breaking” term absorbed}}$$

[see Haber & O'Neil, PRD'06

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$$\begin{cases} m_{H^\pm}^2 = \mu_{22}^2 + \frac{1}{2}\eta_3 v^2, \\ m_A^2 = \mu_{22}^2 + \frac{1}{2}(\eta_3 + \eta_4 - \eta_5)v^2 \end{cases}$$

$$M_{\text{even}}^2 = \begin{bmatrix} \eta_1 v^2 & \eta_6 v^2 \\ \eta_6 v^2 & \mu_{22}^2 + \frac{1}{2}(\eta_3 + \eta_4 + \eta_5)v^2 \end{bmatrix}$$

diag.

$$R_\gamma = \begin{bmatrix} c_\gamma & -s_\gamma \\ s_\gamma & c_\gamma \end{bmatrix}$$

cos(β–α)

$$R_\gamma^T M_{\text{even}}^2 R_\gamma = \begin{bmatrix} m_H^2 & 0 \\ 0 & m_h^2 \end{bmatrix}$$

IV. Bonus: Natural Alignment, w/ ρ_{tt} Protection

General 2HDM w/o Z_2

$$V(\Phi,\Phi') = \mu_{11}^2|\Phi|^2 + \mu_{22}^2|\Phi'|^2 - (\mu_{12}^2\Phi^\dagger\Phi' + \text{h.c.}) + \frac{\eta_1}{2}|\Phi|^4 + \frac{\eta_2}{2}|\Phi'|^4 + \eta_3|\Phi|^2|\Phi'|^2 + \eta_4|\Phi^\dagger\Phi'|^2 + \left\{\frac{\eta_5}{2}(\Phi^\dagger\Phi')^2 + \left[\eta_6|\Phi|^2 + \eta_7|\Phi'|^2\right]\Phi^\dagger\Phi' + \text{h.c.}\right\}$$

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$$c_\gamma^2 = \frac{\eta_1 v^2 - m_h^2}{m_H^2 - m_h^2} \qquad \sin 2\gamma = \frac{2\eta_6 v^2}{m_H^2 - m_h^2}$$

Near Alignment, $c_\gamma \to 0$

$$\eta_1 \cong m_h^2/v^2 \simeq 0.26$$

$$c_\gamma \cong \frac{-\eta_6 v^2}{m_H^2 - m_h^2}$$

Natural Alignment in G2HDM: No need for Small η_6!

Near Alignment,

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$$\mu_{22}^2 + \tfrac{1}{2}(\eta_3 + \eta_4 + \eta_5)v^2$$

Condition:

$$|\eta_6| \lesssim \eta_{3,4,5} \sim \mathcal{O}(1) \lesssim \mu_{22}^2/v^2$$

helps if $\eta_{3,4,5} > 0$, "positivity" (?)

n.b. $m_h^2/v^2 \simeq 0.26$ Not Required.

For $\eta_{(1,)\,3,4,5} \sim \mathcal{O}(1)$ and positive, with η_6 somewhat smaller, the mixing between the CP-even states is small.

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$\eta_6 \sim 1/4$ would result in rather small c_γ

Essence:

$$M^2_{\rm even} = \begin{bmatrix} \eta_1 v^2 & \eta_6 v^2 \\ \eta_6 v^2 & \mu_{22}^2 + \frac{1}{2}(\eta_3 + \eta_4 + \eta_5)v^2 \end{bmatrix}$$

Single term (EWSB)

4 terms

Custodial SU(2) Illustration

$$\eta_4 = \eta_5 \equiv \eta' \Rightarrow m_A = m_{H^+}$$

$$m^2_{H^\pm} = \mu^2_{22} + \frac{1}{2}\eta_3 v^2,$$

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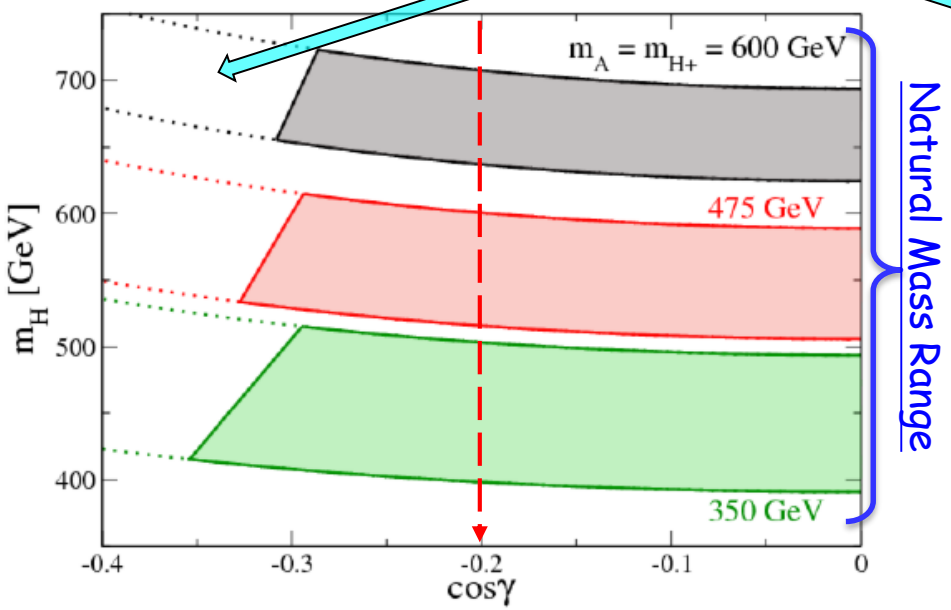
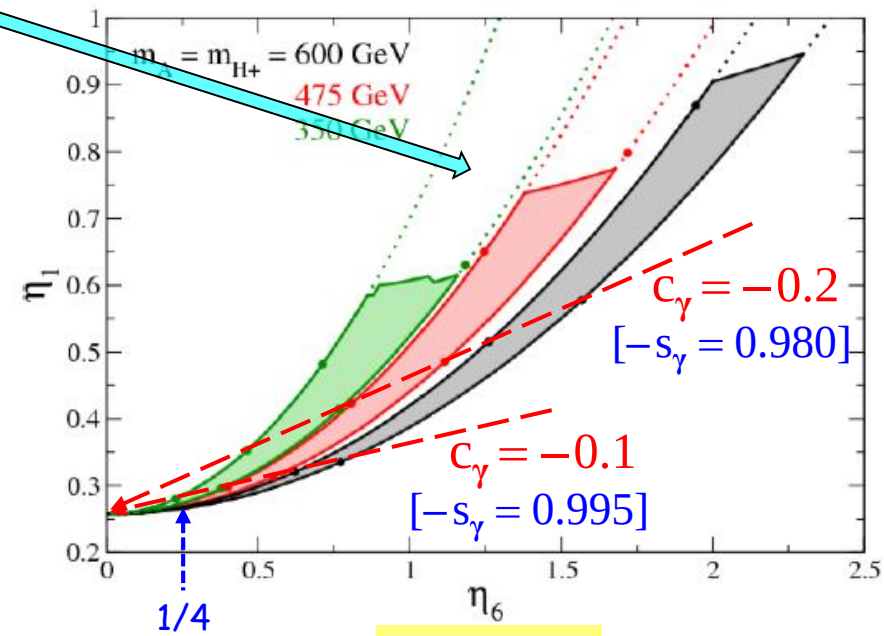
$$\Delta T^{2HDM} = \cancel{\Delta T_{SS}} + \Delta T_{SV}$$





$\eta_6 = O(1)$

Alignment is *Natural* in General 2HDM w/o Z_2

in contrast with fine-tuning in 2HDM-II

Custodial SU(2) Illustration

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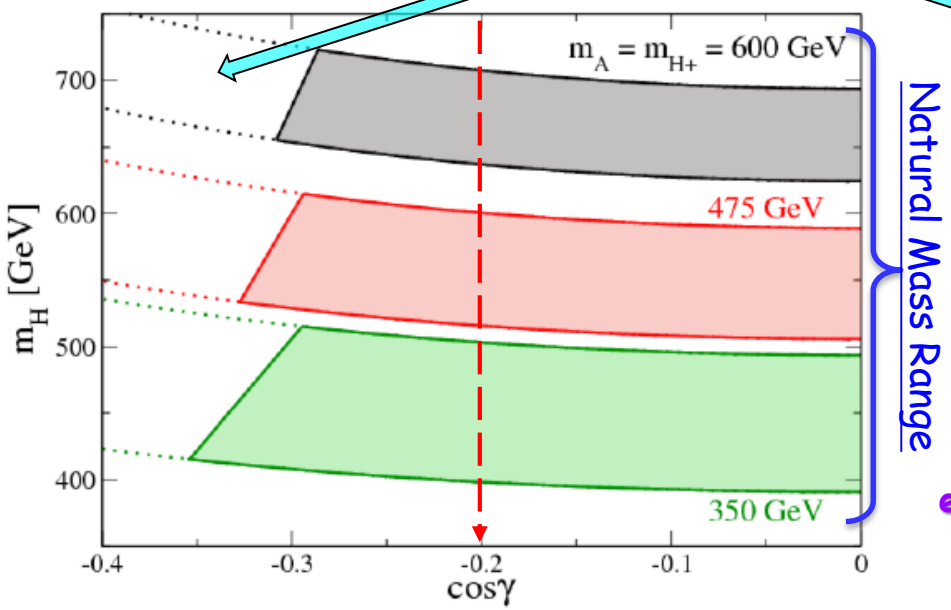
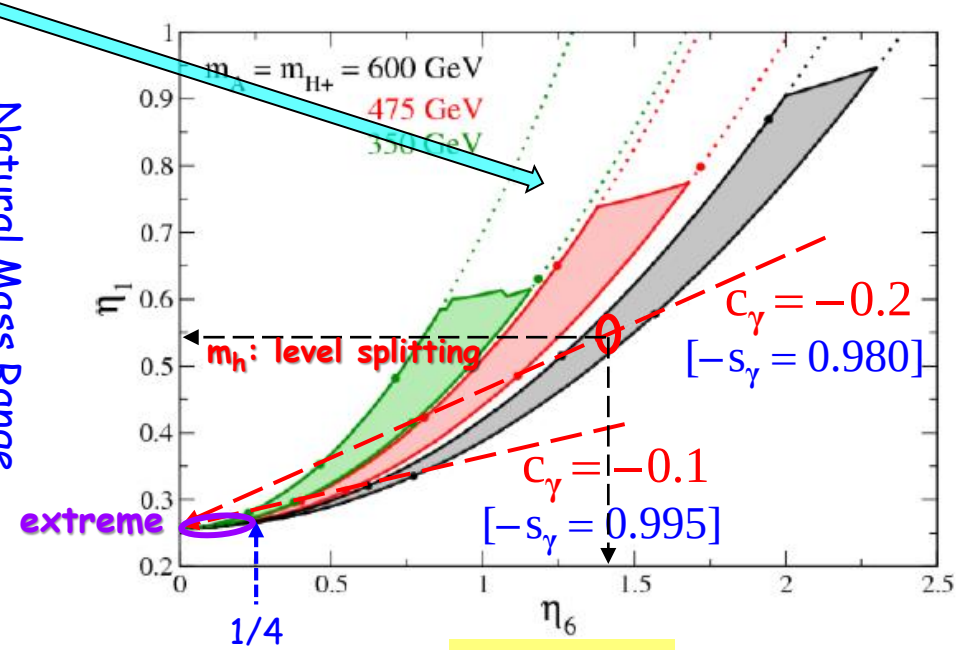




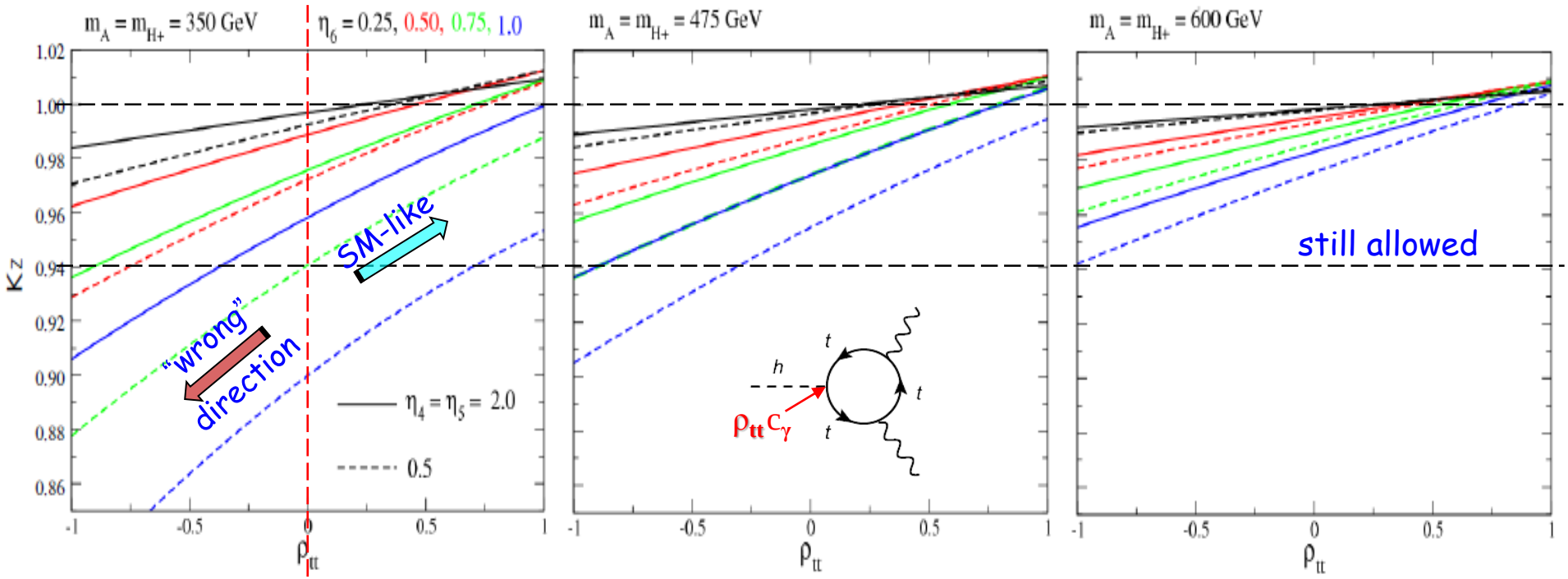
$\eta_6 = O(1)$

Alignment is *Natural* in General 2HDM w/o Z_2

in contrast with fine-tuning in 2HDM-II

One-loop Protection

κ_Z ($\sim \Gamma(h \to ZZ^*)/\Gamma(h \to ZZ^*)|^{\rm SM}$ measured experimentally)



Purely Bosonic Loops ($\mathcal{O}(1)$ couplings)

New Yukawa

$\rho_{tt} > 0$ and $\mathcal{O}(1)$ preferred: "Protects" Alignment

$\Rightarrow$ Original Motivation to Study Alignment in G2HDM

based on WSH & Kikuchi, 1704.03788, PRD'17

V. Pheno & Discussion

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

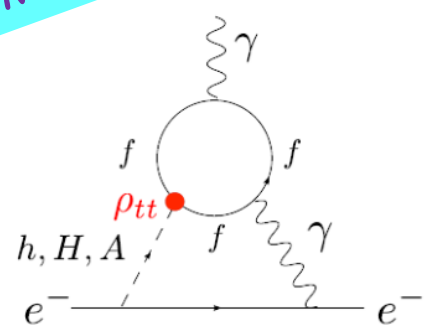
for illustration: $t_\beta = 1$, $c_{\beta-\alpha} = 0.1$

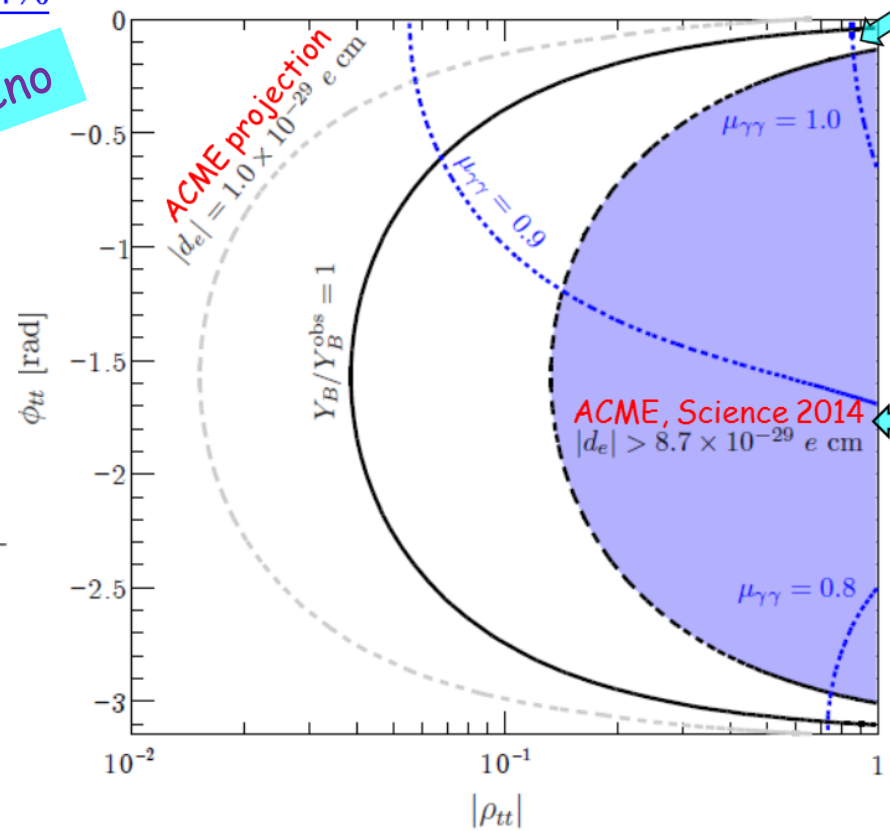
$\mathcal{B}(h \to \mu\tau) < 0.25\%$ CMS 13 TeV (2016)

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

vs $< 0.46\%\ (0.40\%)$ ATLAS (CMS)
0.24%

Much New FPCP Pheno





charged Higgs H^+

$h \to \gamma\gamma$ width reduction

(ρ_{tt} compensate)

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

Barr-Zee

e-EDM (2-loop)

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

$|\rho_{ee}| \sim y_e$

cancellations when imaginary

What does not vanish with Alignment, $c_{\beta-\alpha} \to 0$

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

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

$\mathcal{B}(h \to \mu\tau) < 0.25\%$ 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

vs $< 0.46\%\ (0.40\%)$ ATLAS (CMS)
0.24%

charged Higgs H^+

- EWBG — $\mathcal{O}(1)$ ρ_{tt} & Complex
- $h \to \gamma\gamma$ 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 — $\mathcal{O}(1)$ Higgs Couplings

the charm of EWBG

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

probably hidden in tt(bar)

param. space much broader

$h \to \gamma\gamma$ width reduction
(ρ_{tt} compensate)
$c_{\beta-\alpha} \to 0$

Barr-Zee
e-EDM (2-loop)
but: $c_{\beta-\alpha} \to 0$
$|\rho_{ee}| \sim y_e$
cancellations when imaginary

Niche for Extra Higgses

- $b \to s\gamma$: New Bound $m_{H^+} > 570$ GeV (Misiak-Steinhauser JHEP'17) for 2HDM-II
  - ➔ Misiak bound does not apply in G2HDM: depend on ρ_{tt}, ρ_{tc}, ρ_{cc}, ρ_{bb}
  - ➔ Need targeted study ! [underway

$\bar{u}(V\rho^d R - \rho^u V L)dH^+$

- Parameter space much larger than illustrated:
  - Positivity not necessary;
  - Custodial not necessary (e.g. also Twisted Custodial); H could be lighter than A, H^+
  - Link with EWBG nice, but not necessary
  - Larger μ_{22} bridges to Decoupling

  } ➔ Spectrum Sub-TeV preferred

- H-A mixing: With $\mathrm{Im}\,\rho_{tt}$ needed for BAU, test at collider [under study
- H, A, H^+ Production & Decay: What is spectrum?
  - H, A: hidden by/in gg → tt(bar) ?
  - H^+: hidden by/in tb(bar) ? [tt(bar) BG]
    - ➔ ttH/A & tbH^+ way to go?

Natural Mass Range ?

$$m_A = m_{H^+} = 350,\ 475,\ 600\ \text{GeV}$$

keep $\eta_3 \lesssim 3$

$$\underbrace{\mu_{22}^2/v^2}_{\gtrsim (367\ \text{GeV})^2,\ (519\ \text{GeV})^2,} + \eta_3/2 \simeq 2,\ \underbrace{3.7,\ 6,}$$

- H → tc search Altunkaynak et al., 1506.00651

V. Conclusion : H^0, A^0, $H^\pm$ in Our Time

~~General~~ 2HDM (w/o Z_2)

- EWBG Surprisingly Efficient w/

  $\mathcal{O}(1)$ { Higgs quartics η_i ; New Yukawa ρ_{tt} [and ρ_{tc} }

  N.B. $\mathcal{O}(1)$ Modulo flavor org. (of SM): much smaller Yuk. involving lower gen.

- Much New FPCP Pheno

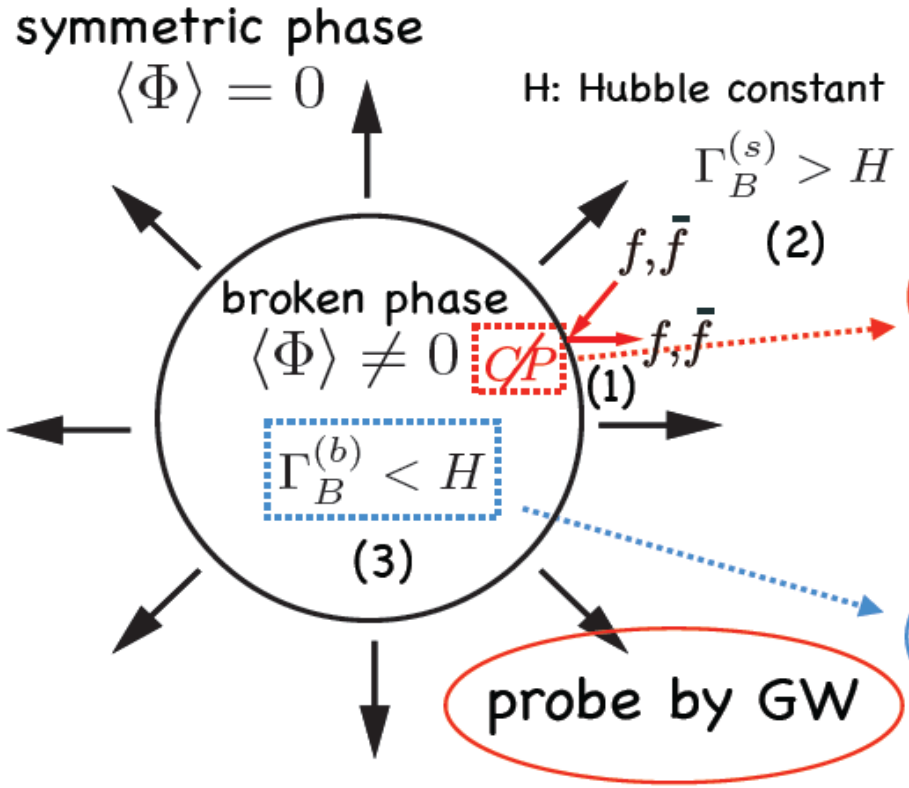
- Alignment Emerges Naturally w/ $\mathcal{O}(1)$ Higgs quartics
  - mild tuning (1/4) ➔ Extreme Alignment
  - mild Alignment ($c_\gamma = -0.2$) ➔ low m_h by level repulsion
  - **sub-TeV H, A, H^+** preferred ➔ rethink LHC Search

- Discover @ LHC!?
  - NOT SUSY!
  - Touch EWBG! [need CPV probe
  - Another Energy Layer! [guaranteed by Landau pole

EWBG in a nutshell

courtesy Eibun Senaha

[Kuzmin, Rubakov, Shaposhnikov, PLB155,36 ('85)]



How do we test this scenario?

-> cannot redo EWPT in lab. exp.

So, test Sakharov'criteria instead.

probe by CPV physics

EDMs, B decays etc

< TeV

probe by collider physics

Higgs physics etc

(1) Asymmetries arise (∵ CPV) but no BAU. $n_B = \underbrace{n_b^L - n_{\bar{b}}^L}_{\neq 0} + \underbrace{n_b^R - n_{\bar{b}}^R}_{\neq 0} = 0$

(2) LH part changes (∵ sphaleron) -> BAU $n_B = \underbrace{n_b^L - n_{\bar{b}}^L}_{\text{changed}} + n_b^R - n_{\bar{b}}^R \to n_B \neq 0$

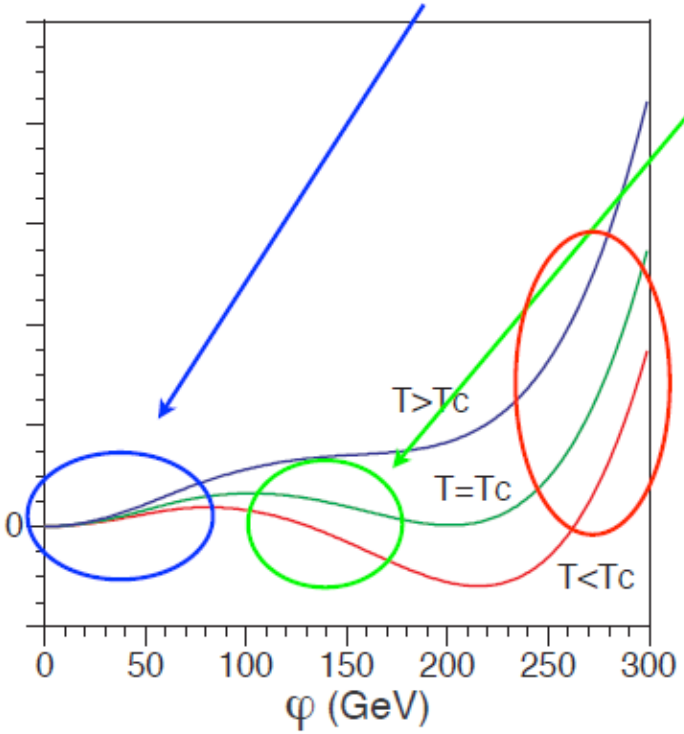
(3) If $\Gamma_B^{(b)} < H$ the BAU can survive.

1st-order EWPT

courtesy Eibun Senaha

Veff

$$V_{\rm eff} \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 \underset{T=T_C}{\rightarrow} \frac{\lambda_{T_C}}{4}\varphi^2(\varphi - v_C)^2$$



$$v_C = \frac{2ET_C}{\lambda_{T_C}} \quad \Rightarrow \quad \frac{v_C}{T_C} = \frac{2E}{\lambda_{T_C}}$$

- Heavy Higgs loops can enhance E.

$$m^2_{i=H,A,H^\pm} = M^2 + \tilde{\lambda}_i\varphi^2$$

non-decoupling

$$V_{\rm eff} \ni \begin{cases} -\tilde{\lambda}^{3/2}T\varphi^3\left(1+\frac{M^2}{\tilde{\lambda}\varphi^2}\right)^{3/2}, & \text{for } M^2 \ll \tilde{\lambda}\varphi^2, \\ -|M|^3T\left(1+\frac{\tilde{\lambda}\varphi^2}{M^2}\right)^{3/2}, & \text{for } M^2 \gtrsim \tilde{\lambda}\varphi^2. \end{cases}$$

decoupling

Non-decoupling heavy Higgs bosons play a central role in enhancing E.

1st-order EWPT

courtesy Eibun Senaha

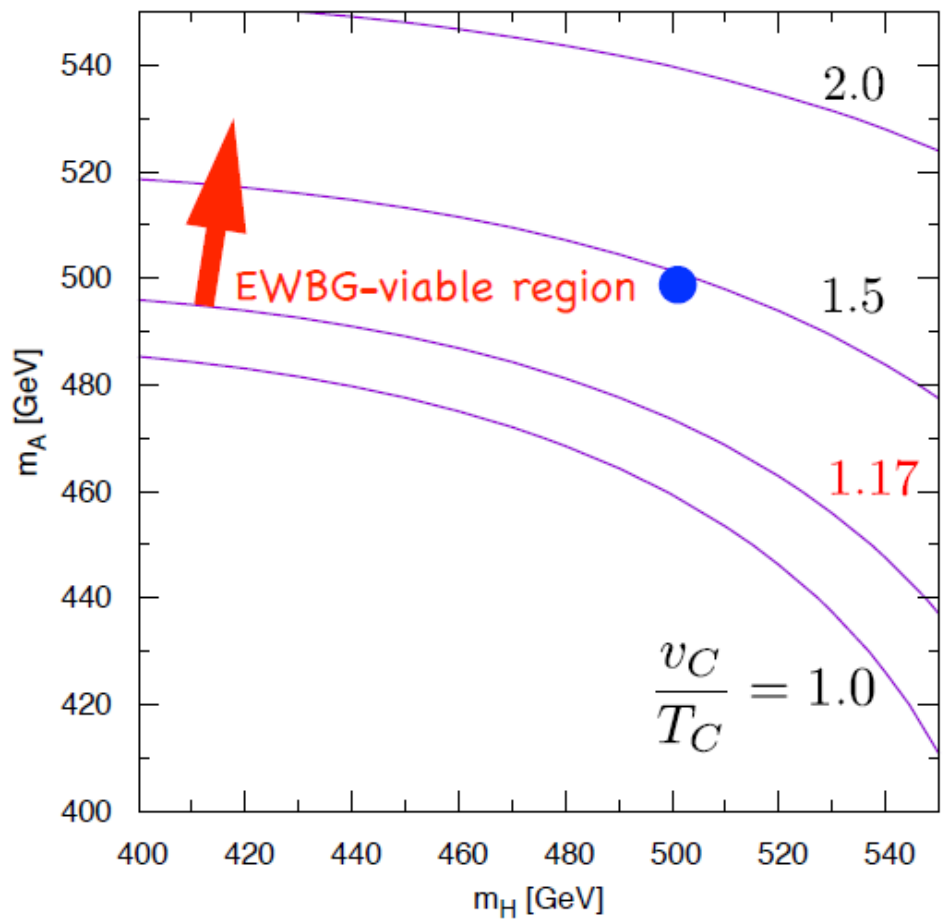
$$s_{\beta-\alpha} = t_\beta = 1, m_{H^\pm} = m_A, \; M = \sqrt{m_3^2/s_\beta c_\beta} = 300 \text{ GeV}$$
$$\lambda_6 = \lambda_7 = 0$$

- EWBG-viable region

  v_C/T_C > 1.17

- Heavy Higgs w/ non-decoupling plays a role.

- Too heavy Higgs could violate perturbativity.



Benchmark point:

$$m_H = m_A = m_{H^\pm} = 500 \text{ GeV}$$
$$\frac{v_C}{T_C} = 1.48$$