Searching for New Scalar Bosons via Triple-Top Signature in cg → ttt(bar)

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19 April @ LIO/Flav-NewPhys, IPNL, Lyon

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Flavour Down Under

Outline

I. Intro: 2HDM & Extra Yukawas

→ Two Top Utilities

II. Bonus 1: EWBG2-t

III. Bonus 2: Alignment from $\mathcal{O}(1)$ Couplings!

IV. LHC Signatures: $cg \to tH^0, tA^0$

1. Same-Sign Dilepton
2. Tri-Top

$H^0/A^0 \to tc(bar); tt(bar)$

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

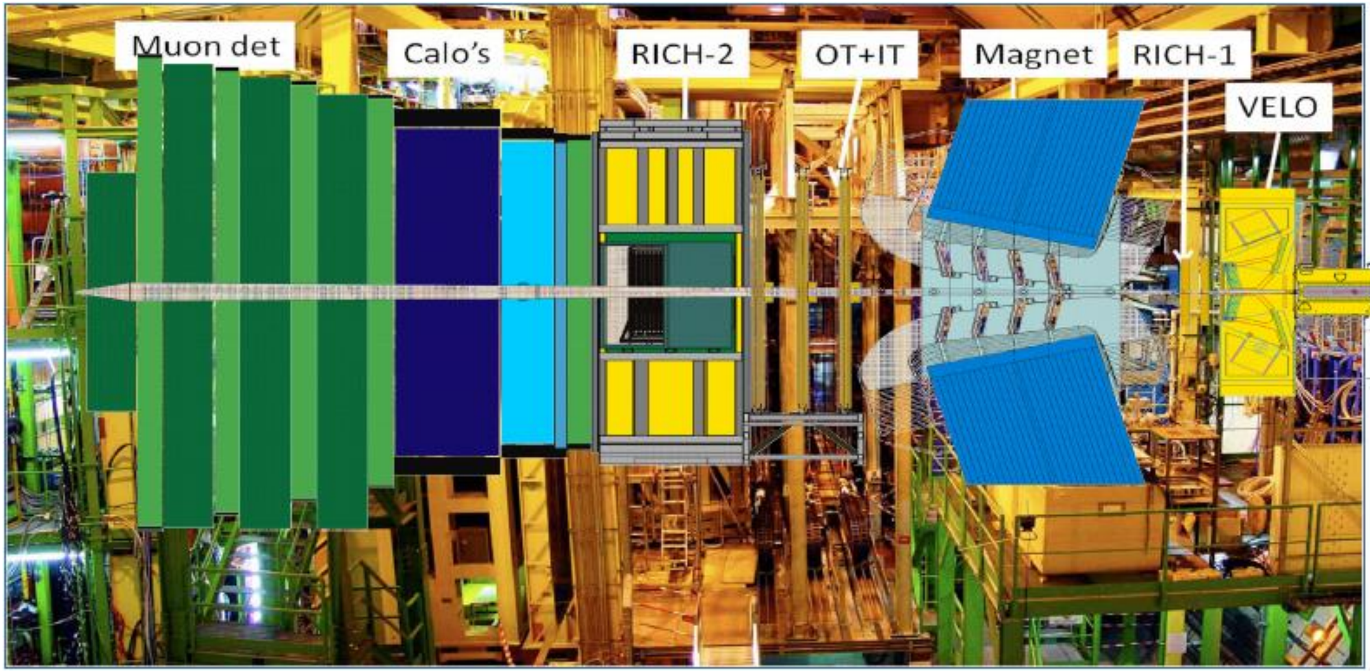
K. Fuyuto, WSH, & E. Senaha, PLB'18
WSH & M. Kikuchi, 1706.07694
M. Kohda, T. Modak, & WSH, PLB'18

Flavour Anomalies

Anomalies come and go, and they mostly go …

Flavour Anomalies have been more persistent.

But now they all source to (fabulous) **LHCb** …



Per physics tradition, need **Belle II** for Confirmation,
If not Competition!

I. Intro: 2HDM & Extra Yukawas

→ Two Top Utilities

symmetry breaking

$$\Phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} \Rightarrow \begin{pmatrix} 0 \\ v \end{pmatrix}$$

Minimum extension of the SM :

2 Higgs Doublet Model : 2HDM

Seems Reasonable

3 copies fermions

$$\Phi_1 = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_3 \\ \phi_4 \end{pmatrix}$$

can be observed H boson.

results in

- 5 Higgs bosons : (h, H, A, H^+, H^-)

Glashow-Weinberg (1977)

"Natural Flavor Conservation" (NFC) Condition:

$\mathbf{M} \propto \mathbf{Y}$ matrix relation

Edict: One Yukawa Matrix per Mass Matrix

Against: ~~Flavor Changing Neutral Higgs Couplings~~

e.g. $\Phi_1 \rightarrow \Phi_u$, v_u for u-type quarks

$\Phi_2 \rightarrow \Phi_d$, v_d for d-type quarks

Implement by some Z_2 mapping of Φ_u & Φ_d

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- 5 Higgs bosons : (h, H, A, H^+, H^-)
- 2 mixing parameters : (α, β)
  - α : mixing angle of CP even h/H
  - $\tan\beta$: ratio of v_u / v_d

Automatic w/ SUSY!

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2HDM-II

Constraint from the measurements :

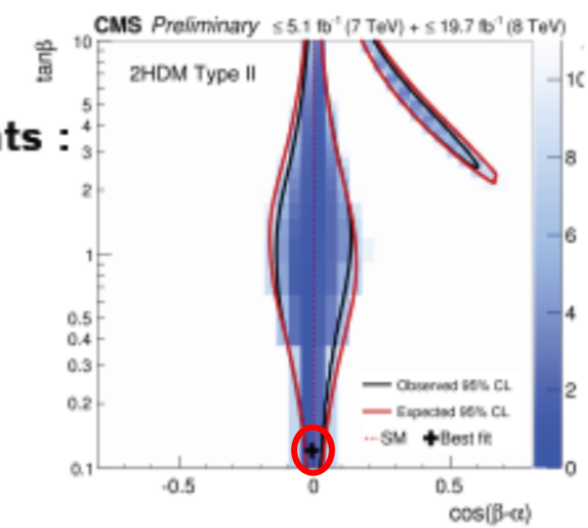
$\cos(\beta-\alpha)$ is very close to "zero".

h ⇒ consistent with SM.

(alignment limit)

h-*H* Don't seem to Mix

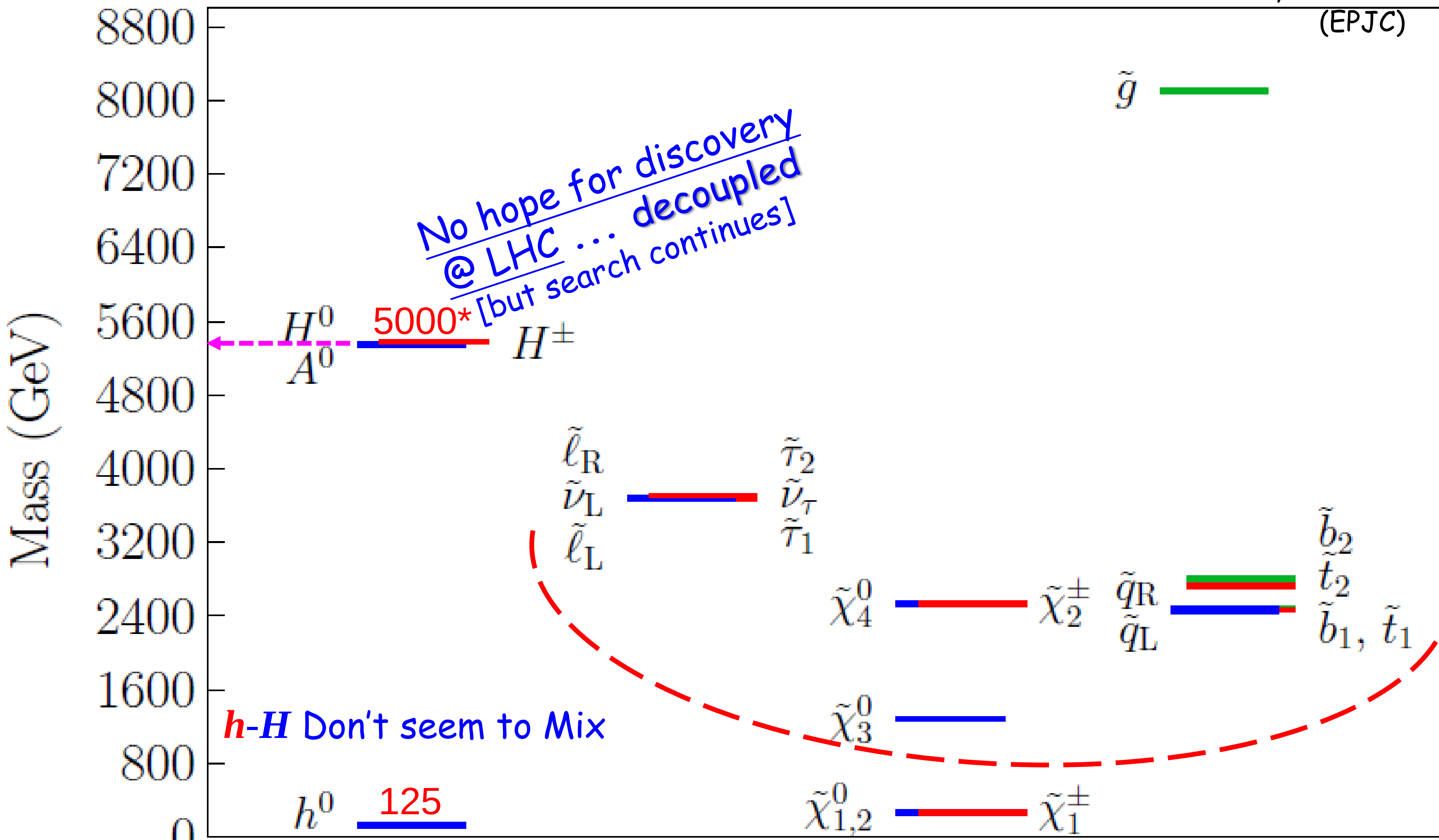
Alignment



August.7.2017 Soshi Tsuno (KEK) LP2017

Minimal SUSY Best Fit (GAMBIT)

GAMBIT, 1705.07917 (EPJC)



* In reality, this mass "fit" is not so stringent: rather flat in m_H.

Direct Search for Exotic Scalars at LHC

mass bounds better for high or low $\tan\beta$

otherwise low m_A allowed

MSSM Higgs searches

Minimum extension of the SM :

2 Higgs Doublet Model : 2HDM

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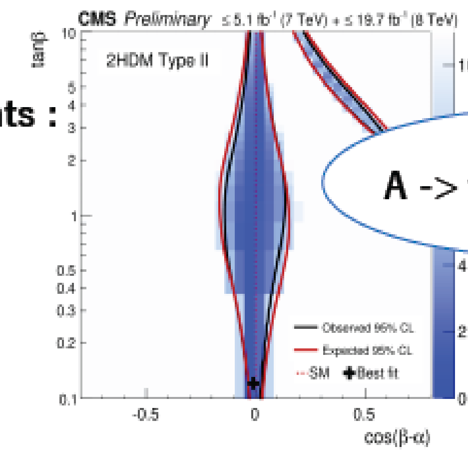
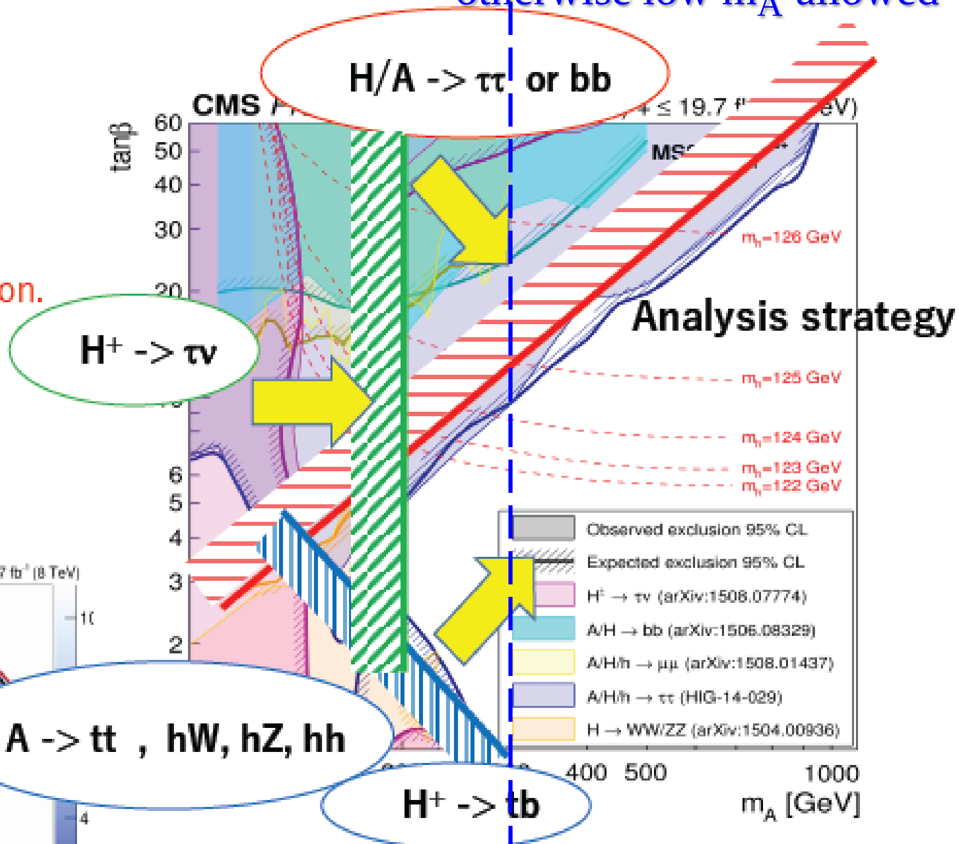


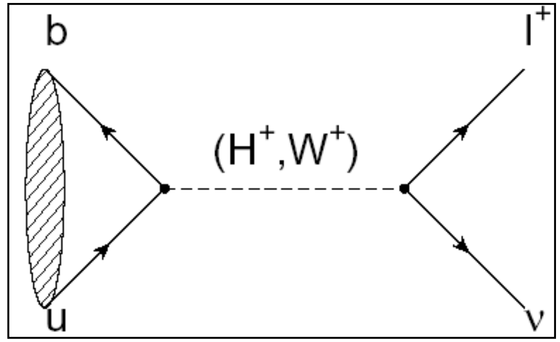


August.7.2017 LP2017 8

$B^+ \to \tau^+\nu$: Powerful H^+ Probe

and inclusive $b \to s\gamma$

Indirect Search



Need Belle II !

$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = \frac{G_F^2 m_B}{8\pi} m_\tau^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

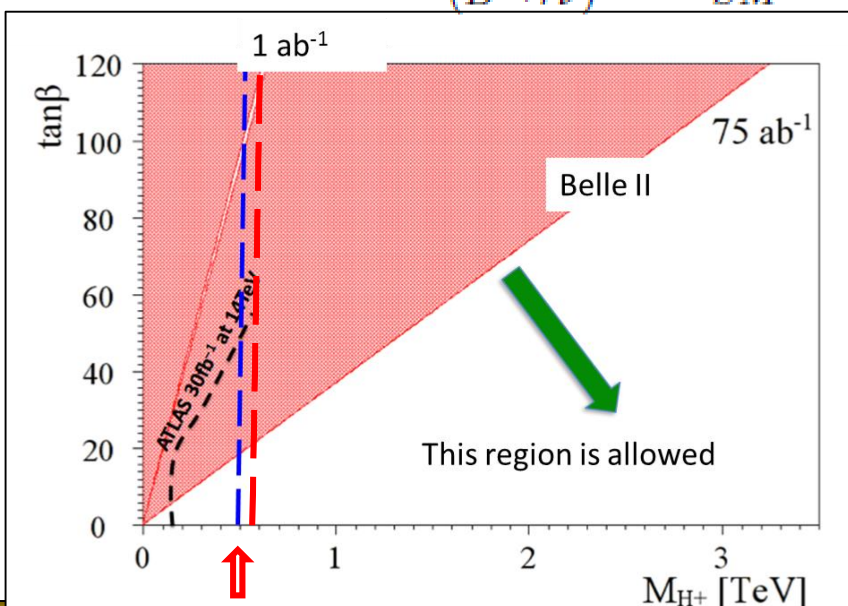
$$\rightarrow \quad \mathcal{B}_{(B\to\tau\nu)} = \mathcal{B}_{SM} \times \left(1 - \tan^2\beta \frac{m_{B^\pm}^2}{m_{H^\pm}^2}\right)^2$$

- physical -

WSH, PRD'93

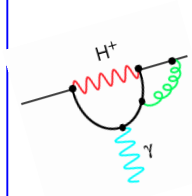
2HDM, Type II

(SUSY)



Current inclusive $b \to s\gamma$ constrains m_{H^+} > 570 [480] GeV at 95% C.L. (independent of tanβ)

Misiak et al. (assuming no other NP) EPJC'17 [PRL'15]



Grinstein & Wise, PLB'88

WSH & Willey, PLB'88

Beats Direct Search at LHC

Browder @ CKM2016

Whither Extra Yukawas?

Known CPV in CKM → Yukawa's. Extra Yukawa's?

Jarlskog Invariant *way too small!*

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)

u-, d-type mass each from separate doublet

→ Same Yuks. as SM

fermion mass-mixing

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

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

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

PLB'92

2012^{+}: *One Higgs* → 2nd Higgs

Highly Plausible!

PLB'13

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

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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.

$$\rho_{ct} \cos(\beta - \alpha) \bar{c} t h^0$$

FCNH modulated by ***h*–*H*** mixing

→ Alignment overtakes 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 overtakes Glashow-Weinberg NFC

General Yukawa interaction for up-type quarks

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

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

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

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

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

diagonal

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

FCNH (Flavor Changing Neutral 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
[2HDM II notation]

2HDM (w/o Z_2): FCNH ρ_{tt}, ρ_{tc}

→ Alignment overtakes Glashow-Weinberg NFC

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

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

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

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

$$\rho = V_L^{u\dagger}\,(-Y_1\, s_\beta + Y_2\, c_\beta)\, V_R^u$$ FCNH (Flavor Changing Neutral H)

Neutral up-type Yukawa interaction

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

→ diag. (SM-*h*)

ρ_{ij} share trickle-down of V_{ij} , and m_i hierarchy

$\rho_{tt} \sim \mathcal{O}(\lambda_t) \sim 1$

ρ_{tc} likewise

} ***H*, *A*** ← FCNH ρ_{ij}

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

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

Bookmark

(what is this?)

High Energy Physics - Phenomenology

Title: Two Top Utilities of Two Higgs Doublets: Electroweak Baryogenesis and Alignment

Authors: George W.-S. Hou
(Submitted on 3 Oct 2017)

Abstract: With two Higgs doublets but without any discrete Z_2 symmetry to forbid flavor changing neutral Higgs couplings, new top Yukawa couplings ρ_{tt} and ρ_{tc} are allowed and naturally complex. Electroweak baryogenesis is remarkably efficient if both ρ_{tt} (and ρ_{tc}) and exotic Higgs quartic couplings are $\mathcal{O}(1)$. Furthermore, the alignment phenomenon, that the observed 125 GeV boson so closely resembles the Standard Model Higgs boson, emerges naturally. One not only has many new flavor and CPV phenomena (modulo SM-like flavor organization plus alignment), but the exotic Higgs bosons H^0, A^0 and H^+ are necessarily sub-TeV in mass, and LHC search should be readjusted.

Comments: 10 pages, 4 figures, talked presented at APS Division of Particles and Fields Meeting (DPF 2017), July 31-August 4, 2017, Fermilab. C170731. arXiv admin note: text overlap with arXiv:1709.01262

II. Bonus 1: EWBG2-t

K. Fuyuto, WSH, & E. Senaha, PLB'18

EWBG2-t: Im ρ_{tt}; "λ_i"

$\sim \mathcal{O}(1)$

folklore

strongly 1st order EW phase transition (EWPT)

Expanding Bubble of Broken Phase

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

"λ_i" 2HDM OK

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

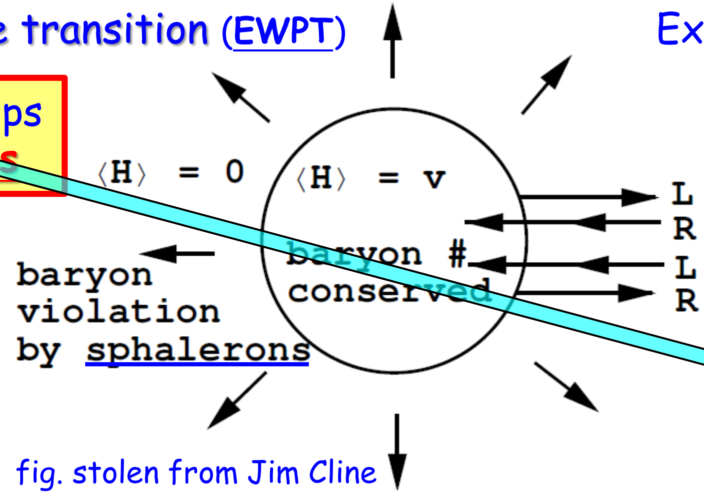


fig. stolen from Jim Cline

To avoid n_B washout:

Hubble const.

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

n_B changing rate (broken phase)

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

vev @ T_C

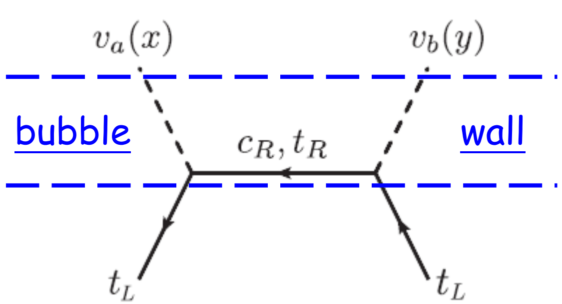
$\sqrt{v_1^2(T_C)+v_2^2(T_C)}$ (keep υ_1, υ_2)

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.

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

CPV Top Interactions
Extra Yukawas

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 (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, 1607.07316

Baryon Asymm. of Universe (BAU) n_B/s

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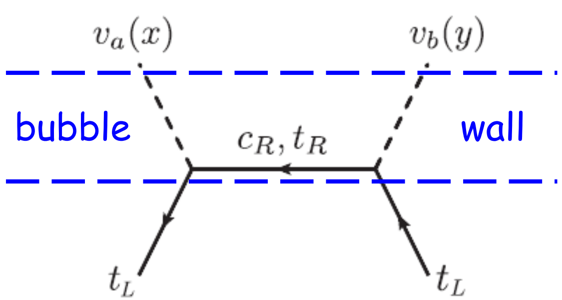


BAU $\Leftarrow$ CPV Top Interactions at Bubble Wall ⟹ n_L

left-handed Top density

skip detail (Transport)

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

z' coord. oppo. bubble exp. dir.

CPV source term

"Jarlskog": both doublets participate

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

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

To understand the 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 $\sqrt{2}Y^{\rm SM} = Y_1 + Y_2$ diag. by just V_R^u

but $-Y_1 + Y_2$ not diag.

solve

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

CPV Source

ρ_{tc} still basically free param.

ρ_{tt} and ρ_{tc} least constrained

B. Altunkaynak et al. PLB'15

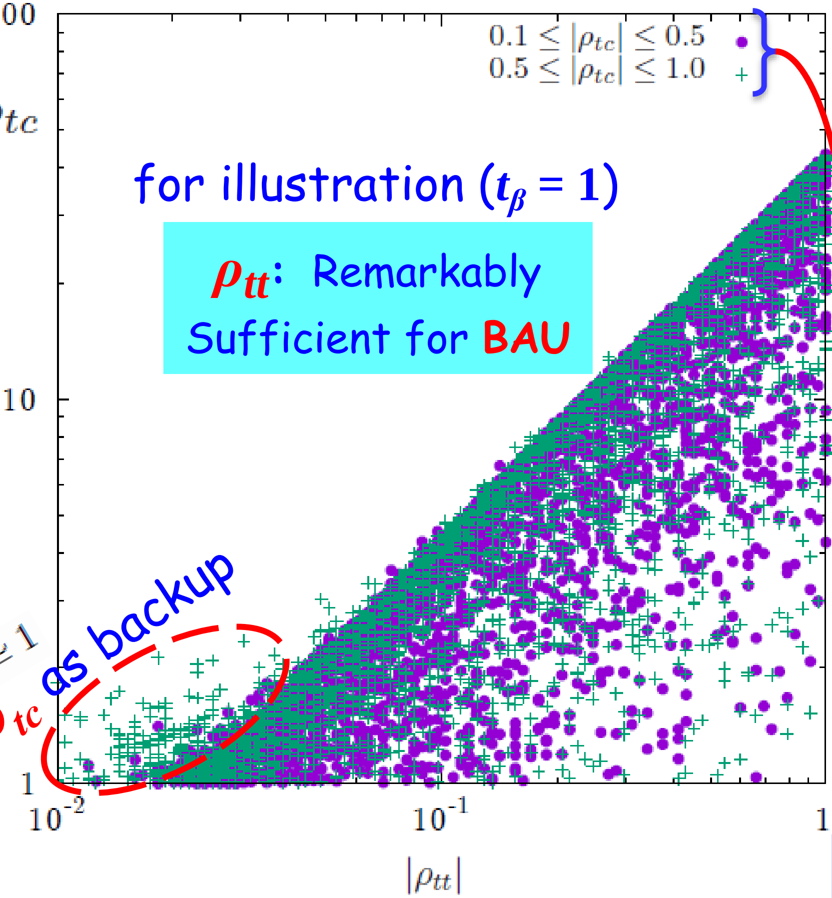
Bonus: Extra Yukawa Drive EWBG!

BaryoGenesis

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

scan over $|\rho_{tc}|$ ϕ_{tt} ϕ_{tc}

Y_B / Y_B^{obs}



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

III. Bonus 2: Alignment from $\mathcal{O}(1)$ Couplings!

WSH & M. Kikuchi, 1706.07694

Condition for (near) Alignment

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

$\mu_{11}^2 < 0$

Higgs basis (tanβ unphysical)

assume CP-Inv.

EWSB

minimization

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

"soft breaking" term absorbed

Davidson & Haber, PRD'05
see Haber & O'Neil, PRD'06, '11

$$m_{H^\pm}^2 = \mu_{22}^2 + \frac{1}{2}\eta_3 v^2,$$

$$m_A^2 = \mu_{22}^2 + \frac{1}{2}(\eta_3 + \eta_4 - \eta_5)v^2$$

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

cos(β–α)

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

diag.

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

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

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

Near Alignment, c_γ small

$$\begin{cases} \eta_1 v^2 - m_h^2 \sim \text{sub-}v^2 \quad (\neq 0) \\ m_H^2 - m_h^2 > \textit{several}\ v^2 \end{cases}$$

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

Alignment in 2HDM: No need for Small η_6!

Higgs basis: w/o or w/ Z_2!

Howie Haber

Large, parameter space for η_i's ~ $\mathcal{O}(1)$

Near Alignment (c_γ small), $$c_\gamma \cong \frac{-\eta_6 v^2}{m_H^2 - m_h^2}$$

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

$$m_H^2 - m_h^2 \; > \; \textit{several } v^2$$

n.b. $m_h^2/v^2 \simeq 0.26$ Not Required; η_6 ~ $\mathcal{O}(1)$ OK

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

μ_{22}^2/v^2 ~ $\mathcal{O}(1)$ also; damp EWBG ⟹ exotic Higgs sub-TeV

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

Single term (EWSB)

4 terms

Alignment is *Emergent* in 2HDM indep. of Z_2

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

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

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

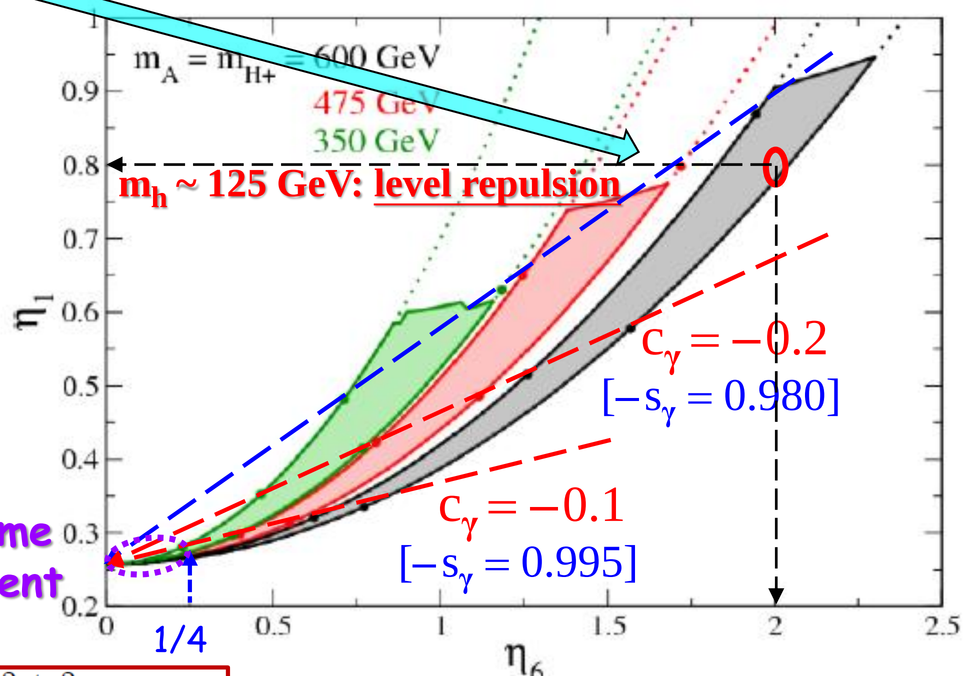
Custodial SU(2) Illustration

~~ΔT_{SS}~~ $+ \Delta T_{SV}$

EW Precision Constraint

η_i's: Higgs Quartic Self-Couplings

$\eta_5 < 3$



extreme alignment

1/4

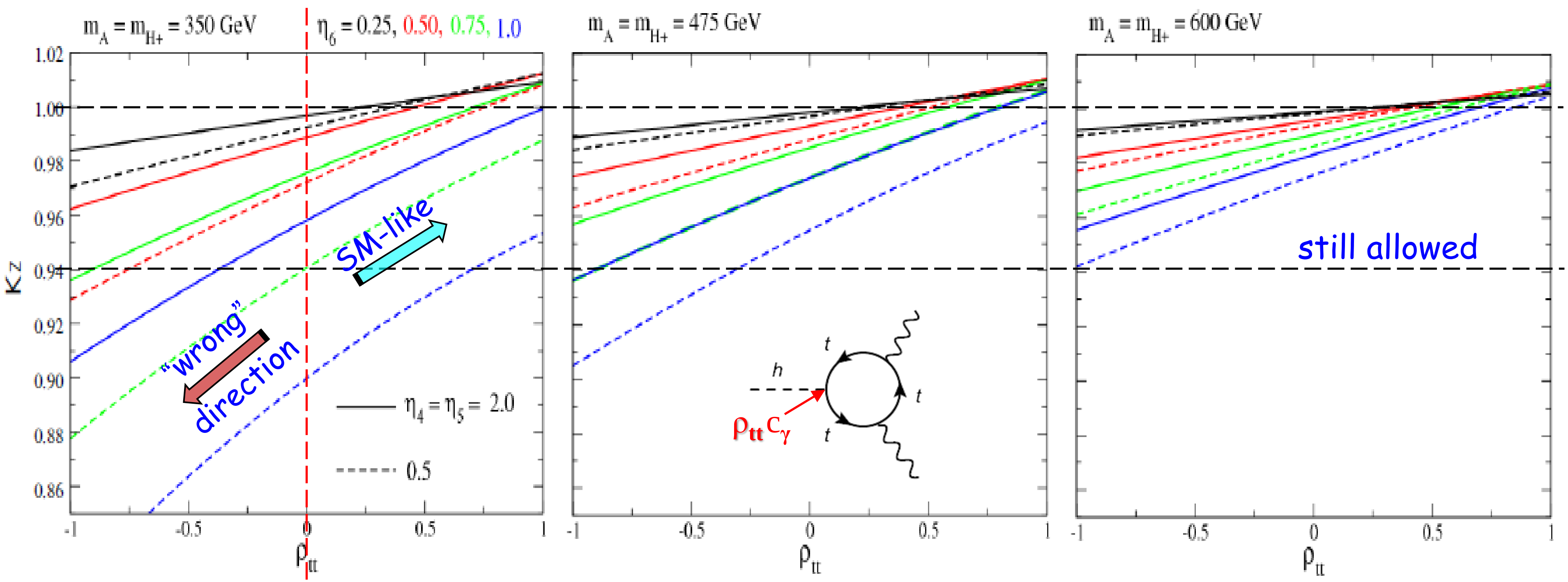
$m_h^2/v^2 \simeq 0.26$

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

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

One-loop Protection

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

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

circumvent alignment protection

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

$\mathcal{B}(t \to ch) \simeq 0.15\%$ 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^+

$\mathcal{O}(1)$ 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

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

probably hidden in tt(bar)

param. space much broader

$h \to \gamma\gamma$ width reduction

(ρ_{tt} compensate)

$c_\gamma \to 0$

Barr-Zee

e-EDM (2 loop)

but: $c_\gamma \to 0$, $|\rho_{ee}| \sim y_e$

cancellations when imaginary

346 W.-S. Hou et al. / Physics Letters B 409 (1997) 344–348

WSH, G.L. Lin, C.Y. Ma, C.P. Yuan

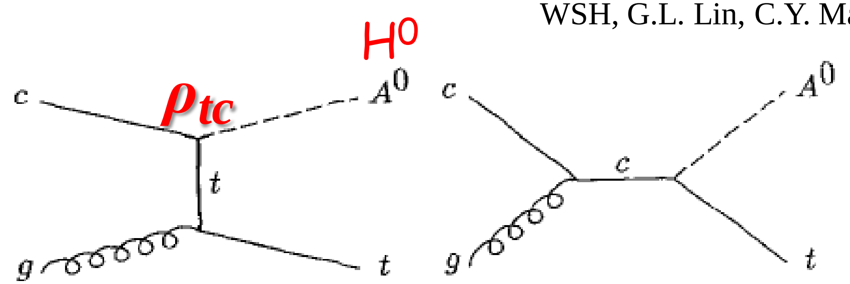


Fig. 1. Subprocess $cg \to tA^0$.

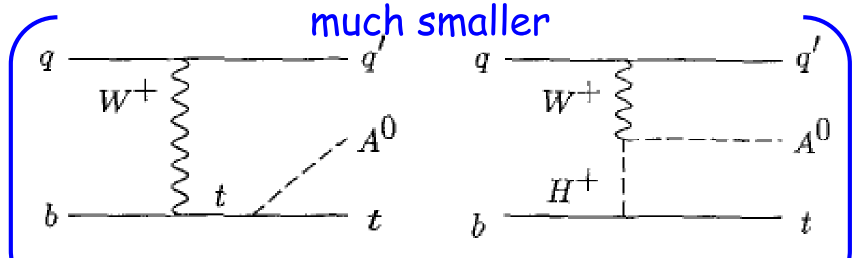


Fig. 3. Subprocess $qb \to q' tA^0$.

IV. LHC Signatures: $cg \to tH^0,\ tA^0$

1. Same-Sign Dilepton
2. Tri-Top

$H^0/A^0 \to tc(\text{bar})$ ρ_{tc}

$tt(\text{bar})$ ρ_{tt}

$$\frac{\rho_{ij}}{\sqrt{2}}\,\bar{u}_{iL}(H^0 + i\,A^0)u_{jR} + \text{h.c.}$$

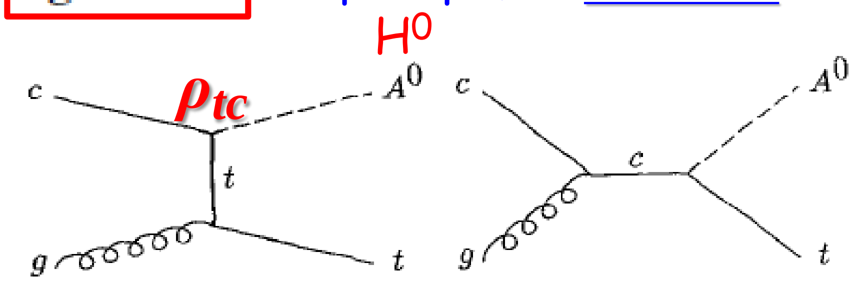
take $\cos\gamma \to 0$

M. Kohda, T. Modak, & WSH, PLB'18

$cg \to tH^0, tA^0$

Barger, Keung, Yencho, PLB'10

$cg \to tS^0$: up to pb, vs fb in SM



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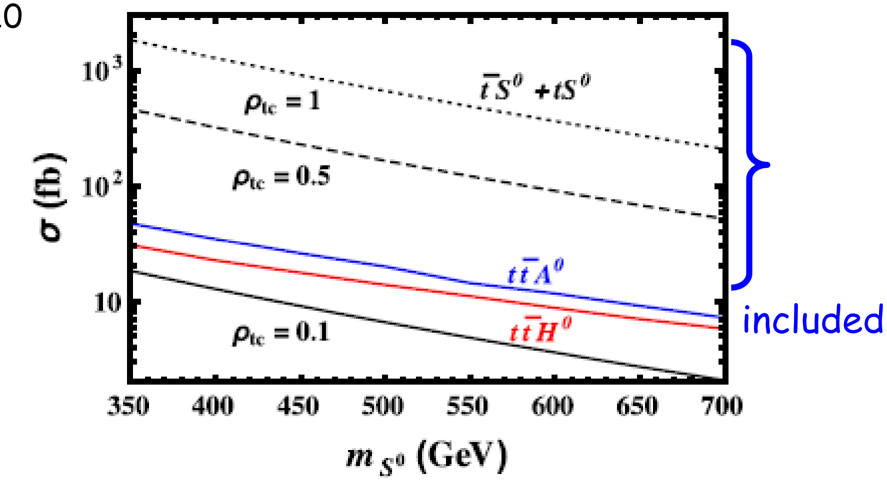
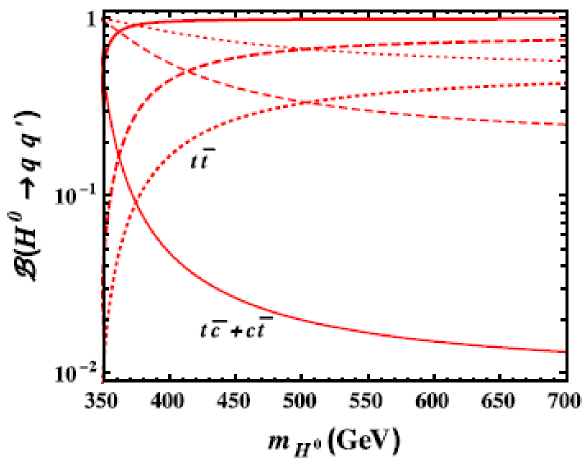
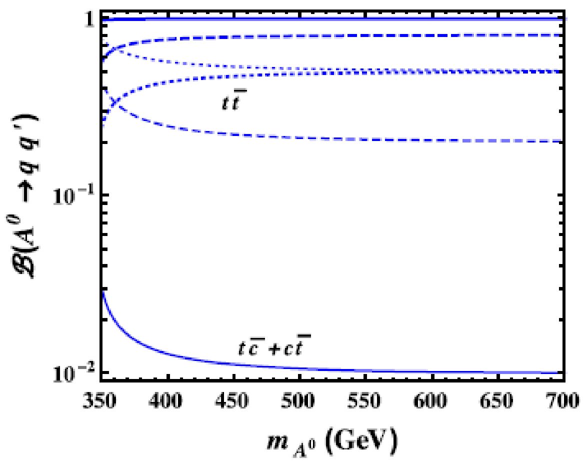


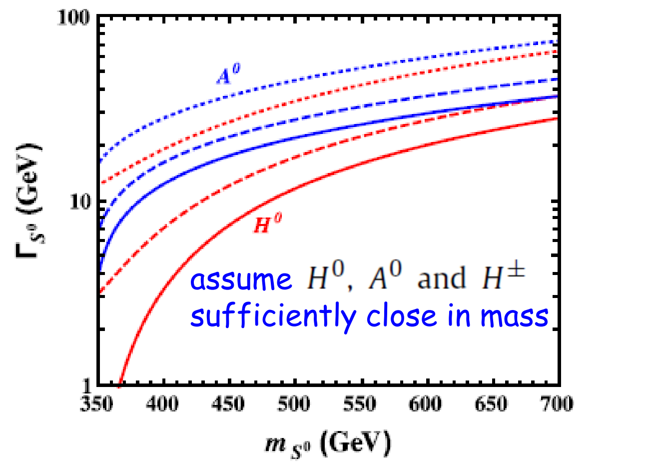
$gg \to S^0 \to t\bar{t}$: interference w/ $gg \to t\bar{t}$
e.g. M. Carena and Z. Liu, JHEP'16

$gg \to S^0 \to t\bar{c}$ ~ s-channel single-top
e.g. B. Altunkaynak et al., PLB'15

Suffer from $\mathbf{m_{tt}}$, $\mathbf{m_{tj}}$ mass resolution







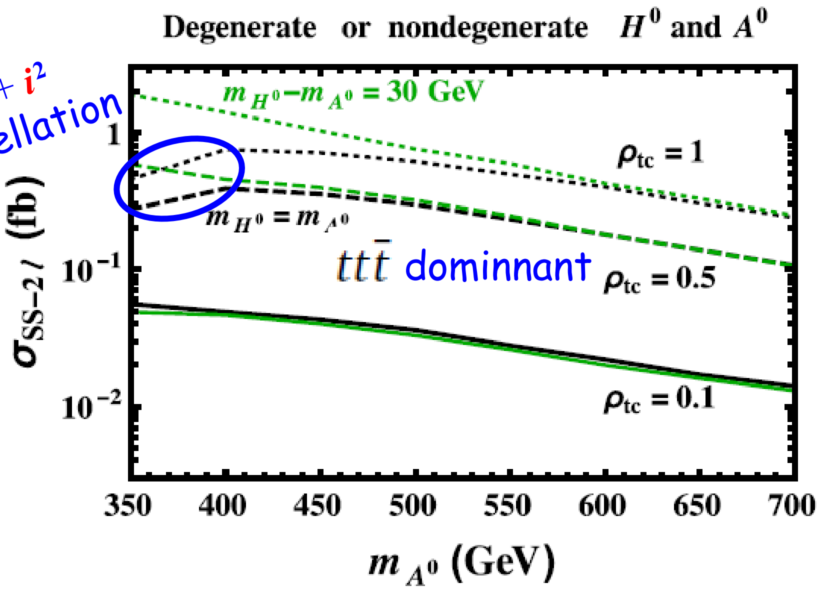
1. Same-Sign Dilepton: $tt\bar{t}$, $tt\bar{c}$ and $t\bar{t}c$

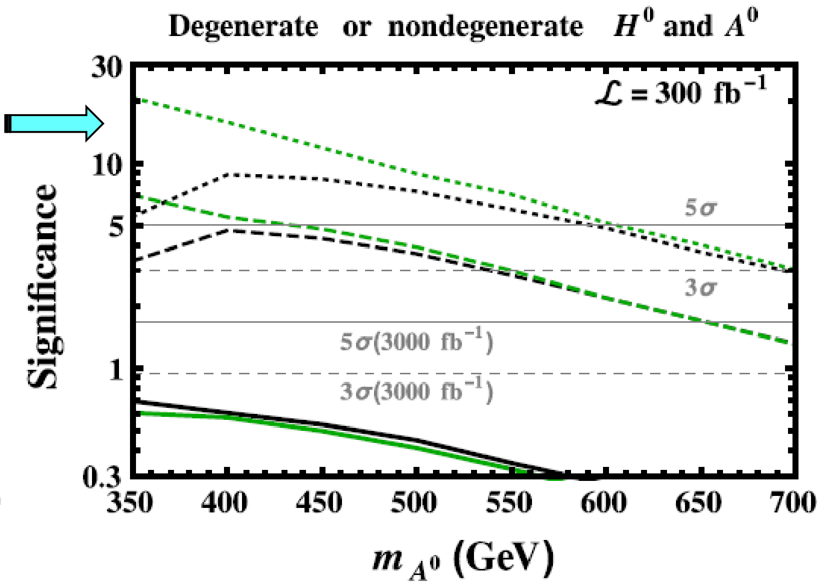
$\ell^+\ell'^+$; bb(b); E_T^{miss}
≥ 3j

"same sign top"
SS2ℓ

MadGraph5_aMC@NLO / NN23LO1 PDF
PYTHIA 6.4 / MLM / DELPHES 3.4.0

p_T
η
ΔR
H_T





NLO/LO	Backgrounds	Cross section (fb)	
1.56	$t\bar{t}Z$	0.04	
1.35	$t\bar{t}W$	0.72	[1 + 1.5 nonprompt*]
1.44	tZ + jets	0.001	
	$3t + j$	0.0002	
	$3t + W$	0.0004	
1.27	$t\bar{t}h$	0.024	
2.05	$4t$	0.04	
1.84	Q-flip [ttj]	0.04	

* CMS, EPJC'17 (SS2ℓ)

- ρ_{tc} = 1: 5σ up to 600 GeV @ 300 fb^{-1}
- ρ_{tc} = 0.5: 5σ beyond 600 GeV @ 3000 fb^{-1}

SS2ℓ can tell if ρ_{tc} ~ 1 mech.
for EWBG is allowed

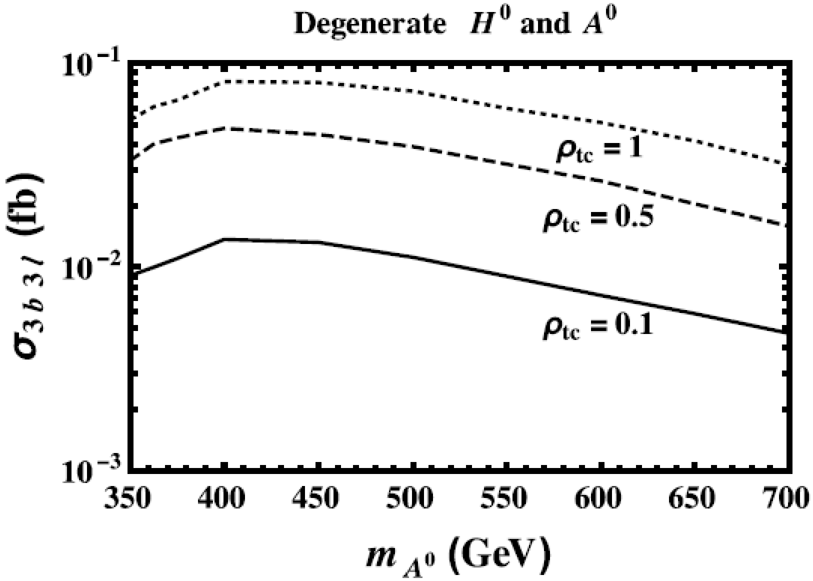
2. Tri-Top: $tt\bar{t}$

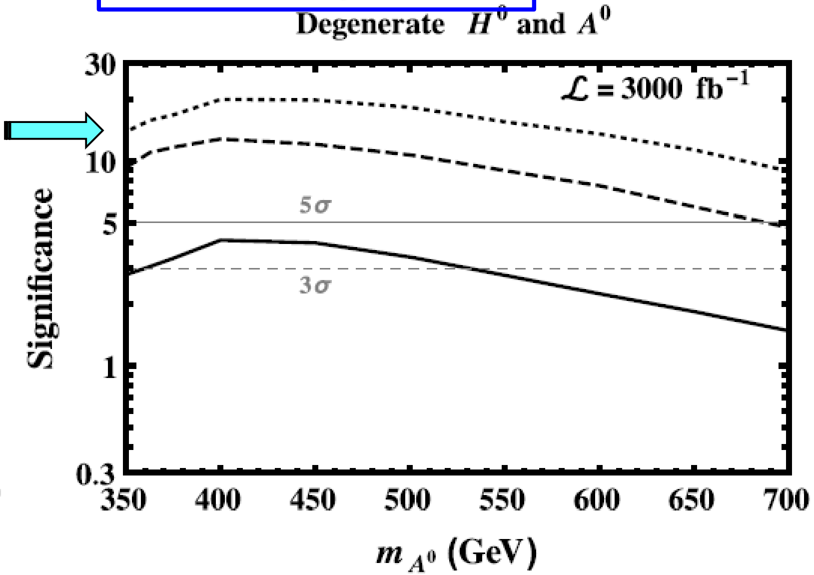
MadGraph5_aMC@NLO / NN23LO1 PDF
PYTHIA 6.4 / MLM / DELPHES 3.4.0

$\ell_1\ell_2\ell_3$; bbb; E_T^{miss}
$\geq 3\ell \quad \geq 3j$

Triple Top

p_T
η
ΔR
H_T





NLO/LO	Backgrounds	Cross section (fb)	Z veto
1.56	$t\bar{t}Z$ + jets	0.0205	(0.0026)
1.35	$t\bar{t}Wb$	0.0017	(0.0015)
1.44	$tZjb$	0.0002	(–)
	$3t + j$	0.0001	(0.0001)
	$3t + W$	0.0004	(0.0003)
1.27	$t\bar{t}h$	0.0015	(0.0013)
2.05	4t	0.0232	(0.0209)
1.84	$t\bar{t}$ + jets (fake)	0.0026	(0.0025)

- $\rho_{tc} > 0.5$: 5σ to 700 GeV & beyond @3000 fb^{-1}
- $\rho_{tc} \sim 0.1$: 3σ up to 500 GeV @3000 fb^{-1}

better than SS2ℓ

Crosscheck Tri-Top w/ SS2ℓ can tell whether ρ_{tt} or $\rho_{tc} \sim 1$ mech. drives EWBG

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

2HDM (w/o Z_2)

- EWBG Remarkably 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 — most modulo c_γ — *a better substitute for NFC*

- Approx. Alignment for $\mathcal{O}(1)$ Higgs quartics ← w/o or w/ Z_2!
  - mild tuning (1/4) ➔ Extreme Alignment
  - mild Alignment ($c_\gamma = -0.2$) ➔ lower m_h by level repulsion
  - sub-TeV H^0, A^0, H^+ preferred ➔ rethink LHC Search

Discover @ LHC!?

$cg \to tH^0/A^0 \to ttc(\text{bar}), ttt(\text{bar})$

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

Much New FPCP Pheno

for illustration: $c_\gamma = 0.1$

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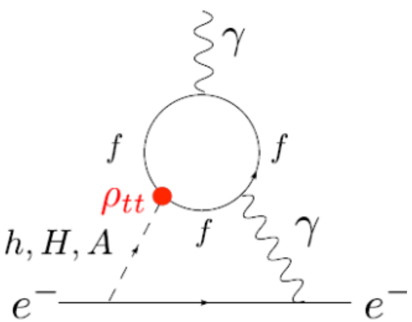

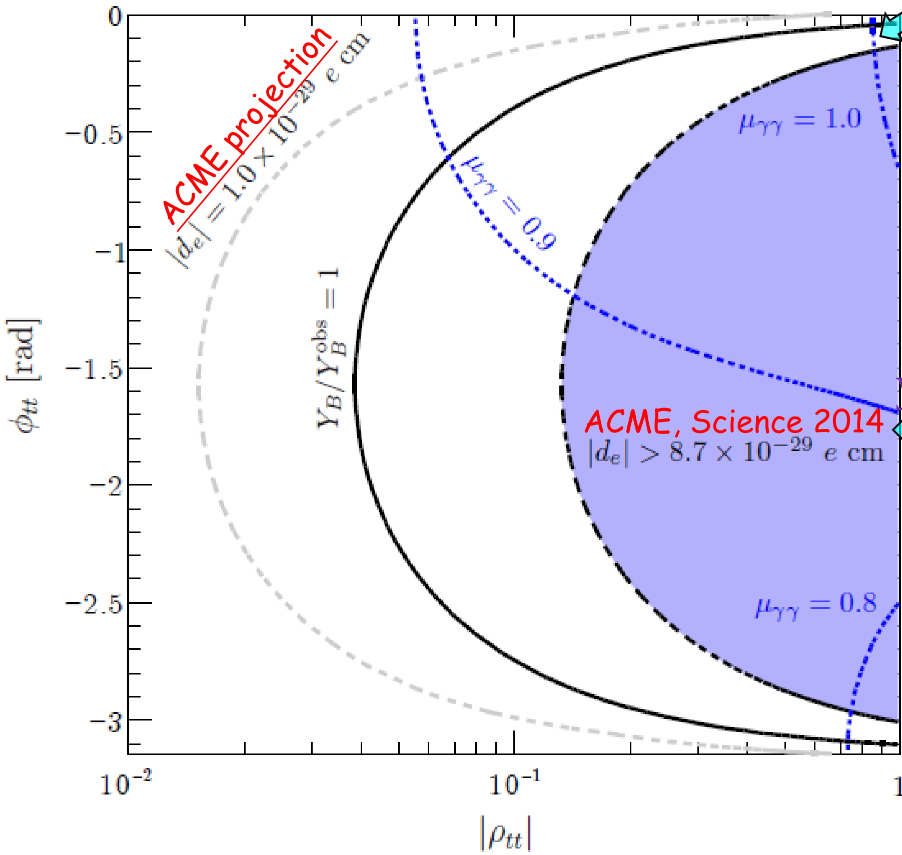

charged Higgs H^+

$h \to \gamma\gamma$ width reduction

(ρ_{tt} compensate)

Barr-Zee

e-EDM (2-loop)

but: $c_\gamma = 0.1$, $|\rho_{ee}| \sim y_e$

cancellations when imaginary

Much New FPCP Pheno

most vanish with $c_\gamma \to 0$ <u>alignment protection</u>

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

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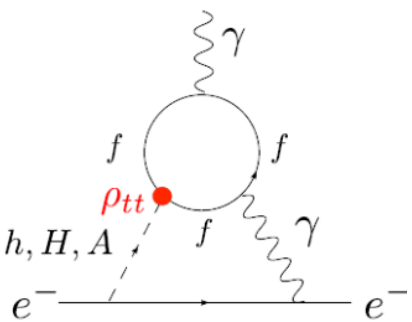
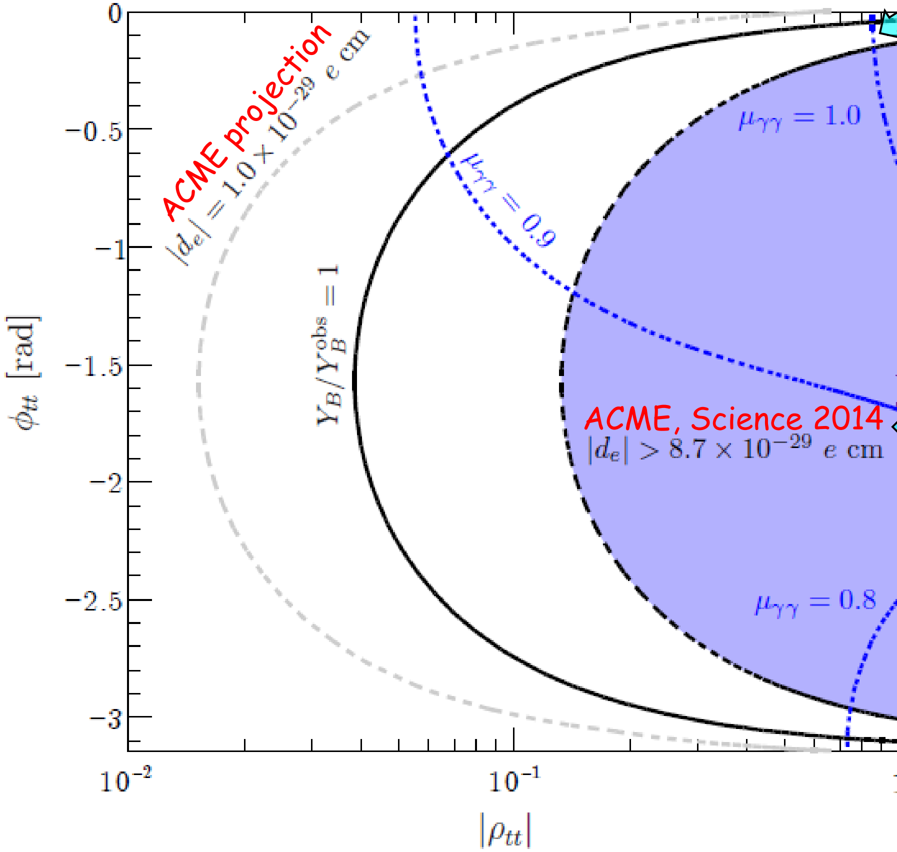
charged Higgs H^+

$h \to \gamma\gamma$ width reduction

(ρ_{tt} compensate) $c_\gamma \to 0$





$y_e = 0$

Barr-Zee e-EDM (2 loop)

but: $c_\gamma \to 0$, $|\rho_{ee}| \sim y_e$

<u>cancellations</u>
<u>when imaginary</u>

* CMS, EPJC'17 (SS2ℓ) w/ 36 fb^{-1}

Not Optimized for "same sign top"