The Case for Extra Yukawas

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Thanks to Francisco and Bohdan and Nuno
+ others for various Intro

Curious

The Case for Extra Yukawas

^

SM2

SM2 $\neq$ SM4½ ☺

The Case for Extra Yukawas

I. Intro: 2HDM-III

Extra Yukawa Coupling Thoughts

II. EWBG

- $\mathcal{O}(1)$ Quartics: 1st Order PT
- $\mathcal{O}(1)$ $\mathbf{Im}\,\rho_{tt}$: Source of CPV

2nd Top Yukawa

III. Extra Yukawas

an Experimental Question

IV. Curious: Alignment

- $\mathcal{O}(1)$ Quartics Consistent!
- Alignment: Replaces Glashow-Weinberg NFC

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

I. Intro: 2HDM-III

Extra Yukawa Coupling Thoughts

a second Higgs

let's assume fundamental, then ...

Highly Plausible!

Known **CPV** in CKM ➔ Yukawa's. **Extra Yukawa**'s?

Jarlskog Invariant *way too small* for Universe!

Killed by Z_2 (Glashow-Weinberg 1977)

Natural Flavor Conservation

Glashow-Weinberg'77 vs (Fritzsch-)Cheng-Sher'87

No Extra Yukawas by Z_2

Genuine Extra Yukawas (2HDM)

fermion mass-mixing

u-, d-type mass each from separate doublet

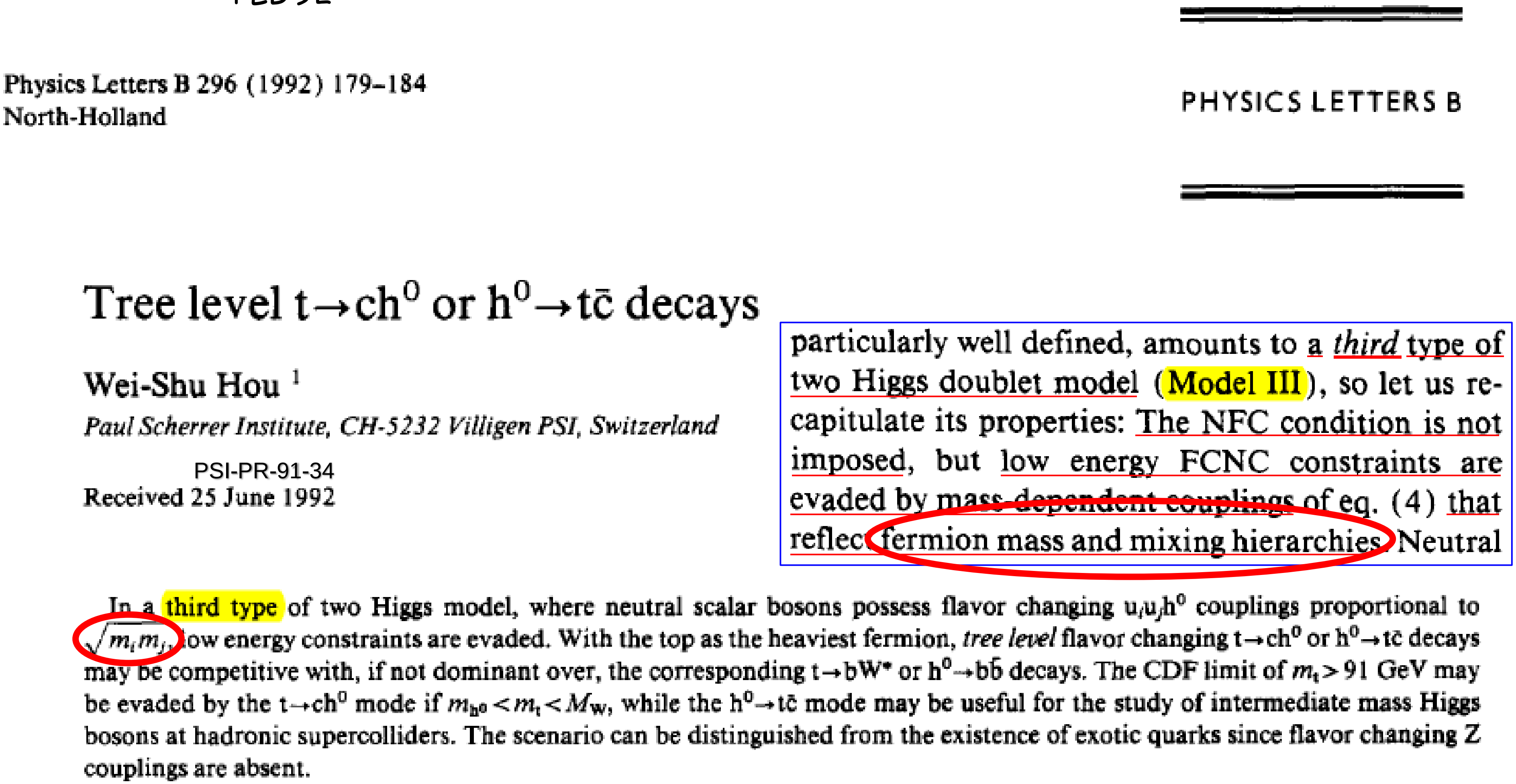
→ Same Yuks. as SM

$$M_{ij} = M_{ij}^{(1)} + M_{ij}^{(2)}$$

FCNC OK, if $\boxed{M_{ij}^{(k)} \sim \underbrace{\Delta_{ij}^{(k)}}_{\sim\, \mathcal{O}(1)} \sqrt{m_i m_j}}$

My take (1991): $t \to ch$

PLB'92



Physics Letters B 296 (1992) 179–184
North-Holland

PHYSICS LETTERS B

Tree level $t \to ch^0$ or $h^0 \to t\bar{c}$ decays

Wei-Shu Hou [1]
Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland

PSI-PR-91-34
Received 25 June 1992

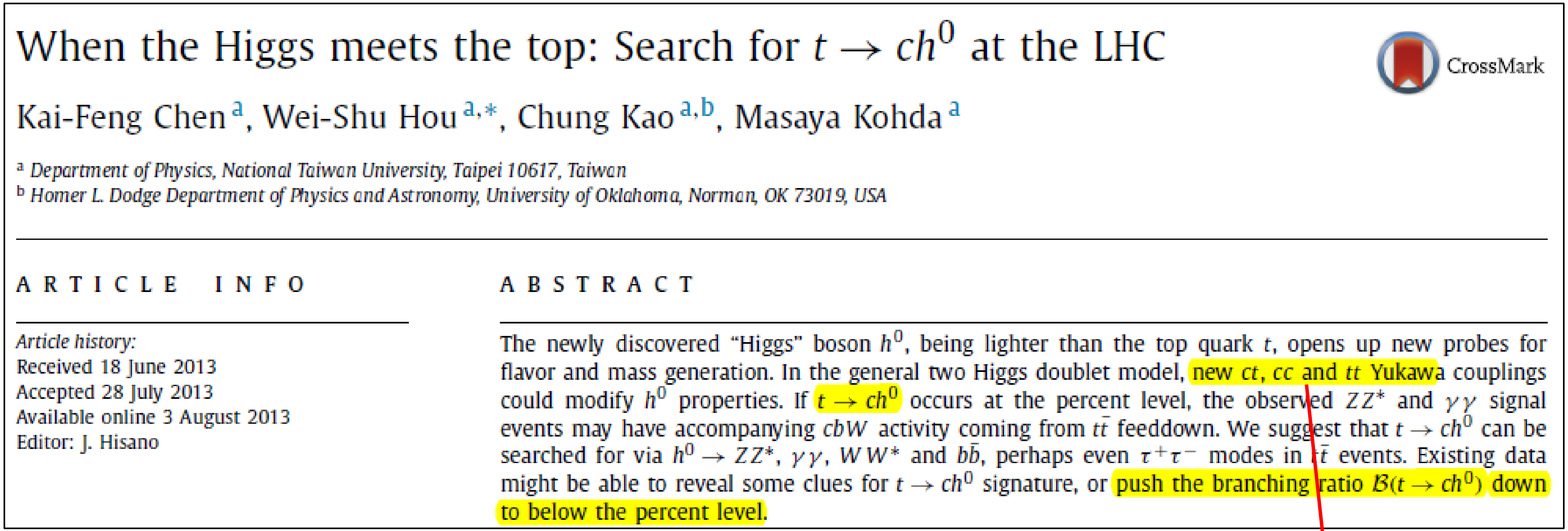
In a third type of two Higgs model, where neutral scalar bosons possess flavor changing $u_iu_jh^0$ couplings proportional to $\sqrt{m_im_j}$, low energy constraints are evaded. With the top as the heaviest fermion, *tree level* flavor changing $t \to ch^0$ or $h^0 \to t\bar{c}$ decays may be competitive with, if not dominant over, the corresponding $t \to bW^*$ or $h^0 \to b\bar{b}$ decays. The CDF limit of $m_t > 91$ GeV may be evaded by the $t \to ch^0$ mode if $m_{h^0} < m_t < M_W$, while the $h^0 \to t\bar{c}$ mode may be useful for the study of intermediate mass Higgs bosons at hadronic supercolliders. The scenario can be distinguished from the existence of exotic quarks since flavor changing Z couplings are absent.

particularly well defined, amounts to a *third* type of two Higgs doublet model (Model III), so let us recapitulate its properties: The NFC condition is not imposed, but low energy FCNC constraints are evaded by mass-dependent couplings of eq. (4) that reflect fermion mass and mixing hierarchies. Neutral

2012+: *One Higgs* → 2nd Higgs

Highly Plausible !

PLB'13



When the Higgs meets the top: Search for $t \to ch^0$ at the LHC

CrossMark

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ABSTRACT

The newly discovered "Higgs" boson h^0, being lighter than the top quark t, opens up new probes for flavor and mass generation. In the general two Higgs doublet model, new ct, cc and tt Yukawa couplings could modify h^0 properties. If $t \to ch^0$ occurs at the percent level, the observed ZZ^* and $\gamma\gamma$ signal events may have accompanying cbW activity coming from $t\bar{t}$ feeddown. We suggest that $t \to ch^0$ can be searched for via $h^0 \to ZZ^*$, $\gamma\gamma$, WW^* and $b\bar{b}$, perhaps even $\tau^+\tau^-$ modes in $t\bar{t}$ events. Existing data might be able to reveal some clues for $t \to ch^0$ signature, or push the branching ratio $\mathcal{B}(t \to ch^0)$ down to below the percent level.

$$\boxed{\rho_{ct}\underbrace{\cos(\beta-\alpha)}\bar{c}th^0}$$

FCNH modulated by *h*–*H* mixing

→ "Alignment" could overtake Glashow-Weinberg NFC

$\sqrt{m_i m_j}$ only scaffold

$$\begin{pmatrix}\rho_{cc} & \rho_{ct}\\ \rho_{tc} & \rho_{tt}\end{pmatrix}$$

Extra Yukawas

2HDM (w/o Z_2): FCNH ρ_{ij}

→ Alignment can overtake Glashow-Weinberg NFC

General Yukawa interaction for up-type quarks

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

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

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

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

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

diagonal

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

FCNH (Flavor Changing Neutral H)

Neutral up-type Yukawa interaction

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

alignment limit !

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

→ diag. (SM-h)

→ FCNH $\boxed{\rho_{ij}}$

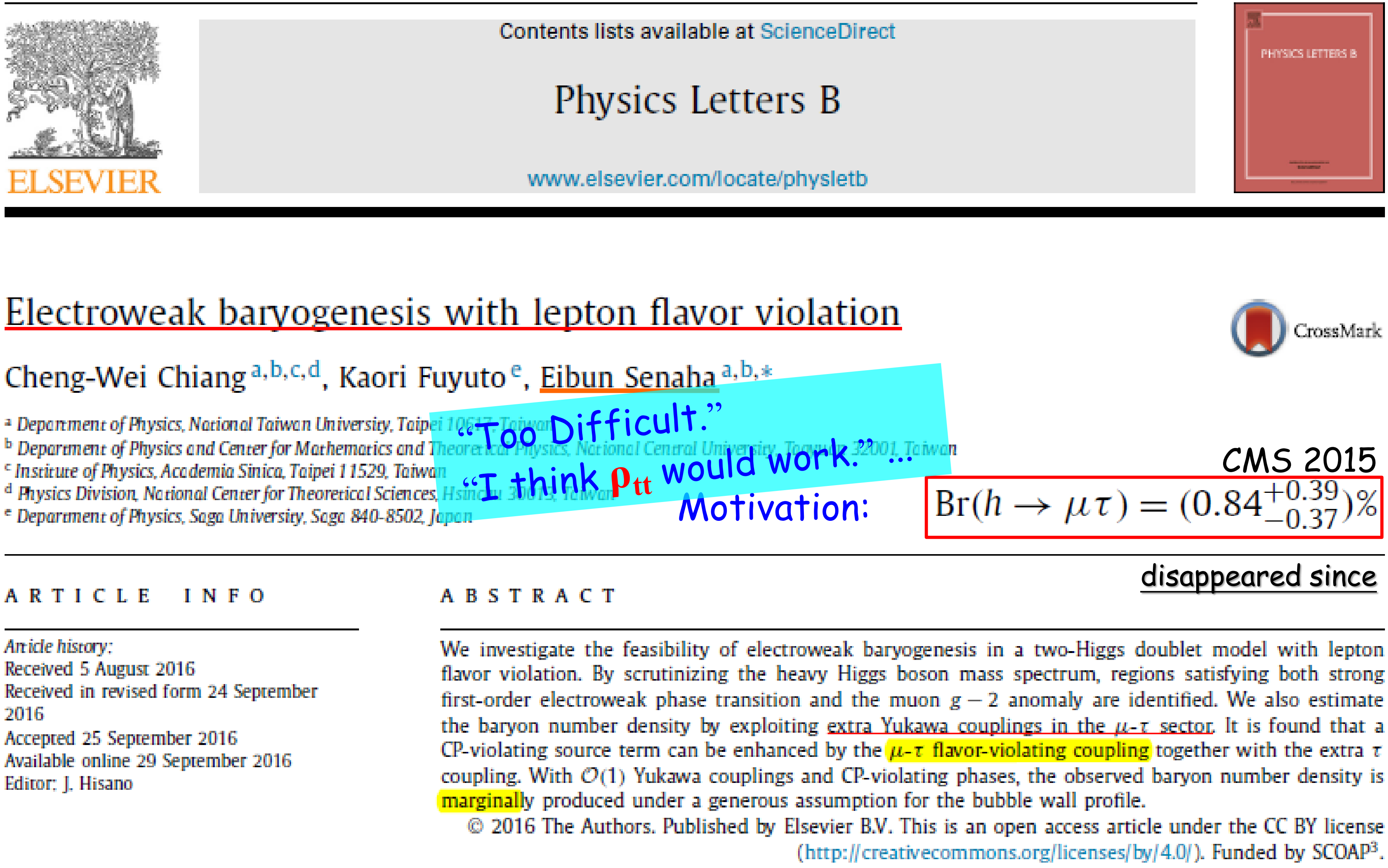
$\boxed{|\rho_{ij}|e^{i\phi_{ij}}}$

N.B. $\tan\beta$ unphysical
[2HDM II notation]

II. ElectroWeak BaryoGenesis

$\left\{ \begin{array}{ll} \mathcal{O}(1) \text{ Quartics:} & 1^{st} \text{ Order PT} \\ \mathcal{O}(1)\ \mathbf{Im}\,\boldsymbol{\rho}_{tt}\text{:} & \text{Source of CPV} \end{array} \right.$

2nd Top Yukawa



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Electroweak baryogenesis with lepton flavor violation

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“Too Difficult.”

“I think ρ_{tt} would work.” …

Motivation:

CMS 2015

$$\boxed{\mathrm{Br}(h \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%}$$

disappeared since

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ABSTRACT

We investigate the feasibility of electroweak baryogenesis in a two-Higgs doublet model with lepton flavor violation. By scrutinizing the heavy Higgs boson mass spectrum, regions satisfying both strong first-order electroweak phase transition and the muon $g-2$ anomaly are identified. We also estimate the baryon number density by exploiting extra Yukawa couplings in the μ-τ sector. It is found that a CP-violating source term can be enhanced by the μ-τ flavor-violating coupling together with the extra τ coupling. With $\mathcal{O}(1)$ Yukawa couplings and CP-violating phases, the observed baryon number density is marginally produced under a generous assumption for the bubble wall profile.

EWBG2: $\overbrace{\text{“}\lambda_i\text{”}; \quad \mathrm{Im}\,\rho_{tt}}^{\sim\,\mathcal{O}(1)}$

folklore

strongly 1st order EW phase transition (EWPT)

Expanding Bubble of Broken Phase

Extra Higgs Thermal Loops
w/ $\mathcal{O}(1)$ Higgs Quartics

“λ_i” 2HDM OK

see e.g. Kanemura, Okada, Senaha, PLB'05

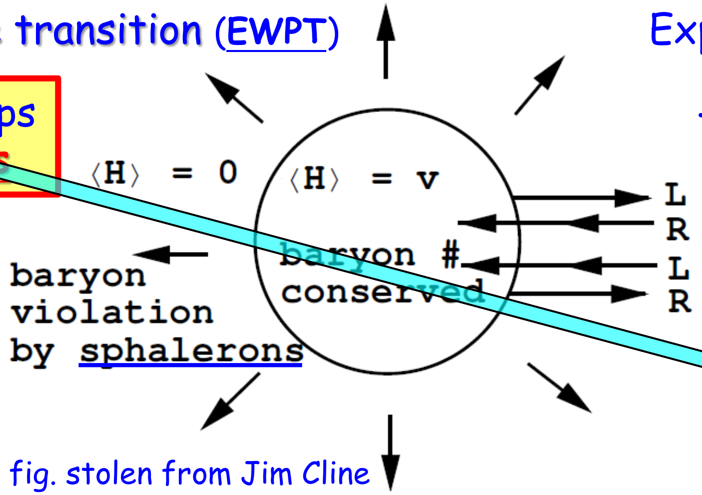


fig. stolen from Jim Cline

To avoid n_B washout:

Hubble const.

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

n_B changing rate (broken phase)

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

vev @ T_C

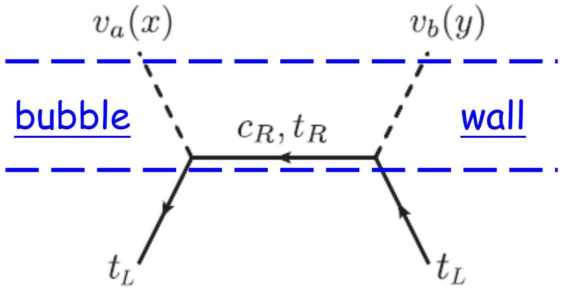
$\sqrt{v_1^2(T_C)+v_2^2(T_C)}$ (keep υ_1, υ_2)

Baryon Asymm. of Universe (BAU) n_B/s

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

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
$\boxed{n_L}$	l.h. fermion density (l.h. top density)
z'	coord. oppo. bubble exp. dir.

K. Fuyuto, WSH, & E. Senaha, PLB'18 [1705.05034]

CPV Top Interactions

Extra Yukawas

CPV source term

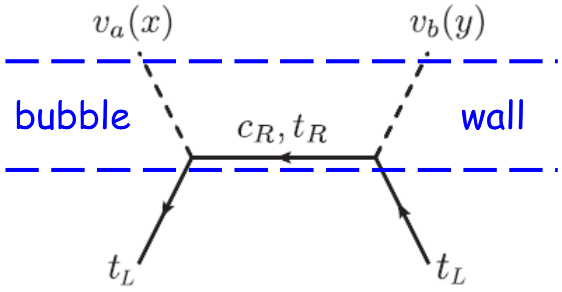
$$\boxed{S_{i_L j_R}(Z) = N_C F\, \mathrm{Im}\left[(Y_1)_{ij}(Y_2)^*_{ij}\right] v^2(Z)\, \partial_{t_Z}\beta(Z)}$$

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

* See e.g. Chiang, Fuyuto, Senaha, PLB'16

Baryon **A**symm. of **U**niverse (**BAU**) **n_B/s**

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



BAU ⇐ **CPV Top Interactions** at Bubble Wall

left-handed Top density

$\boxed{n_L}$

skip detail (Transport)

K. Fuyuto, WSH, & E. Senaha, PLB'18 [1705.05034]

z' coord. oppo. bubble exp. dir.

CPV Top Interactions

Extra Yukawas

CPV source term

"Jarlskog": both doublets participate

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

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

To understand the EWBG scatter plot to follow, suppose (H.K. Guo et al. 1609.09849)

$(Y_1)_{tc} \neq 0,\ (Y_2)_{tc} \neq 0,\ (Y_1)_{tt} = (Y_2)_{tt} \neq 0$ (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_R^u

but $-Y_1 + Y_2$ not diag.

solve

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

CPV Source

ρ_{tc} still basically free param.

ρ_{tt} and ρ_{tc} least constrained

Altunkaynak, WSH, Kao, Kohda, McCoy PLB'15

K. Fuyuto, WSH, & E. Senaha, PLB'18 [1705.05034]

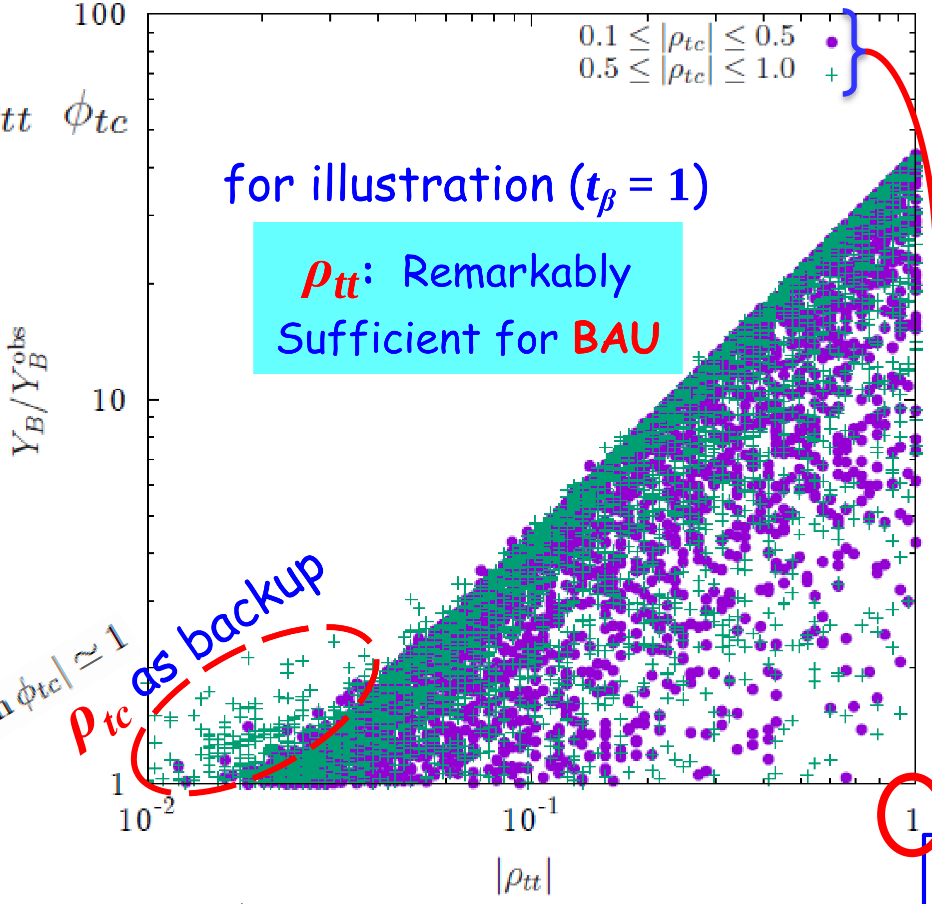
Bonus: Extra Yukawa Drive EWBG!

BaryoGenesis

Fuyuto, WSH, & Senaha, PLB'18
[1705.05034]

scan over $|\rho_{tc}|$ ϕ_{tt} ϕ_{tc}

$Y_B/Y_B^{\rm obs}$



for illustration ($t_\beta = 1$)

ρ_{tt}: Remarkably Sufficient for **BAU**

ρ_{tc} as backup

$|\sin\phi_{tc}| \simeq 1$

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

Altunkaynak et al., 1506.00651

no obvious diff.

⇒ ρ_{tt} driven!

the charm of EWBG

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

sub-TeV

small ρ_{tt}

$$\overbrace{T_C = 119.2\ \text{GeV} \quad v_C = 176.7\ \text{GeV}}^{v_C/T_C\ >\ \mathcal{O}(1)} \quad v_w = 0.4 \quad \Delta\beta = 0.015 \quad D_q = 8.9/T \quad D_H = 101.9/T$$

$$m_{t_L} = 0.59T \quad m_{t_R} = 0.62T \quad m_{c_R} = 0.50T \quad \Gamma_{q_{L,R}} = 0.22T \quad \Gamma_B^{(s)} = 120\alpha_W^5 T \quad \Gamma_{ss} = 16\alpha_s^4 T$$

III. Extra Yukawas — an Experimental Question

- When h(125) was found lighter than top, there is no way to stop the experimentalist, young or not so young (e.g. Daniel Fournier) from $t \to ch$ searching, because s/he ***can***.
- If s/he was told that Glashow&Weinberg somehow forbade it since 1977, the response would be … *What!?* … … (pause) … *– Splendid, so much the better, Can Not Lose!*
- The bottom line: It is a PDG Entry. [my bottom line for 4G search at LHC]

Note: tch coupling is dimension-4, *Not a Higher Dim. Operator*.
It is in the form of a Yukawa coupling, but forbidden in SM.
It *implies* an Extra Scalar Doublet to have Extra Yukawa Couplings.

By generalization, it should be extended to Extra Yukawa Couplings for $\mathbf{i}, \mathbf{j} = \mathbf{1}–\mathbf{3}$, and for $\mathbf{F} = \mathbf{u}, \mathbf{d}, \boldsymbol{\ell}$.

Existence of Extra Yukawas is an Experimental Issue

IV. Curious: Alignment

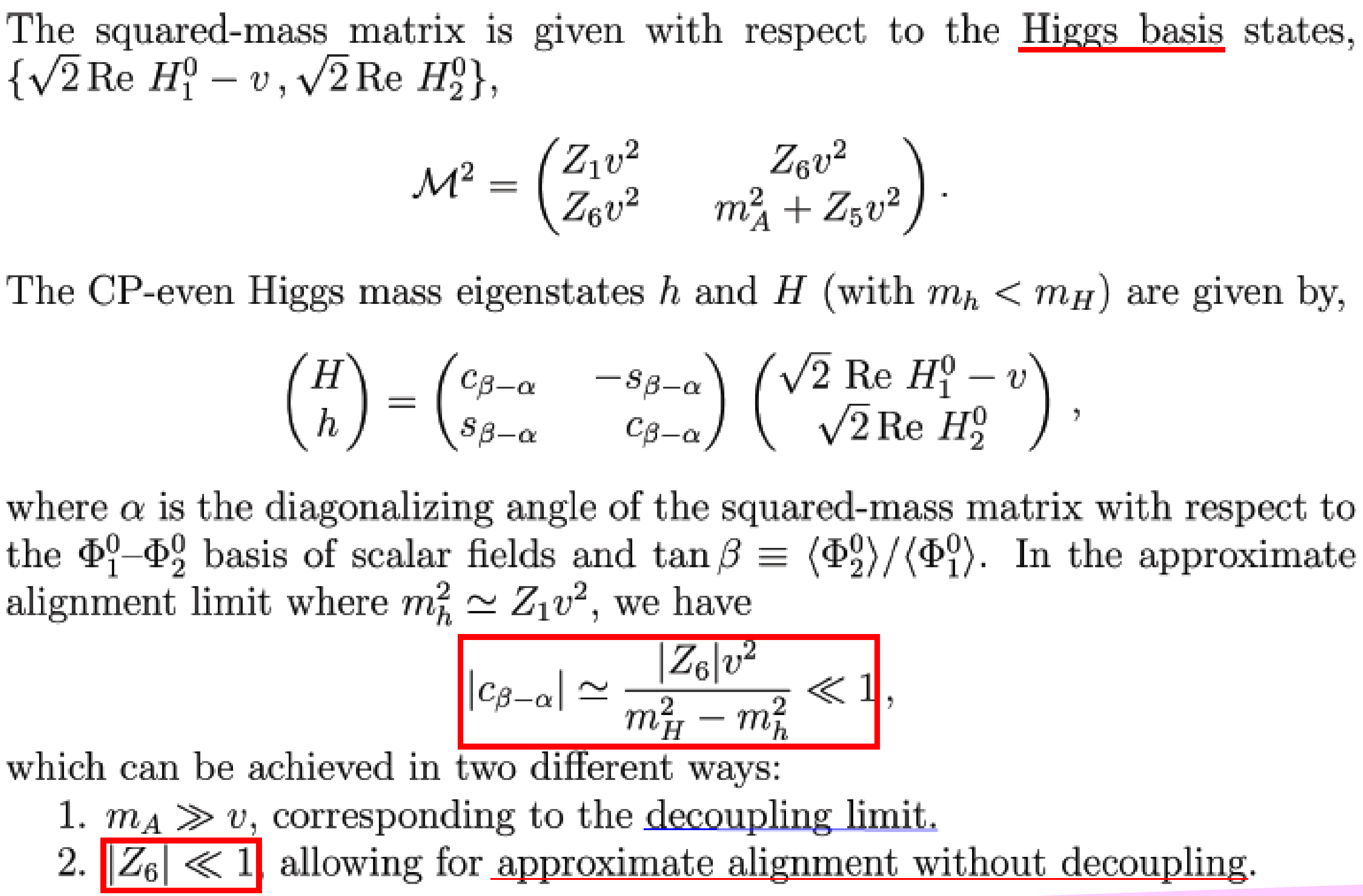
$$\begin{cases} \mathcal{O}(1) \text{ Quartics Consistent !} \\ \underline{\text{Alignment}}\text{: Replaces Glashow-Weinberg NFC} \end{cases}$$

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

BSM H Outlook

Howie Haber @ Toyama, 3/2017

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 (MSSM)

Alignment w/o decoupling seems not easy ...

Alignment: $\tan\beta,\ m^2_{12}$ vs $\eta_6,\ \eta_7;\ \mu_{22}$

2HDM-II vs 2HDM w/o Z_2

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

Higgs basis

($\tan\beta$ unphysical)

assume CP-Inv.

EWSB

minimization

$$\mu_{11}^2 = -\frac{1}{2}\eta_1 v^2, \quad \underbrace{\mu_{12}^2 = \frac{1}{2}\eta_6 v^2,}_{}$$

[see Haber & O'Neil, PRD'06

"soft breaking" term absorbed

η_6 is unique mixing parameter

Alignment: $\tan\beta$, m^2_{12} vs $\eta_6, \eta_7; \mu_{22}$

2HDM-II vs 2HDM w/o Z_2

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

Higgs basis

($\tan\beta$ unphysical)

assume CP-Inv.

EWSB

minimization

$$\mu_{11}^2 = -\frac{1}{2}\eta_1 v^2, \quad \underbrace{\mu_{12}^2 = \frac{1}{2}\eta_6 v^2,}_{}$$

[see Haber & O'Neil, PRD'06

"soft breaking" term absorbed

η_6 is unique mixing parameter

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

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

cos(β–α)

$$M^2_{\rm even} = \begin{bmatrix} \eta_1 v^2 & \eta_6 v^2 \\ \eta_6 v^2 & \mu_{22}^2 + \frac{1}{2}(\eta_3+\eta_4+\eta_5)v^2 \end{bmatrix} \xrightarrow{\text{diag.}} R_\gamma^T M^2_{\rm even} R_\gamma = \begin{bmatrix} m_H^2 & 0 \\ 0 & m_h^2 \end{bmatrix}$$

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

Near Alignment,
c_γ small

$$\Longrightarrow \left\{\begin{aligned} \eta_1 v^2 - m_h^2 &\sim \text{sub-}v^2 \\ m_H^2 - m_h^2 &> \textit{several}\ v^2 \end{aligned}\right. \Longrightarrow \boxed{c_\gamma \cong \frac{-\eta_6 v^2}{m_H^2 - m_h^2}}$$

Alignment can be *Emergent* in 2HDM w/o Z_2

in contrast with fine-tuning in 2HDM-II

$\boxed{\eta_4 = \eta_5 \equiv \eta'}$ ⟹ $\boxed{m_A = m_{H+}}$

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

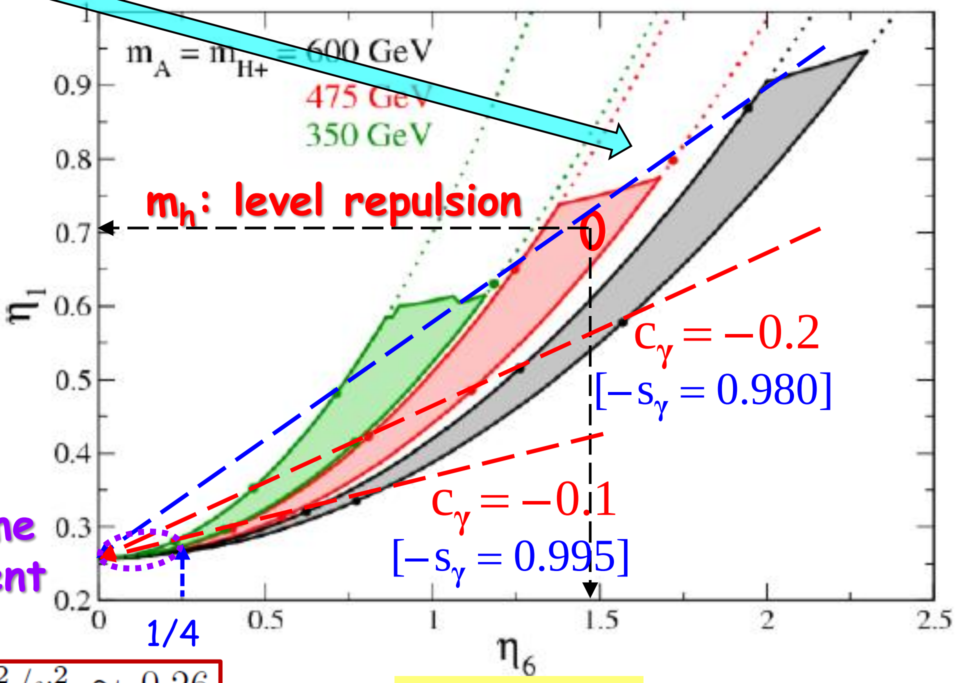
Custodial SU(2) Illustration

$\cancel{\Delta T_{SS}} + \Delta T_{SV}$

EW Precision Constraint

$\eta_5 < 3$

η_i's: Higgs Self-Couplings



m_h: level repulsion

$c_\gamma = -0.2$

$[-s_\gamma = 0.980]$

$c_\gamma = -0.1$

$[-s_\gamma = 0.995]$

extreme alignment

1/4

$\boxed{m_h^2/v^2 \simeq 0.26}$

$\eta_6 = \mathcal{O}(1)$

Quite Allowed!

$\mathcal{O}(1)$ Higgs (quartic) self-couplings → Near Alignment: c_γ Small

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

- **Higgs** boson h^0 125 GeV in mass discovered in 2012, H^0, A^0, $H^\pm$
  if remnant member of fundamental Higgs doublet → 2nd Doublet Reasonable

- Exquisite CKM "**Flavor**" picture (mass-mixing structure) at B Factories & LHCb
  → The Flavor physicists feel the Yukawa *Dynamics* in their bones!

- Happy marriage of Glashow-Weinberg NFC and SUSY for years: 2HDM-II
  Alignment: h^0 resembles SM Higgs! → 2nd Doublet is Multi-TeV (decoupled)?
  and SUSY not seen ...

- Remove NFC, i.e. allow Flavor-Changing Neutral Higgs Couplings
  → *Alignment* can *Emerge* for $\mathcal{O}(1)$ Higgs Quartic Self-Couplings
  WSH & M. Kikuchi, EPL'18
  - H^0, A^0, $H^\pm$ at Sub-TeV! → Potential LHC Discovery
  - **Extra Yukawa's**: ρ_{ij} esp. ρ_{tt}, ρ_{tc} → Impact Flav. Phys. & CP Violation
    $\mathcal{O}(1)$ no time to touch ...
    Fuyuto, WSH, Seneha, PLB'18
  - **Bonus**: account for Baryon Asymmetry of the Universe !?

triple-top!

Verification: Extra Higgs Discovery @ LHC (e.g. $cg \to tH, tA$)

Broad Future **FPCP** Program

Kohda, Modak, WSH, PLB'18

Thank you!

SM2: SM with 2nd Higgs Doublet

No further assumptions,
except learn from *Nature*.

"FPCP" Review: Chang, Chen, WSH, PNPP'17
"HEP Window" Review: WSH, 1901.04033

Much New FPCP Pheno

most vanish with $c_\gamma \to 0$ alignment protection

for illustration: $c_\gamma = 0.1$ $c_\gamma \to 0$

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

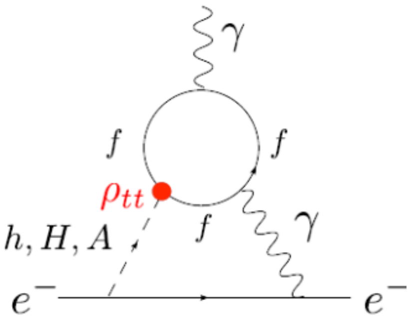
vs < ~~0.46%~~ (~~0.40%~~) ATLAS (CMS)

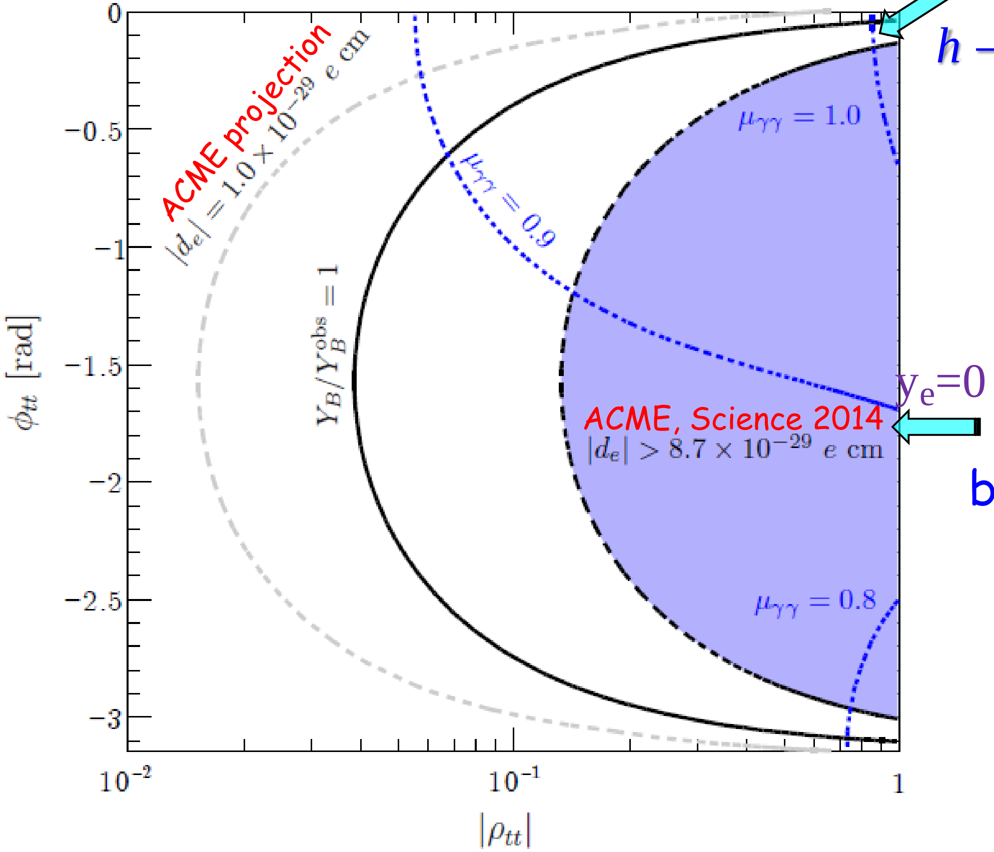
0.22% ATLAS 1707.01404

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

$c_\gamma \to 0$

⇨ $\mathcal{B}(\tau \to \mu\gamma) \lesssim 10^{-8}$ Belle II





charged Higgs H^+

$h \to \gamma\gamma$ width reduction

(ρ_{tt} compensate)

$c_\gamma \to 0$

Barr-Zee

e-EDM (2 loop)

but: $\left\{ \begin{array}{l} c_\gamma \to 0, \\ |\rho_{ee}| \sim y_e \end{array} \right.$

cancellations when imaginary

What does not vanish with Alignment, $c_\gamma \to 0$

circumvent alignment protection

for illustration: $c_\gamma = 0.1$

$c_\gamma \to 0$

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

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

0.22% ATLAS 1707.01404

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

$c_\gamma \to 0$

⇨ $\mathcal{B}(\tau \to \mu\gamma) \lesssim 10^{-8}$ Belle II

charged Higgs H^+

$h \to \gamma\gamma$ width reduction

(ρ_{tt} compensate)

$c_\gamma \to 0$

$\mathcal{O}(1)$ ρ_{tt} & Complex

$\mathcal{O}(1)$ Higgs Quartics

- **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**

the charm of EWBG

$$\boxed{\underbrace{m_H = m_A}_{} = m_{H^\pm} = 500\ {\rm GeV}}$$

probably hidden in tt(bar)

param. space much broader

Barr-Zee

e-EDM (2-loop)

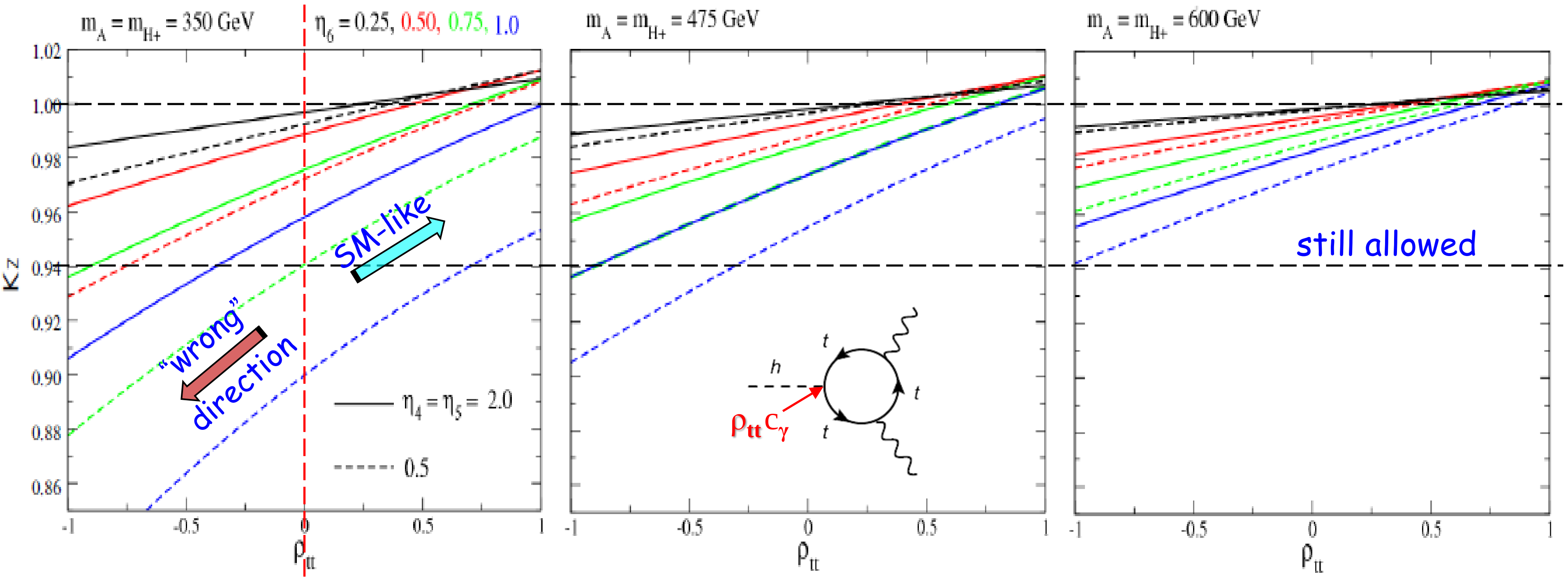
but: $c_\gamma \to 0$,

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

cancellations when imaginary

ρ_{tt}
One-loop Protection

κ_Z ($\sim |\Gamma_{h\to ZZ^*}/\Gamma^{\rm SM}_{h\to ZZ^*}|^{1/2}$ 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]