Probing Top Changing Neutral Higgs Couplings at the LHC

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Chionanthus retusus blossom on NTU campus

National Taiwan University

Probing TCNH Couplings at Colliders

H, A

I. Flavor Changing Neutral Higgs: $t \to ch$ Search

II. Theoretical Framework: 2HDM w/o Z_2

III. Top-associated H/A Production

- Collider constraints on ρ_{tc}
- Same-Sign Top: $cg \to tH/tA \to tt\bar{c}$
- Triple-Top: $cg \to tH/A \to tt\bar{t}$

IV. Bottom-associated H^+ Production

H^+

- Flavor and Collider constraints
- Collider Signature for $cg \to bH^+ \to bt\bar{b}$

~~V. Discussion~~

VI. Summary and Prospects

WSH and Tanmoy Modak, 2012.05735
(MPLA'21-BriefRev.)

I. Intro

FCNH — an Experimental Question

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

PLB'92

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

PSI-PR-91-34
Received 25 June 1992

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

Cheng-Sher

In a third type of two Higgs model, where neutral scalar bosons possess flavor changing $u_i u_j h^0$ couplings proportional to $\sqrt{m_i m_j}$, 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.

per mille

< 1.1 10^{-3}	95	[1] AABOUD	19S	ATLS	combination of $t \to Hc$ ($H \to WW$, ZZ, $\tau\tau$, $\gamma\gamma$, $b\bar{b}$)

$t \to Hc$ ...

sub%

< 7.9	95	[9] AAD	14AA	ATLS	$t \to Hq$ (q=u,c; $H \to \gamma\gamma$)
<13	95	[10] CHATRCHYAN	14R	CMS	$t \to Hc$ ($H \to \geq 2\,\ell$)
< 5.6	95	[11] KHACHATRY...	14Q	CMS	$t \to Hc$ ($H \to \gamma\gamma$ or lep-

H here is h(125)

per mille

<2.5 × 10^{-3}	95	[1] SIRUNYAN	18BH	CMS

$H^0 \to \mu\tau$ ...

~~% hint!~~

[5] KHACHATRYAN 15Q search for $H^0 \to \mu\tau$ with τ decaying electronically or hadronically in 19.7 fb^{-1} of pp collisions at E_{cm} = 8 TeV. The fit gives B($H^0 \to \mu\tau$) = $(0.84^{+0.39}_{-0.37})$% with a significance of 2.4 σ.

2012^{+}: *One Higgs* → 2^{nd} 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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Gestalt Switch

move away from Cheng-Sher "Ansatz"

A R T I C L E I N F O

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A B S T R A C T

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

$\sqrt{m_i m_j}$ only scaffold

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

Extra Yukawas!

[Haber notation]

Get serious searching for H, A, H^+ via Extra Yukawas !

II. Theoretical Framework: 2HDM w/o Z_2

general 2HDM (g2HDM)

2HDM (w/o Z_2): FCNH ρ_{ij}

Yukawa matrices $\mathbf{Y}^f$: $\bar{\ell}_L Y^e \Phi e_R \quad \bar{q}_L Y^d \Phi d_R \quad \bar{q}_L \tilde{Y}^u \Phi u_R$

diagonalize $\mathbf{Y}^f$: fermion masses

2nd Yukawa matrices $\mathbf{P}^f$: $\bar{\ell}_L P^e \Phi' e_R \quad \bar{q}_L P^d \Phi' d_R \quad \bar{q}_L \tilde{P}^u \Phi' u_R$

diagonalize $\mathbf{P}^f$: ρ^f Yuk. matrices

nondiagonal (& Complex)

Yukawa Couplings in Mass Basis:

$$-\frac{1}{\sqrt{2}} \sum_{f=u,d,\ell} \bar{f}_i \Big[\big(-\lambda_i^f \delta_{ij} s_\gamma + \rho_{ij}^f c_\gamma\big) h + \big(\lambda_i^f \delta_{ij} c_\gamma + \rho_{ij}^f s_\gamma\big) H - i\,\mathrm{sgn}(Q_f) \rho_{ij}^f A \Big] R\, f_j$$

$$-\bar{u}_i \left[(V \rho^d)_{ij} R - (\rho^{u\dagger} V)_{ij} L \right] d_j H^+ - \bar{\nu}_i \rho_{ij}^\ell R\, \ell_j H^+ + h.c.$$

Alignment limit → diag. (SM-h)

→ FCNH ρ_{ij}

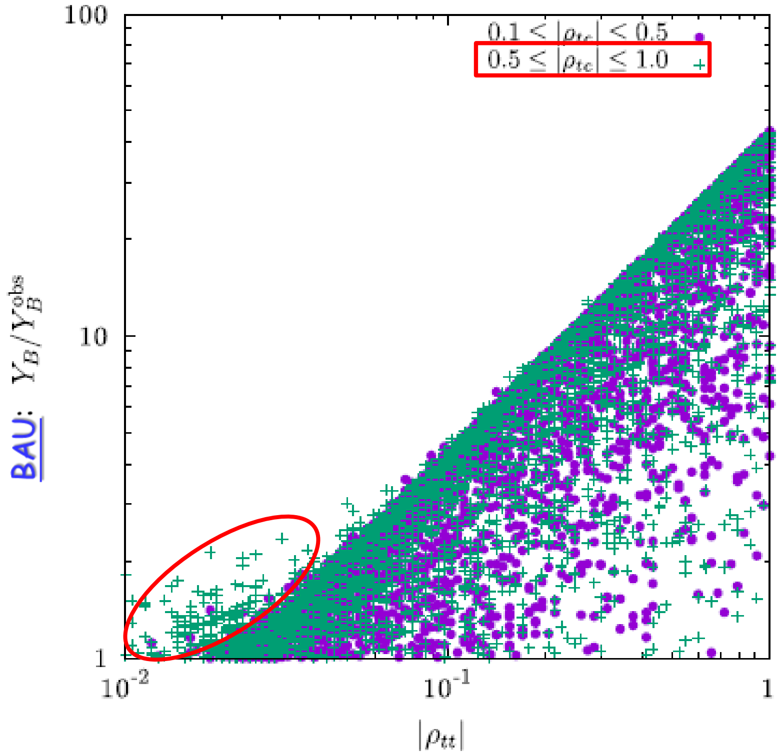
$|\rho_{ij}| e^{i\phi_{ij}}$

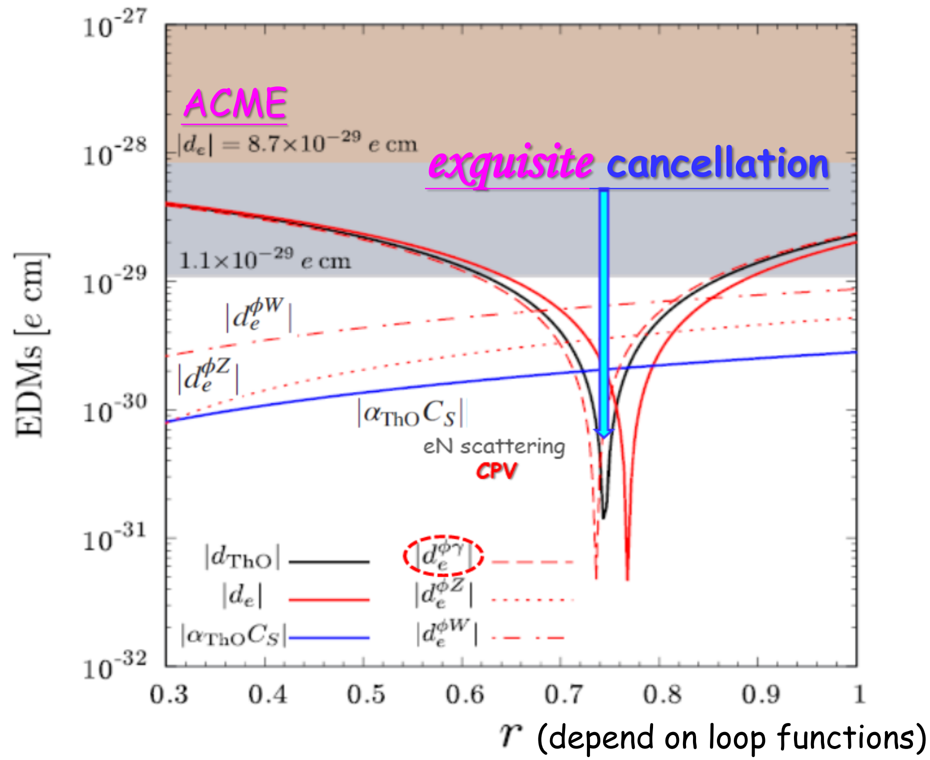
CKM enters for Charged Higgs

N.B. ρ_{tt} and ρ_{tc} can separately drive EWBG!
Fuyuto, WSH, Senaha, PLB'18 & PRD-RC'20

ρ_{tt} and ρ_{tc} can separately drive EWBG!

Fuyuto, WSH, Senaha, PLB'18 & PRD-RC'20





EWBG ⇐ $\lambda_t \mathrm{Im}\rho_{tt}$ robust driver

$\mathcal{O}(\lambda_t) \approx 1$

[ρ_{tc} as backup

ρ_{ee}

$$\frac{\mathrm{Im}\,\rho_{ff}}{\mathrm{Im}\,\rho_{tt}} = r\,\frac{\lambda_f}{\lambda_t}$$

$$\frac{\mathrm{Re}\,\rho_{ff}}{\mathrm{Re}\,\rho_{tt}} = -r\,\frac{\lambda_f}{\lambda_t}$$

Follow SM Pattern!

w/o Z_2

H, A, H^+ Spectrum Fit for the LHC

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

$V(\Phi) \sim -\mu^2|\Phi|^2 + \lambda|\Phi|^4$

$v^2 \sim \mu^2/\lambda$

$\mu_{11}^2 = -\eta_1 v^2/2$

$\mu_{12}^2 = \frac{1}{2}\eta_6 v^2$

2nd min. cond.

WSH & Kikuchi, EPL'18

η_6: sole param. for h-H mixing (c_γ)

$$M_{\text{even}}^2 = \begin{bmatrix} \eta_1 v^2 & \eta_6 v^2 \\ \eta_6 v^2 & m_A^2 + \eta_5 v^2 \end{bmatrix}$$

Dim'less params. $\mathcal{O}(1)$ ("Naturalness"):

η_i with $i = 1$–7; μ_{22}^2/v^2 ⇨ H, A, H^+

Search Zone

GeV

800

700

600

"unnatural"

500

400

$t\bar{t}$

300

incredulous (next page)

v.e.v.

200

t

h

100

W Z

ν neutrino

$e\,\mu\,\tau$ lepton

d s b down-type

u c up-type

γ g vector

scalar

N.B. $\mathcal{O}(1)$ η_i's needed for 1st order Phase Trans. (PT), prerequisite for ElectroWeak BaryoGenesis.

See e.g. Basler, Mühlleitner, Müller, JHEP'20

Flavor Design: replace (Un)*Natural* Flavor Conserv.

Where Are They? What hides **H**, **A**, **H^+** effects from our view?

1. Mass-Mixing Hierarchy: Yuk. matrices ρ^f trickle off off-diagonal

2. *Alignment*: Expt. find h rather close to SM Higgs → **c_γ small!** ⇨ controls $\{ t \to ch,\ h \to \tau\mu \}$

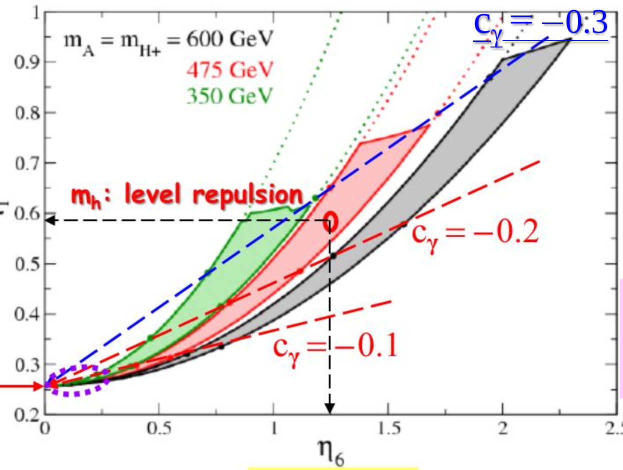
h-H mixing

Search Zone

$$M^2_{\rm even} = \begin{bmatrix} \eta_1 v^2 & \eta_6 v^2 \\ \eta_6 v^2 & m_A^2 + \eta_5 v^2 \end{bmatrix}$$

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

$\eta_1 = \mathcal{O}(1)$



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

NOT in conflict w/ $\mathcal{O}(1)$ η_i's!

WSH&Kikuchi, EPL'18

H, **A**, **H^+**

$t\bar{t}$

(*alignment*) incredulous

3. Small/Near-diagonal ρ^d matrix! *Nature* has her *mysterious* ways!

[K^0, B^0 and B_s meson mixings our most sensitive probes!]

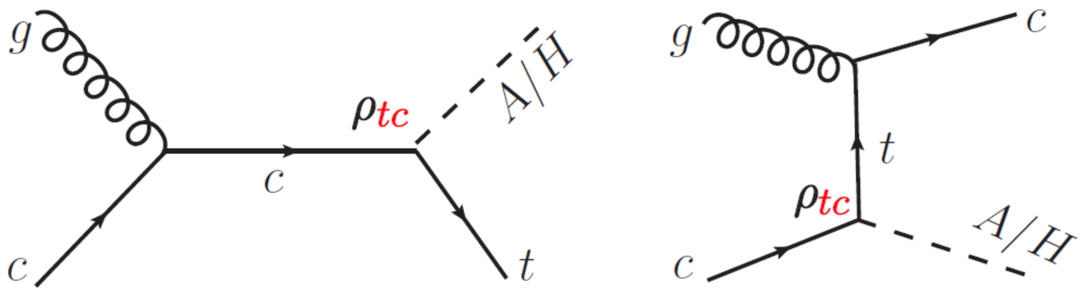
GeV: 800, 700, 600, 500, 400, 300, 200, 100

t, h, W Z

ν neutrino | eμτ lepton | dsb down-type | uc up-type | γ g vector | scalar

$$cg \to tH/tA \to tt\bar{c},\ tt\bar{t}$$

III. Top-associated H/A Production



$H/A \to t\bar{t},\ t\bar{c}$

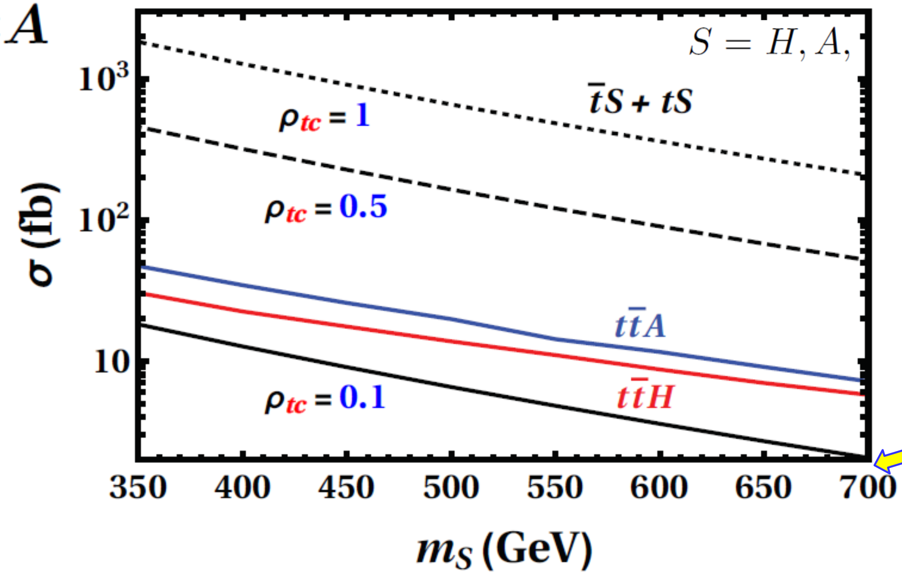
$\rho_{tt},\ \rho_{tc}$

Kohda, Modak, WSH, PLB'18
WSH, Hsu, Modak, PRD'20

Parton Cross Sections and BRs

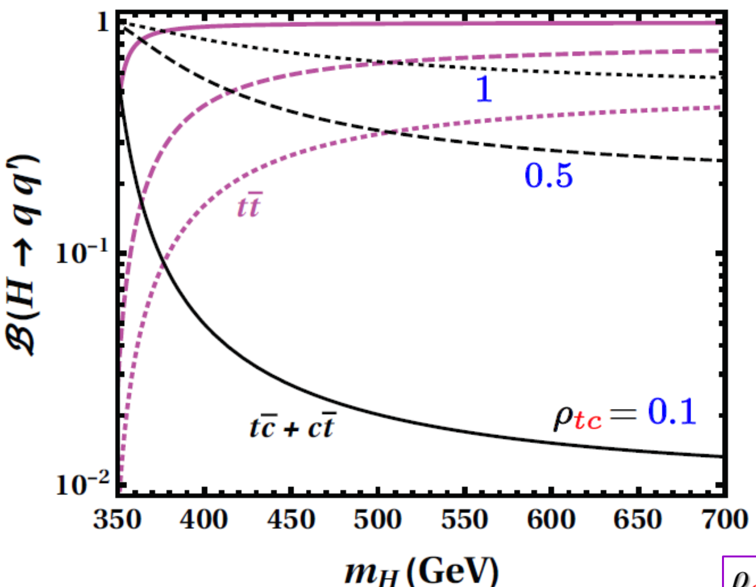
$\rho_{tt} = 1$

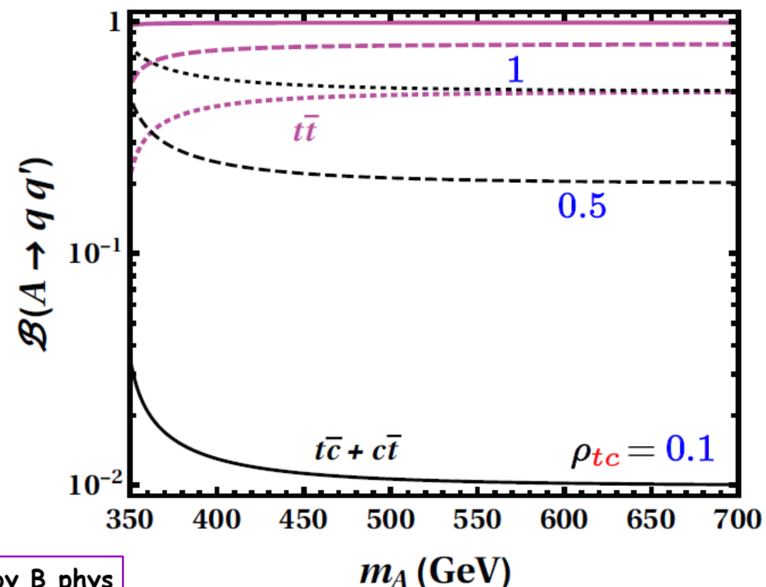
$cg \to tH/tA$



SM ttt(bar) ~ fb
Barger, Keung, Yencho, PLB'10

$H/A \to t\bar{t},\ t\bar{c}$





ρ_{ct} small by B phys

Collider constraints on ρ_{tc}

$\rho_{tt} = 0$

$cg \xrightarrow{\rho_{tc}} tH/tA \xrightarrow{\rho_{tc}} tt\bar{c}$ feeds

MadGraph/PYTHIA/Delphes/jets&MLM…

$t\bar{t}W$ Control Region of CMS 4t search (ATLAS CRttW2ℓ less constraining)

CMS EPJC'20

- Same-sign dilepton (w/ Drell-Yan veto)
- 2–5 jets (w/ 2 j_b)
- Sum over jets

137 fb^{-1}

$p_{T,\ell} > 25, 20$ GeV, $|\eta_e| < 2.5$, $|\eta_\mu| < 2.4$

$|\eta_j| < 2.4$, satisfying one of

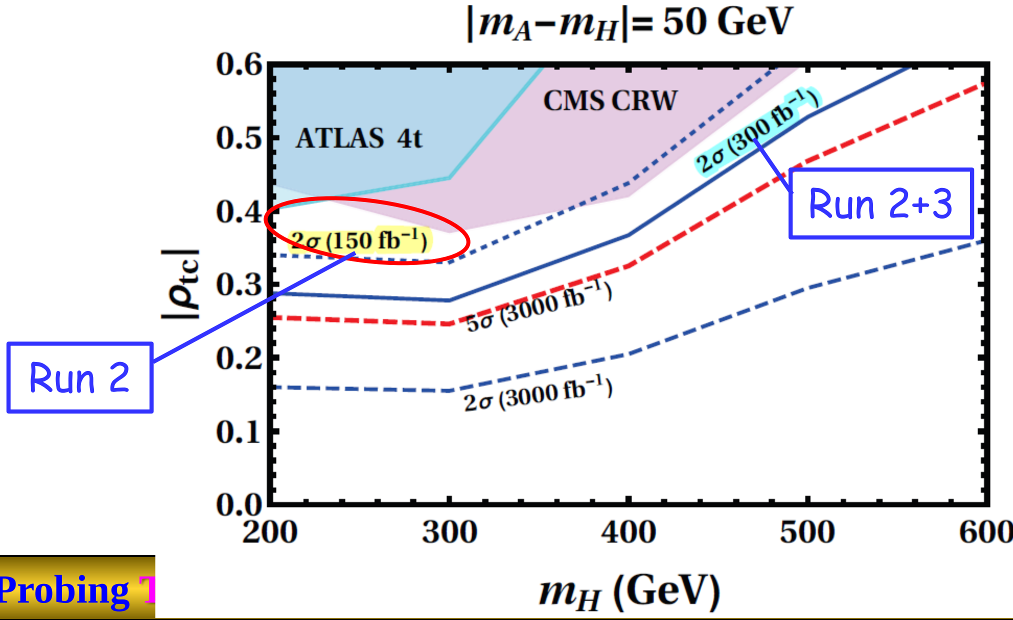
(i) $p_{T,b_1} > 40$ GeV, $p_{T,b_2} > 40$ GeV,

(ii) $p_{T,b_1} > 20$ GeV, $p_{T,b_2} = 20$–40 GeV, $p_{T,j_3} > 40$ GeV

(iii) $p_{T,b_{1,2}} = 20$–40 GeV, $p_{T,j_{3,4}} > 40$ GeV.

$H_T = \sum p_{T,j} > 300$ GeV, and $\not{E}_T > 50$ GeV

➔ observed 338 evts, expect 335 ± 18



- Proximity of A-H almost double effect
  → Power of 4t search on ρ_{tc} [tapers off for heavy Higgs]
- Improve w/ Optimized study (next page)
- 4t Search can also Improve

WSH, Hsu, Modak, PRD'20

Same-sign top: $cg \xrightarrow{\rho_{tc}} tH/tA \xrightarrow{\rho_{tc}} tt\bar{c}$ $+j$

$\rho_{tt} = 0$

WSH, Hsu, Modak, PRD'20

- Same-sign dilepton (ee, eμ, μμ)
  - $\geq 3j$ ($\geq 2j_b$; ≥ 1 non-j_b)
  - Sum over jets *and* leptons

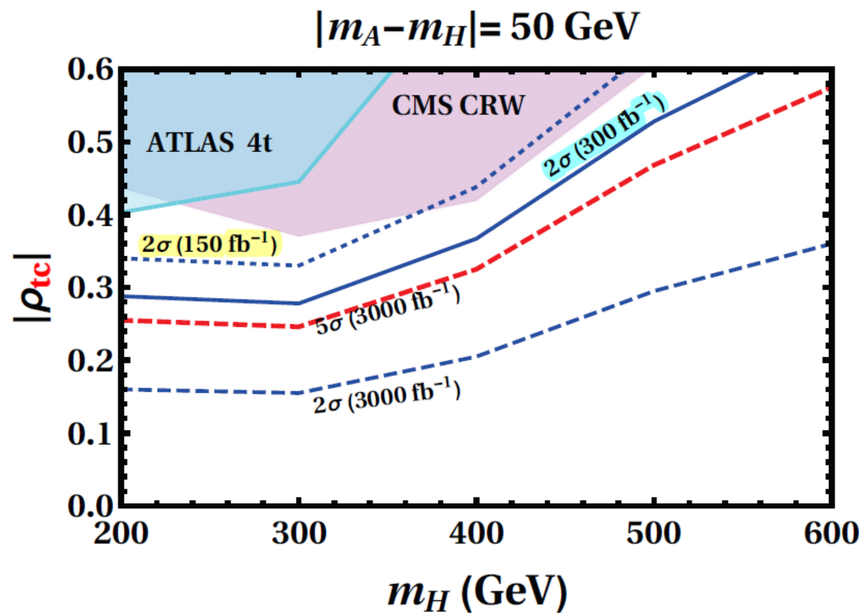
$p_T^{\ell_1(\ell_2)} > 25\,(20)$ GeV $\quad |\eta| < 2.5$

all jets $p_T > 20$ GeV and $|\eta| < 2.5$

all jets/leptons sep. by $\Delta R_{ij} > 0.4$

$H_T > 300$ GeV, $\not{E}_T > 35$ GeV

ρ_{tc} alone



ρ_{tu} alone

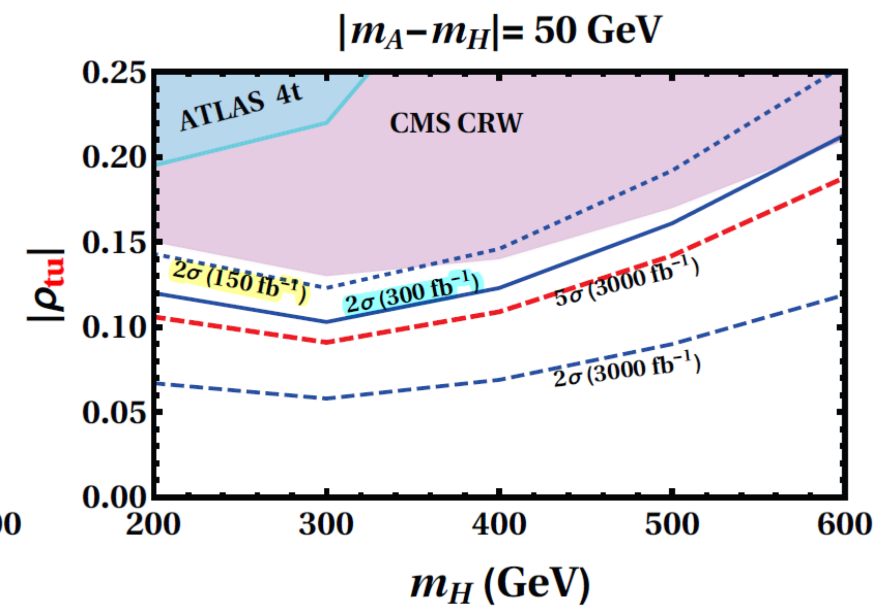


Table for S & B in backup.

Triple-top: $cg \xrightarrow{\rho_{tc}} tH/A \xrightarrow{\rho_{tt}} tt\bar{t}$

Kohda, Modak, WSH, PLB'18

Recall $\sigma_{3t} < \sigma_{4t}$ in SM

$3\ell3b$ process

$\rho_{tt} = 1$

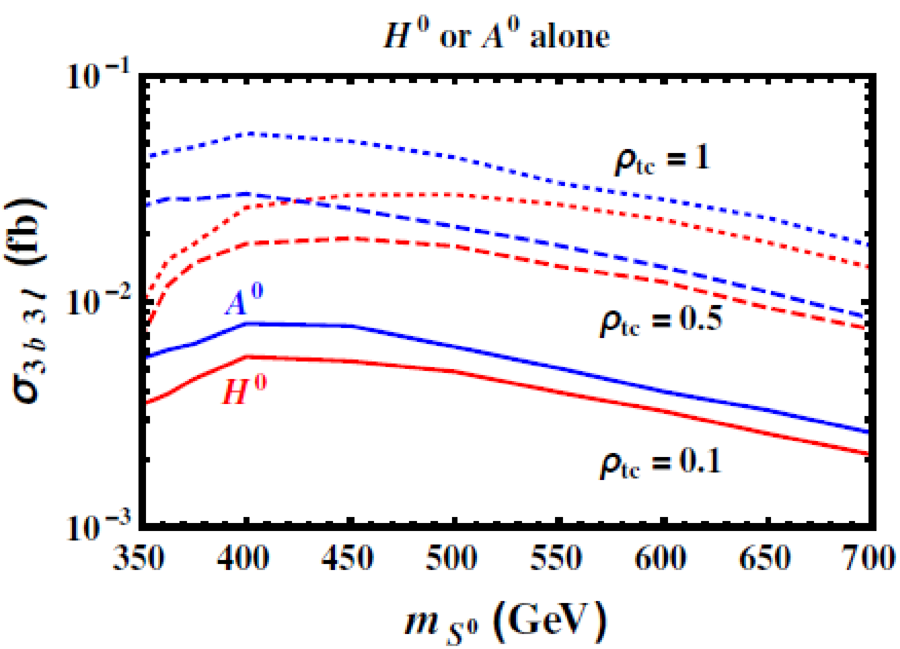
(K-fac.)	(Z-veto)
$t\bar{t}Z$ + jets (1.56)	0.0205 (0.0026)
$4t$ (2.04)	0.0232 (0.0209)
$t\bar{t}W$ + jets (1.35)	0.0017 (0.0015)
$t\bar{t}h$ (1.27)	0.0015 (0.0013)
tZj + jets (1.44)	0.0002 —
$t\bar{t}$ + jets (fake)	0.0026 (0.0025) pb

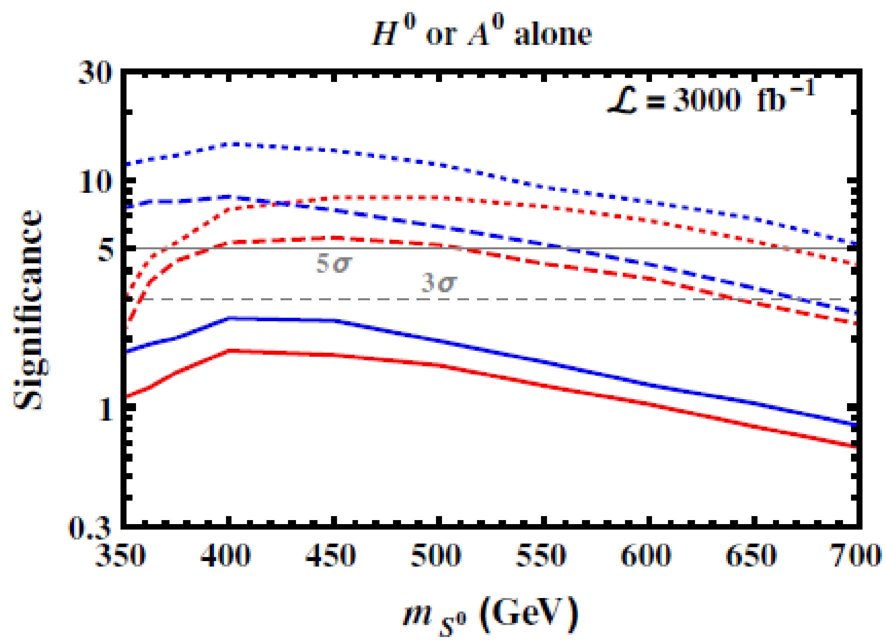
more exquisite: $\geq 3\ell$; $\geq 3j$; ($\geq 3j_b$); $\not{E}_T$

Excellent Reach @ HL-LHC

Should revisit.

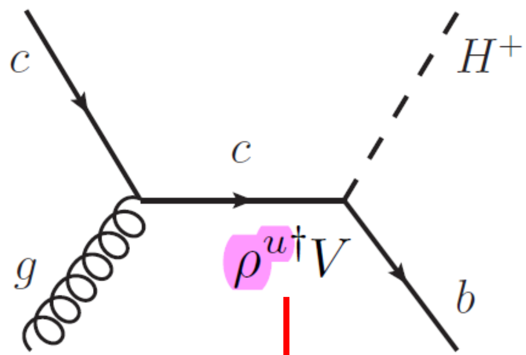
But perhaps after SS2t w/ Full Run 2?

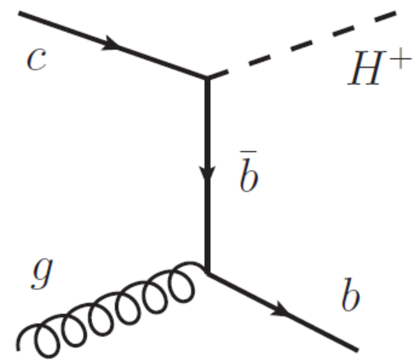




$$\overset{\rho_{tc}V_{tb}}{cg \to bH^+} \overset{\rho_{tt}V_{tb}}{\to b t \bar{b}}$$

IV. Bottom-associated H^+ Production





$H^+ \to t\bar{b}$

$\rho_{tt}V_{tb}$

CKM-enhanced
w.r.t. 2HDM II

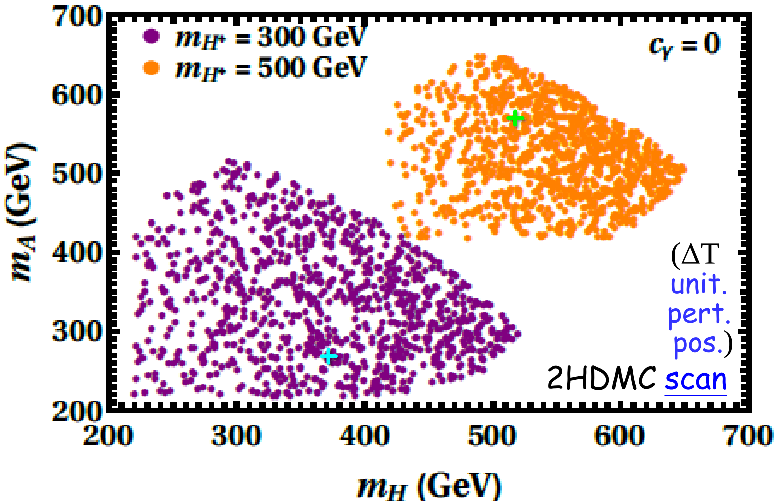
not apparent

$\rho_{tc}V_{tb}$

Iguro, Tobe, NPB'17
Gori, Grojean, Juste, Paul, JHEP'18
Nierste, Tabet, Ziegler, PRL'20
[w/o collider study/detail]

Flavor/Collider Constraints

Ghosh, WSH, Modak, PRL'20 [1912,10613]



Two Benchmark Points (from 2HDMC scan w/ $c_\gamma = 0$)

	η_2	η_3	η_4	η_5	η_7	$\frac{\mu_{22}^2}{v^2}$	m_{H^+}	m_A	m_H
BP1	1.40	0.62	0.53	1.06	−0.79	1.18	300	272	372
BP2	0.71	0.69	1.52	−0.93	0.24	3.78	500	569	517

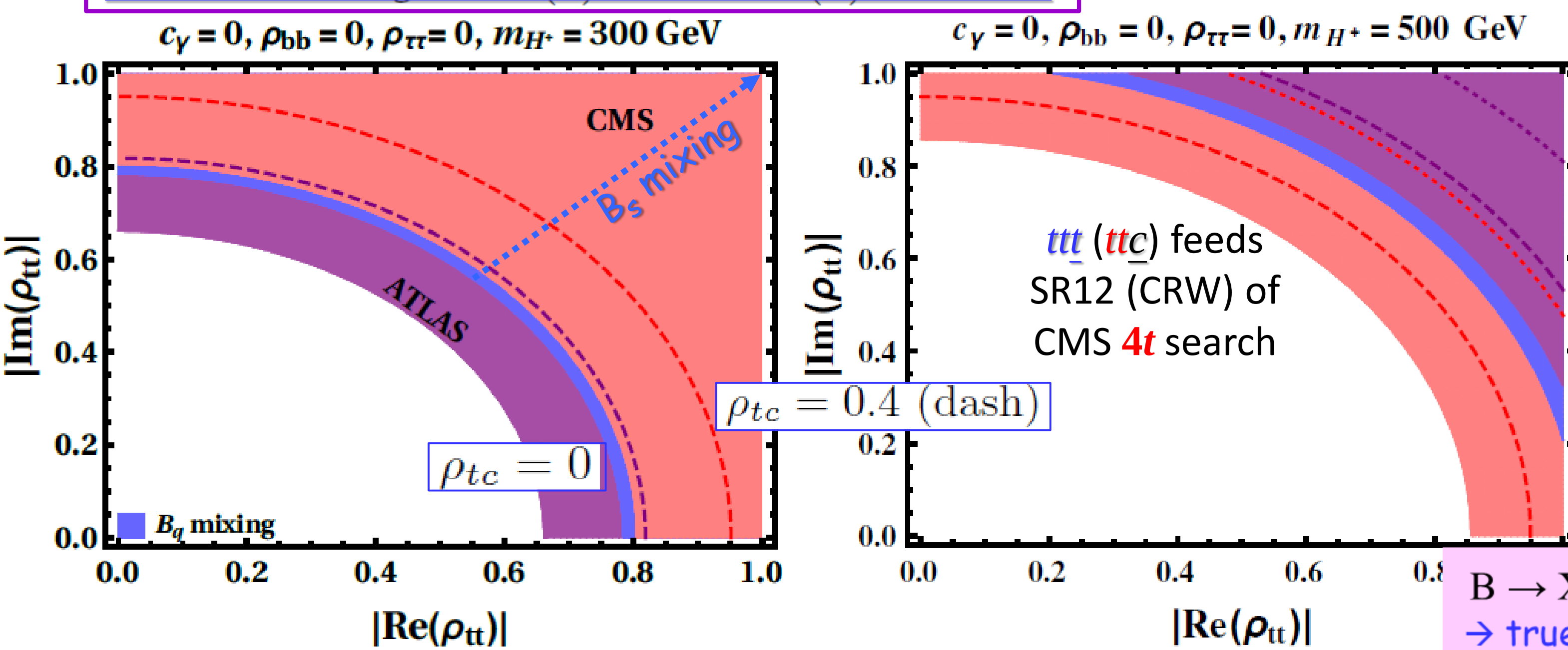
$H^+ \not\to AW^+,\ HW^+$

	$t\bar{t}js$	tj	$Wtjs$	$t\bar{t}h$	$t\bar{t}Z$	other	B_{tot}	Sig
BP1	1546	42	27	4.2	1.5	3.1	1627	11.4
BP2	1000	27	16	2.9	1.2	1.9	1049	9.3

(fb)

- Will take (conservative) $\rho_{tt} \sim \rho_{tc} \sim 0.5$
- Need expt'l study (*large param. space*)!

ATLAS & CMS $bg \to \bar{t}(b)H^+ \to \bar{t}(b)t\bar{b}$ bounds



and 0.8 (dots)
"dilution"

$B \to X_s\gamma$: many params.
→ true constraint "open"

Collider signature: $cg \xrightarrow{\rho_{tc} V_{tb}} bH^+ \xrightarrow{\rho_{tt} V_{tb}} bt\bar{b}$ ↳ $b\ell\nu_\ell$

Ghosh, WSH, Modak, PRL'20 [1912,10613]

- 3b1ℓ Signature (e, μ)
  - ≥ 3j w/ $3j_b$
  - Sum over jets *and* lepton [BP1 (BP2)]

$p_T^\ell > 30$ GeV
$|\eta| < 2.5$
$p_T > 20$ GeV
$\Delta R_{ij} > 0.4$
$\not{E}_T > 35$ GeV
$H_T > 350\ (400)$ GeV

Expts can optimize

Conservatively take $|\rho_{tc}| = 0.4$, $|\rho_{tt}| = 0.6$

$H^+ \to c\bar{b}, t\bar{b}$ { 50 : 50 BP1; 36 : 64 BP2 }

Other: Drell–Yan, W + jets, $4t$, $t\bar{t}W$, tWh

m_{H^+}		$t\bar{t}j$s	tj	Wtjs	$t\bar{t}h$	$t\bar{t}Z$	Other	$B_{\rm tot}$	Sig
300	BP1	1546	42	27	4.2	1.5	3.1	1627	11.4
500	BP2	1000	27	16	2.9	1.2	1.9	1049	9.3

fb

LO to NLO K factors not shown.

➔ For 137, 300, 600 fb^{-1}, Significance* at

~ 3.3σ, 4.9σ, 6.9σ for BP1
~ 3.4σ, 5.0σ, 7.1σ for BP2

Could show Evidence @ Run 2,
Discovery possible w/ Run 2 ⊕ 3

* ~ 3.5σ (~1σ) for BP1 (BP2) for SS2tj

V. Conclusion

H, **A**, **H$^{\pm}$**: well hidden so far (fermion mass-mixing ⊕ alignment)

- One extra doublet: 4 exotic Higgs/No holds barred (let *Nature* BE)

  ➔ 1 ⊕ 3 sets of extra *dim-4* couplings (Not EFT!)

  Quartics Yukawas — Needed for 1st order EWPT and Flav/**CP V**, resp.

- Intriguing: *extra* Yukawa ρ_{tt} drives B.A.U., work w/ ρ_{ee} to cover eEDM (?)

- Advocate 3 type of searches: param. space much *larger* (Discussion items)
  - Same-sign Top + *j*: $cg \to tH/tA \to tt\bar{c}$
  - Triple-Top: $cg \to tH/A \to tt\bar{t}$
  - Charged H^{+}: $cg \to bH^{+} \to bt\bar{b}$

  Sub-TeV **H**, **A**, **H^{+}** can go a long way, but may emerge @ Run 2 (⊕ 3).

Let's Find these extra **H**, **A**, **H^{+}** bosons and crack the ***Flavor***** code!

* One page in Backup

Thank you!

Theoretical Framework

g2HDM: Φ "mass giver", Φ' exotic

~~Z_2~~

General CP-conserving 2HDM potential (Higgs basis)

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

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

$$\mu_{11}^2 = -\eta_1 v^2/2 \qquad \mu_{12}^2 = \eta_6 v^2/2 \qquad > 0$$

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

Davidson & Haber, PRD'05 WSH, Kikuchi, EPL'18

$$M_{\text{even}}^2 = \begin{bmatrix} \eta_1 v^2 & \eta_6 v^2 \\ \eta_6 v^2 & m_A^2 + \eta_5 v^2 \end{bmatrix} \qquad c_\gamma^2 = \cos^2\gamma = \frac{\eta_1 v^2 - m_h^2}{m_H^2 - m_h^2} \quad \text{and} \quad s_{2\gamma} = \sin(2\gamma) = \frac{2\eta_6 v^2}{m_H^2 - m_h^2}$$

alignment: c_γ small

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

CPV (mostly) from 2nd Yukawa matrices:

$$-\frac{1}{\sqrt{2}}\sum_{f=u,d,\ell}\bar{f}_i\left[\left(-\lambda_i^f\delta_{ij}s_\gamma + \rho_{ij}^f c_\gamma\right)h + \left(\lambda_i^f\delta_{ij}c_\gamma + \rho_{ij}^f s_\gamma\right)H - i\,\text{sgn}(Q_f)\rho_{ij}^f A\right]Rf_j - \bar{u}_i\left[(V\rho^d)_{ij}R - (\rho^{u\dagger}V)_{ij}L\right]d_j H^+ - \bar{\nu}_i\rho_{ij}^\ell R\ell_j H^+ + \text{h.c.}$$

complex

Davidson & Haber, PRD'05 Altunkaynak, WSH, Kao, Kohda, McCoy PLB'15

WSH, Hsu, Modak, PRD'20

- Same-sign dilepton (ee, eμ, μμ)
  - $\geq 3j$ ($\geq 2j_b$; ≥ 1 non-j_b)
  - Sum over jets *and* leptons

$p_T^{\ell_1(\ell_2)} > 25\,(20)$ GeV $|\eta| < 2.5$

all jets $p_T > 20$ GeV and $|\eta| < 2.5$

all jets/leptons sep. by $\Delta R_{ij} > 0.4$

$H_T > 300$ GeV, $\not{E}_T > 35$ GeV

$m_A = m_H + 50$ GeV for $\rho_{tc} = 1$

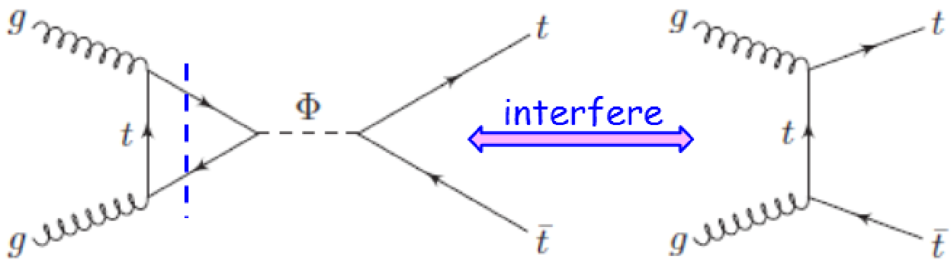
Signal Cross Section in fb (m_H in GeV)	Backgrounds	Cross Section (fb)
3.83 (200)	$t\bar{t}W$ [1.35 (1.27)] ⊕ 1.5x	1.31
4.12 (300)	$t\bar{t}Z$ [1.56]	1.97
2.35 (400)	$4t$ [2.04]	0.092
1.14 (500)	$t\bar{t}h$ [1.27]	0.058
0.75 (600)	Q-flip [1.84/1.27]	0.024
	tZ + jets [1.44]	0.007

Numbers in brackets in second column are LO to NLO K factors.

CMS "A → tt(bar)" hint

CMS JHEP'20 — 35.6 fb^{-1} (2016 data)

"a signal-like excess for the pseudoscalar hypotheses (largest) at 400 GeV, $\Gamma_{tot} = 4\%$, 3.5σ local (1.9σ LEE)"



- *Intriguing !*
- Needs large ρ_{tt}

  Cannot make it work* easily …
- To be Watched (Full Run 2, both expts)

* See e.g. 2103.13082.

Revenge of *Flavor* (& CPV?) in g2HDM

e.g. $B \to \mu\nu$

1903.03016 [PLB'20]

Enhanced $B \to \mu\bar{\nu}$ Decay at Tree Level as Probe of Extra Yukawa Couplings

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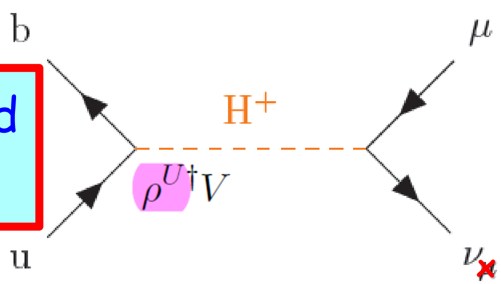
(Dated: April 26, 2019)

With no New Physics seen at the LHC, a second Higgs doublet remains attractive and plausible. The ratio $\mathcal{R}_B^{\mu/\tau} = \mathcal{B}(B \to \mu\bar{\nu})/\mathcal{B}(B \to \tau\bar{\nu})$ is predicted at 0.0045 in both the Standard Model and the type II two Higgs doublet model, but it can differ if extra Yukawa couplings exist in Nature, which we deem an experimental issue. Considering recent Belle update on $B \to \mu\bar{\nu}$, we show that in the general two Higgs doublet model, the ratio could be up by a factor of two, which can be probed by the Belle II experiment with just a few ab^{-1}.

Competitive with ATLAS/CMS: probe $\rho_{tu}\rho_{\tau\mu}$

$$\mathcal{B}(B \to \ell\bar{\nu}_\ell)\big|^{\text{2HDM II}} = r_H\, \mathcal{B}(B \to \ell\bar{\nu}_\ell)\big|^{\text{SM}}$$

WSH, PRD'93 [$B \to \tau\nu$]



ρ_{tu} enhanced by V_{tb}/V_{ub}

$\rho_{\tau\mu}$ enters!

Conclusion.— With a second Higgs doublet quite plausible, the existence of extra Yukawa couplings is an experimental issue. The SM and 2HDM II predict the ratio $\mathcal{R}_B^{\mu/\tau} = \mathcal{B}(B \to \mu\bar{\nu})/\mathcal{B}(B \to \tau\bar{\nu})$ to be 0.0045, which offers a unique test. Through $\bar{\nu}_\tau$ flavor, the $\rho_{\tau\mu}$ coupling can enhance $B \to \mu\bar{\nu}$, while $B \to \tau\bar{\nu}$ is SM-like. If enhancement of $\mathcal{R}_B^{\mu/\tau}$ is uncovered by Belle II with just a few ab^{-1}, then the many extra Yukawa couplings — fundamental flavor parameters associated with a second Higgs doublet — would need to be unraveled.