Flavorful Higgs Bosons

Wolfgang Altmannshofer
altmanwg@ucmail.uc.edu

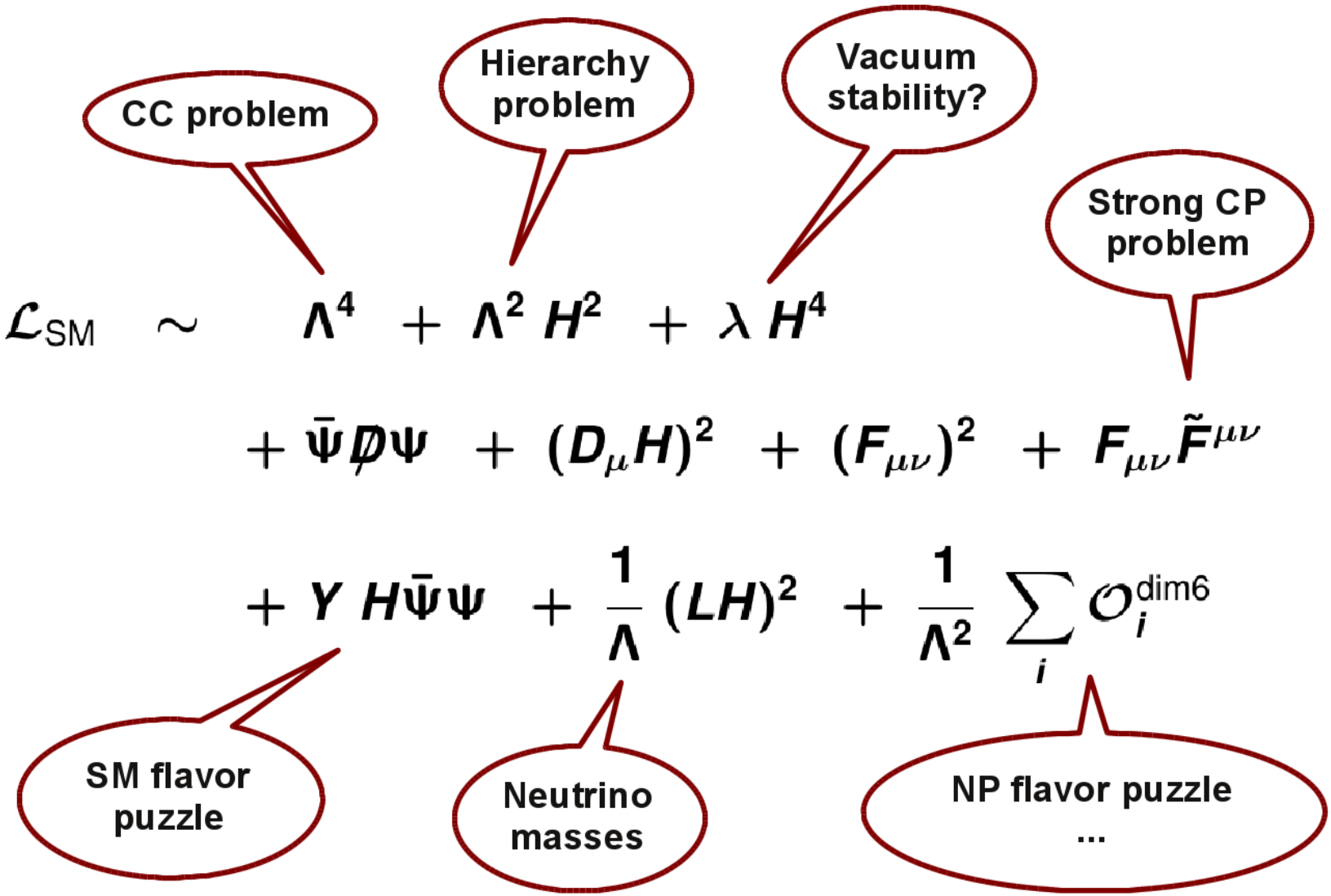
Exotic Higgs Workshop,

SLAC, November 8, 2016

The Standard Model as Effective Theory

$$\mathcal{L}_{\text{SM}} \sim \Lambda^4 + \Lambda^2 H^2 + \lambda H^4$$
$$+ \bar{\Psi} \not{D} \Psi + (D_\mu H)^2 + (F_{\mu\nu})^2 + F_{\mu\nu} \tilde{F}^{\mu\nu}$$
$$+ Y H \bar{\Psi} \Psi + \frac{1}{\Lambda} (LH)^2 + \frac{1}{\Lambda^2} \sum_i \mathcal{O}_i^{\text{dim6}}$$

The Standard Model as Effective Theory



What is the New Physics scale Λ ?

The Standard Model as Effective Theory

Invariant under a $SU(3)^5 \times U(1)^5$ flavor symmetry

$$\mathcal{L}_{SM} \sim \Lambda^4 + \Lambda^2 H^2 + \lambda H^4 + \bar{\Psi} \not{D} \Psi + (D_\mu H)^2 + (F_{\mu\nu})^2 + F_{\mu\nu} \tilde{F}^{\mu\nu} + Y H \bar{\Psi} \Psi + \frac{1}{\Lambda} (LH)^2 + \frac{1}{\Lambda^2} \sum_i \mathcal{O}_i^{\text{dim6}}$$

The Standard Model as Effective Theory

Invariant under a $SU(3)^5 \times U(1)^5$ flavor symmetry

$$\mathcal{L}_{SM} \sim \Lambda^4 + \Lambda^2 H^2 + \lambda H^4 + \bar{\Psi} \not{D} \Psi + (D_\mu H)^2 + (F_{\mu\nu})^2 + F_{\mu\nu}\tilde{F}^{\mu\nu} + Y H \bar{\Psi} \Psi + \frac{1}{\Lambda}(LH)^2 + \frac{1}{\Lambda^2} \sum_i \mathcal{O}_i^{\text{dim6}}$$

Only renormalizable source of flavor breaking

New Physics in Higgs Couplings

$$\mathcal{L}_{\text{Yukawa}} = Y_{ij}\, \bar{\Psi}_i \Psi_j\, H$$

In the Standard Model the Yukawa couplings are the only sources of flavor and CP violation

$\rightarrow$ the couplings of the Higgs to fermion mass eigenstates are flavor diagonal and CP conserving

$$\frac{1}{v} \begin{pmatrix} m_{u,d,e} & 0 & 0 \\ 0 & m_{c,s,\mu} & 0 \\ 0 & 0 & m_{t,b,\tau} \end{pmatrix}$$

New Physics in Higgs Couplings

$$\mathcal{L}_{\text{Yukawa}} = Y_{ij}\,\bar{\Psi}_i \Psi_j\, H + \frac{\tilde{Y}_{ij}}{\Lambda^2}\,\bar{\Psi}_i \Psi_j\, H^3$$

In the Standard Model the Yukawa couplings are the only sources of flavor and CP violation

$\rightarrow$ the couplings of the Higgs to fermion mass eigenstates are flavor diagonal and CP conserving

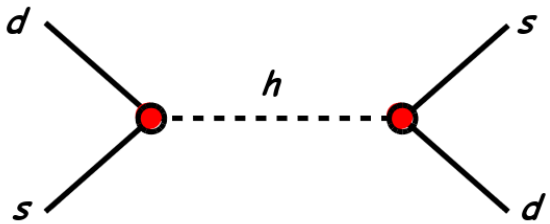
$$\frac{1}{v}\begin{pmatrix} m_{u,d,e} & 0 & 0 \\ 0 & m_{c,s,\mu} & 0 \\ 0 & 0 & m_{t,b,\tau} \end{pmatrix} + \frac{v^2}{\Lambda^2}\begin{pmatrix} \star & \star & \star \\ \star & \star & \star \\ \star & \star & \star \end{pmatrix}$$

1) New Physics can modify the flavor diagonal Higgs couplings
2) New Physics can lead to flavor and CP violating Higgs couplings

Flavor Violating Couplings

$$\frac{v^2}{\Lambda^2}\begin{pmatrix} \star & \star & \star \\ \star & \star & \star \\ \star & \star & \star \end{pmatrix}$$

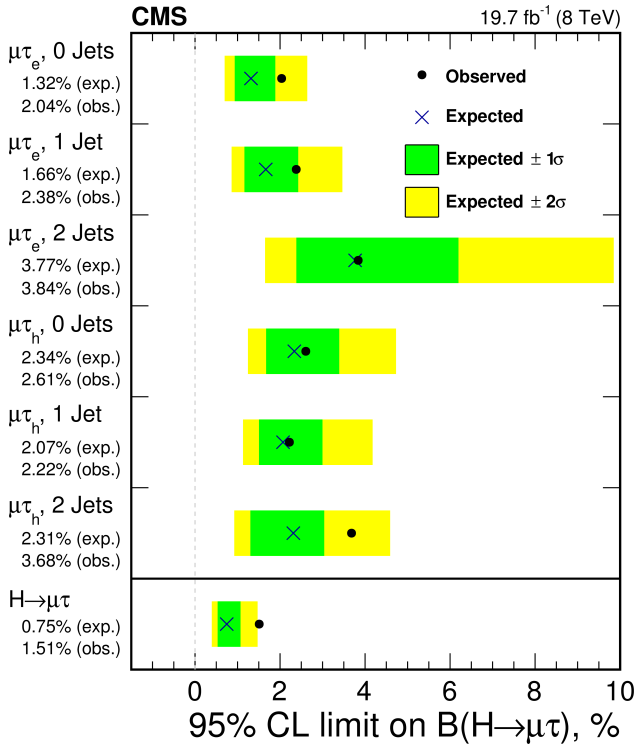
strong constraints on flavor violating Higgs couplings from low energy flavor observables in the quark sector and for $\mu \to e$ transitions

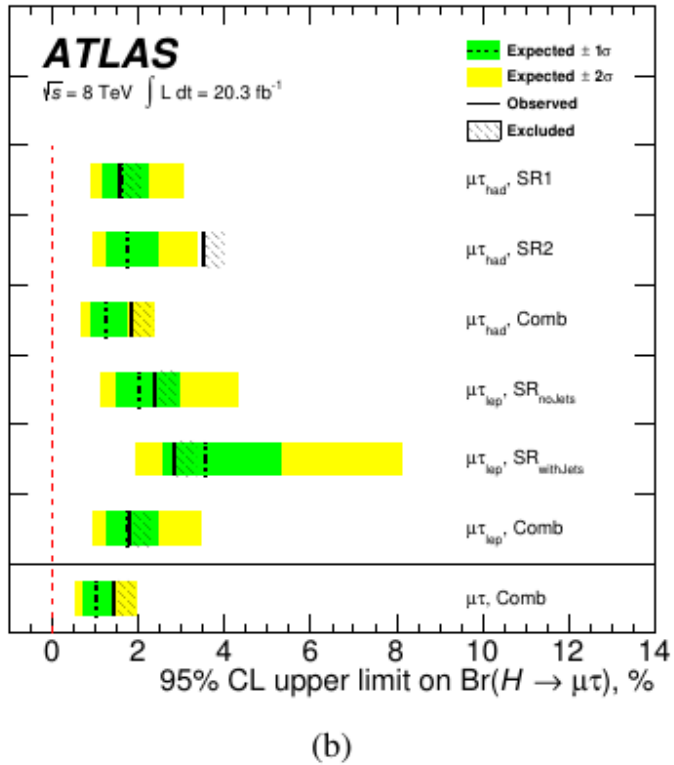


Technique	Coupling	Constraint
D^0 oscillations [48]	$\lvert Y_{uc}\rvert^2$, $\lvert Y_{cu}\rvert^2$	$< 5.0 \times 10^{-9}$
	$\lvert Y_{uc}Y_{cu}\rvert$	$< 7.5 \times 10^{-10}$
B_d^0 oscillations [48]	$\lvert Y_{db}\rvert^2$, $\lvert Y_{bd}\rvert^2$	$< 2.3 \times 10^{-8}$
	$\lvert Y_{db}Y_{bd}\rvert$	$< 3.3 \times 10^{-9}$
B_s^0 oscillations [48]	$\lvert Y_{sb}\rvert^2$, $\lvert Y_{bs}\rvert^2$	$< 1.8 \times 10^{-6}$
	$\lvert Y_{sb}Y_{bs}\rvert$	$< 2.5 \times 10^{-7}$
K^0 oscillations [48]	$\mathrm{Re}(Y_{ds}^2)$, $\mathrm{Re}(Y_{sd}^2)$	$[-5.9 \ldots 5.6] \times 10^{-10}$
	$\mathrm{Im}(Y_{ds}^2)$, $\mathrm{Im}(Y_{sd}^2)$	$[-2.9 \ldots 1.6] \times 10^{-12}$
	$\mathrm{Re}(Y_{ds}^* Y_{sd})$	$[-5.6 \ldots 5.6] \times 10^{-11}$
	$\mathrm{Im}(Y_{ds}^* Y_{sd})$	$[-1.4 \ldots 2.8] \times 10^{-13}$
single-top production [49]	$\sqrt{\lvert Y_{tc}^2\rvert + \lvert Y_{ct}\rvert^2}$	< 3.7
	$\sqrt{\lvert Y_{tu}^2\rvert + \lvert Y_{ut}\rvert^2}$	< 1.6
$t \to hj$ [50]	$\sqrt{\lvert Y_{tc}^2\rvert + \lvert Y_{ct}\rvert^2}$	< 0.34
	$\sqrt{\lvert Y_{tu}^2\rvert + \lvert Y_{ut}\rvert^2}$	< 0.34
D^0 oscillations [48]	$\lvert Y_{ut}Y_{ct}\rvert$, $\lvert Y_{tu}Y_{tc}\rvert$	$< 7.6 \times 10^{-3}$
	$\lvert Y_{tu}Y_{ct}\rvert$, $\lvert Y_{ut}Y_{tc}\rvert$	$< 2.2 \times 10^{-3}$
	$\lvert Y_{ut}Y_{tu}Y_{ct}Y_{tc}\rvert^{1/2}$	$< 0.9 \times 10^{-3}$
neutron EDM [37]	$\mathrm{Im}(Y_{ut}Y_{tu})$	$< 4.4 \times 10^{-8}$

Blankenburg, Ellis, Isidori'12; Harnik, Kopp, Zupan '12; ...

A Hint for $h \to \tau\mu$?





(b)

2.4σ excess in $h \to \tau\mu$ at CMS

(1502.07400)

$\text{BR}(h \to \tau\mu) = (0.84^{+0.39}_{-0.37})\%$

not excluded by other results

(1508.03372/1604.07730/CMS-PAS-HIG-16-005)

$\text{BR}(h \to \tau\mu) < 1.43\%$ (ATLAS)

$\text{BR}(h \to \tau\mu) < 1.2\%$ (CMS)

Flavor Violating Higgs in the EFT

$$\mathcal{L} = Y\ \bar{\psi}\psi\ H + \frac{\tilde{Y}}{\Lambda^2}\ \bar{\psi}\psi H^3$$

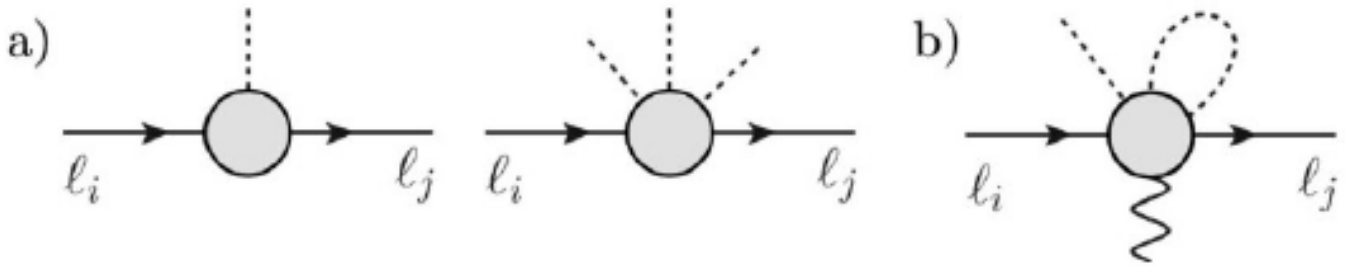
flavor violating higgs couplings if Y and $\tilde{Y}$ are not aligned

Flavor Violating Higgs in the EFT

$$\mathcal{L} = Y\ \bar{\Psi}\Psi\ H + \frac{\tilde{Y}}{\Lambda^2}\ \bar{\Psi}\Psi H^3 + \frac{c}{\Lambda^2}\ \bar{\Psi}\sigma_{\mu\nu}\Psi\ H\ F^{\mu\nu}$$

flavor violating higgs couplings if Y and $\tilde{Y}$ are not aligned

generically one also expects flavor violating dipoles at dim. 6 level



Contributions to lepton Yukawa couplings (a) , electromagnetic dipole (b)

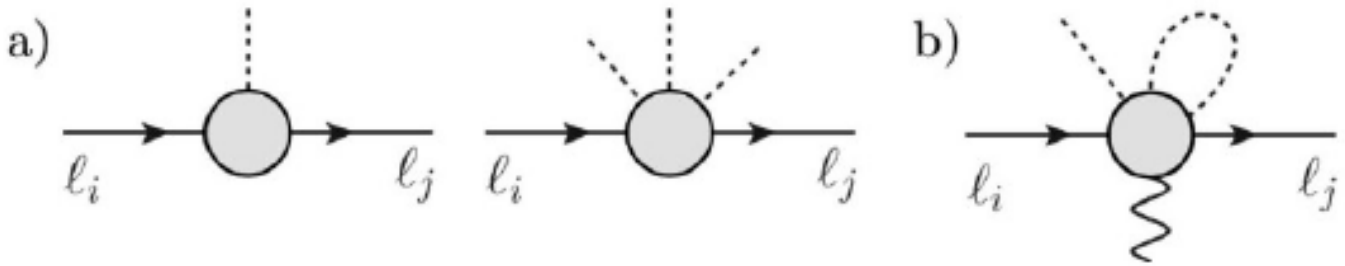
WA, Gori, Kagan, Silvestrini, Zupan 1507.07927

Flavor Violating Higgs in the EFT

$$\mathcal{L} = Y\ \bar{\Psi}\Psi\ H + \frac{\tilde{Y}}{\Lambda^2}\ \bar{\Psi}\Psi H^3 + \frac{c}{\Lambda^2}\ \bar{\Psi}\sigma_{\mu\nu}\Psi\ H\ F^{\mu\nu}$$

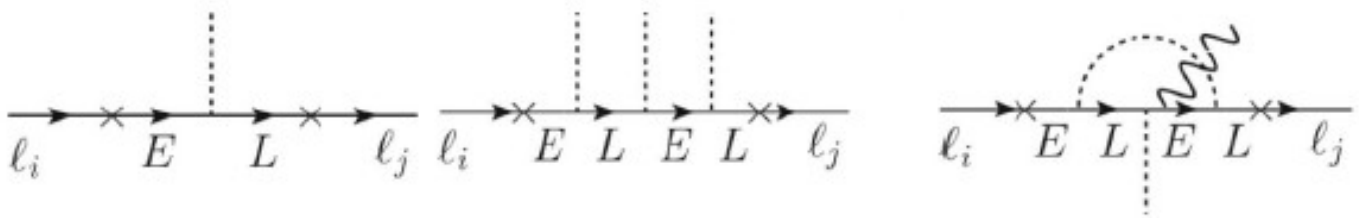
flavor violating higgs couplings if Y and $\tilde{Y}$ are not aligned

generically one also expects flavor violating dipoles at dim. 6 level



Contributions to lepton Yukawa couplings (a) , electromagnetic dipole (b)

Example for a realization:



WA, Gori, Kagan, Silvestrini, Zupan 1507.07927

"Bound" on $h \to \tau\mu$

$$\mathcal{L} = Y\ \bar{\Psi}\Psi\ H + \frac{\tilde{Y}}{\Lambda^2}\ \bar{\Psi}\Psi H^3 + \frac{c}{\Lambda^2}\ \bar{\Psi}\sigma_{\mu\nu}\Psi\ H\ F^{\mu\nu}$$

$$\text{generically we expect}\ \ c \sim \tilde{Y}\frac{e}{16\pi^2}$$

under this assumption we find a "bound" on $h \to \tau\mu$

$$\text{BR}(h \to \tau\mu) \sim 26 \times \text{BR}(\tau \to \mu\gamma) \lesssim 10^{-6}$$

(orders of magnitude below current and future sensitivities)

WA, Gori, Kagan, Silvestrini, Zupan 1507.07927

Models for Sizable $h \to \tau\mu$

Fine tune away $\tau \to \mu\gamma$

Clever model building

Additional source of EWSB / fermion masses

Models for Sizable $h \to \tau\mu$

Fine tune away $\tau \to \mu\gamma$

Clever model building

Additional source of EWSB / fermion masses

$$\mathcal{L} = Y\ \bar{\Psi}\Psi\ H$$

$$+\frac{\tilde{Y}}{\Lambda_1^2}\ \bar{\Psi}\Psi H^3 + \frac{c}{\Lambda_2^2}\ \bar{\Psi}\sigma_{\mu\nu}\Psi\ H\ F^{\mu\nu}$$

arrange the new physics sector such that $\Lambda_1 \ll \Lambda_2$

WA, Carena, Crivellin 1604.08221

Models for Sizable $h \to \tau\mu$

Fine tune away $\tau \to \mu\gamma$

Clever model building

$$\mathcal{L} = Y\ \bar{\Psi}\Psi\ H$$

$$+\frac{\tilde{Y}}{\Lambda_1^2}\ \bar{\Psi}\Psi H^3 + \frac{c}{\Lambda_2^2}\ \bar{\Psi}\sigma_{\mu\nu}\Psi\ H\ F^{\mu\nu}$$

arrange the new physics sector such that $\Lambda_1 \ll \Lambda_2$

WA, Carena, Crivellin 1604.08221

Additional source of EWSB / fermion masses

$$\mathcal{L} = Y\ \bar{\Psi}\Psi\ H$$

$$+\tilde{Y}\ \bar{\Psi}\Psi\langle X\rangle + \frac{c}{\Lambda^2}\ \bar{\Psi}\sigma_{\mu\nu}\Psi\ H\ F^{\mu\nu}$$

can decouple the dipole

WA, Gori, Kagan, Silvestrini, Zupan 1507.07927

Two Sources of Fermion Masses

let's consider a second source of fermion masses

$$\mathcal{M} = \mathcal{M}_0 + \Delta\mathcal{M}$$

- $\mathcal{M}_0$: due to the (main component of the) 125 GeV Higgs
  provides the bulk of the 3rd generation masses
- $\Delta\mathcal{M}$: due to some other source
  mainly responsible for the 1st and 2nd generation masses

WA, Gori, Kagan, Silvestrini, Zupan 1507.07927; Ghosh et al. 1508.01501; Botella et al. 1602.08011

Two Sources of Fermion Masses

let's consider a second source of fermion masses

$$\mathcal{M} = \mathcal{M}_0 + \Delta\mathcal{M}$$

- $\mathcal{M}_0$: due to the (main component of the) 125 GeV Higgs
  provides the bulk of the 3rd generation masses
- $\Delta\mathcal{M}$: due to some other source
  mainly responsible for the 1st and 2nd generation masses

will focus on 2HDM realization, where one Higgs has rank 1 Yukawas

$$\mathcal{M}_0 \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_\tau \end{pmatrix}, \quad \Delta\mathcal{M} \simeq \begin{pmatrix} m_e & O(m_e) & O(m_e) \\ O(m_e) & m_\mu & O(m_\mu) \\ O(m_e) & O(m_\mu) & O(m_\mu) \end{pmatrix}$$

(similar in the quark sector)

WA, Gori, Kagan, Silvestrini, Zupan 1507.07927; Ghosh et al. 1508.01501; Botella et al. 1602.08011

Flavor Diagonal Couplings of the 125 GeV Higgs

Compare to other extended Higgs sectors

	W,Z	up quarks	down quarks	leptons
	κ_V	κ_t, κ_c, κ_u	κ_b, κ_s, κ_d	κ_τ, κ_μ, κ_e
2HDM type 1				
2HDM type 2				
flavorful 2HDM				

Flavor Diagonal Couplings of the 125 GeV Higgs

Compare to other extended Higgs sectors

	W,Z κ_V	up quarks κ_t, κ_c, κ_u	down quarks κ_b, κ_s, κ_d	leptons κ_τ, κ_μ, κ_e
2HDM type 1	$s_{\beta-\alpha}$	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$
2HDM type 2	$s_{\beta-\alpha}$	$\frac{c_\alpha}{s_\beta}$	$\frac{-s_\alpha}{c_\beta}$	$\frac{-s_\alpha}{c_\beta}$
flavorful 2HDM				

Flavor Diagonal Couplings of the 125 GeV Higgs

Compare to other extended Higgs sectors

	W,Z κ_V	up quarks κ_t, κ_c, κ_u	down quarks κ_b, κ_s, κ_d	leptons κ_τ, κ_μ, κ_e
2HDM type 1	$s_{\beta-\alpha}$	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$
2HDM type 2	$s_{\beta-\alpha}$	$\frac{c_\alpha}{s_\beta}$	$\frac{-s_\alpha}{c_\beta}$	$\frac{-s_\alpha}{c_\beta}$
flavorful 2HDM	$s_{\beta-\alpha}$	$\frac{c_\alpha}{s_\beta}, \frac{-s_\alpha}{c_\beta}, \frac{-s_\alpha}{c_\beta}$	$\frac{c_\alpha}{s_\beta}, \frac{-s_\alpha}{c_\beta}, \frac{-s_\alpha}{c_\beta}$	$\frac{c_\alpha}{s_\beta}, \frac{-s_\alpha}{c_\beta}, \frac{-s_\alpha}{c_\beta}$

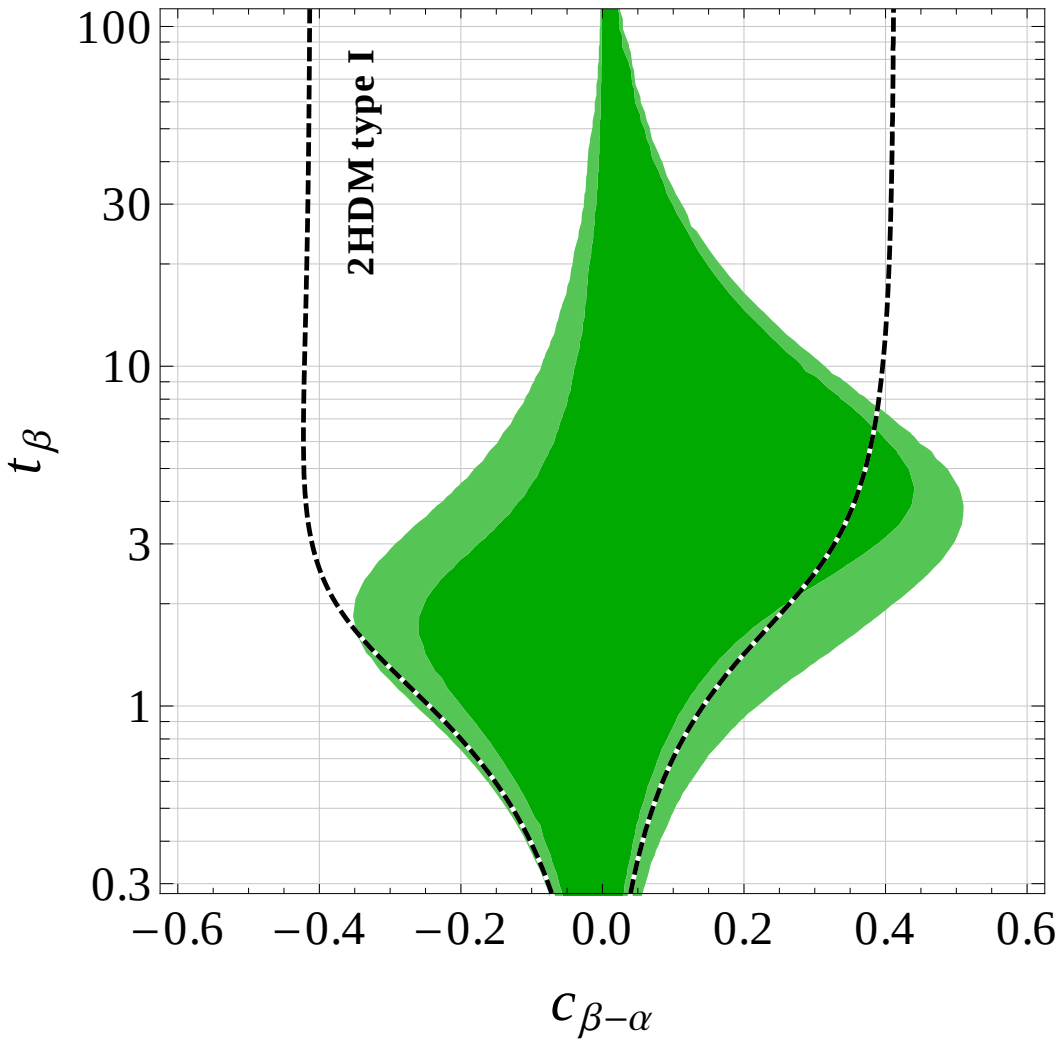
(in the flavorful 2HDM there are additional corrections to the κ's of the order of $O(m_c/m_t)$, $O(m_s/m_b)$, $O(m_\mu/m_\tau)$)

Constraints from Higgs Rates

measurements of Higgs rates constrain α/β parameter space

for low tan β expect constraints similar to 2HDM type 1

for large tan β couplings to charm and muons can be strongly enhanced



Flavor Violating Couplings of the Higgs

in general the fermion masses and the h couplings cannot be diagonalized simultaneously

e.g. $$\frac{y_{\mu\tau}}{y_\mu^{\rm SM}} = -\frac{\Delta\mathcal{M}_{\mu\tau}}{m_\mu}\frac{\cos(\beta-\alpha)}{\sin\beta\cos\beta}$$

Flavor Violating Couplings of the Higgs

in general the fermion masses and the h couplings cannot be diagonalized simultaneously

e.g. $$\frac{y_{\mu\tau}}{y_\mu^{\rm SM}} = -\frac{\Delta\mathcal{M}_{\mu\tau}}{m_\mu}\frac{\cos(\beta-\alpha)}{\sin\beta\cos\beta}$$

generic expectations for lepton flavor violating Higgs decays

$$\begin{aligned}
\text{BR}(h\to\tau\mu) &\sim \frac{m_\mu^2}{3m_b^2} \sim 10^{-3}\\
\text{BR}(h\to\tau e) &\sim \frac{m_e^2}{3m_b^2} \sim 10^{-7}\\
\text{BR}(h\to\mu e) &\sim \frac{m_e^2 m_\mu^2}{3m_\tau^2 m_b^2} \sim 10^{-10}
\end{aligned}$$

Additional Flavor Violating Signatures

flavor violating
rare top decays with
branching ratios as large as

$$\mathrm{BR}(t \to ch) \sim |V_{cb}|^2 \sim 10^{-3}$$

$$\mathrm{BR}(t \to uh) \sim |V_{ub}|^2 \sim 10^{-5}$$

might be in reach of the
high luminosity LHC

WA, Gori, Kagan, Silvestrini, Zupan 1507.07927 + in preparation

Additional Flavor Violating Signatures

flavor violating
rare top decays with
branching ratios as large as

$$\mathrm{BR}(t \to ch) \sim |V_{cb}|^2 \sim 10^{-3}$$

$$\mathrm{BR}(t \to uh) \sim |V_{ub}|^2 \sim 10^{-5}$$

might be in reach of the
high luminosity LHC

lepton flavor violating
rare B meson decays
with sizable branching ratios

$$\mathrm{BR}(B_s \to \tau\mu) \sim \text{few} \times 10^{-7}$$

$$\mathrm{BR}(B \to K\tau\mu) \sim \text{few} \times 10^{-7}$$

$$\mathrm{BR}(B \to K^*\tau\mu) \sim \text{few} \times 10^{-7}$$

LHCb might be sensitive
to the K^* and K rates

WA, Gori, Kagan, Silvestrini, Zupan 1507.07927 + in preparation

Couplings of the Heavy Scalar

Compare to other extended Higgs sectors

	W,Z κ_V^H	up quarks κ_t^H, κ_c^H, κ_u^H	down quarks κ_b^H, κ_s^H, κ_d^H	leptons κ_τ^H, κ_μ^H, κ_e^H
2HDM type 1				
2HDM type 2				
flavorful 2HDM				

Couplings of the Heavy Scalar

Compare to other extended Higgs sectors

	W,Z κ_V^H	up quarks κ_t^H, κ_c^H, κ_u^H	down quarks κ_b^H, κ_s^H, κ_d^H	leptons κ_τ^H, κ_μ^H, κ_e^H
2HDM type 1	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\,\frac{s_\alpha}{c_\beta}$	$\frac{1}{t_\beta}\,\frac{s_\alpha}{c_\beta}$	$\frac{1}{t_\beta}\,\frac{s_\alpha}{c_\beta}$
2HDM type 2	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\,\frac{s_\alpha}{c_\beta}$	$t_\beta\,\frac{c_\alpha}{s_\beta}$	$t_\beta\,\frac{c_\alpha}{s_\beta}$
flavorful 2HDM				

Couplings of the Heavy Scalar

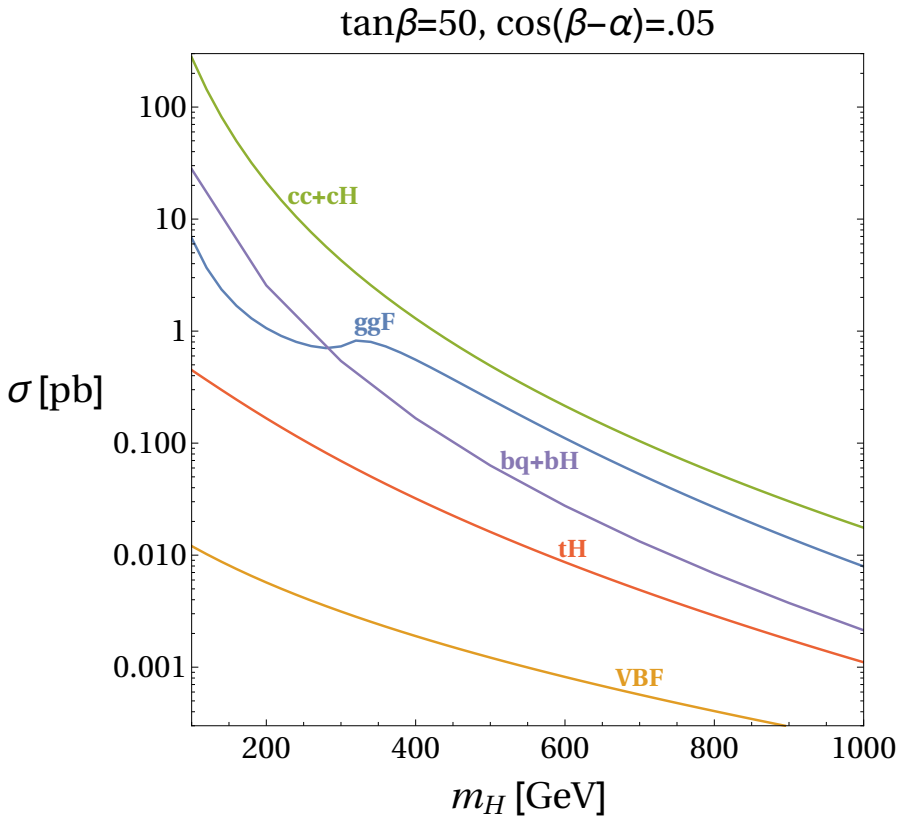
Compare to other extended Higgs sectors

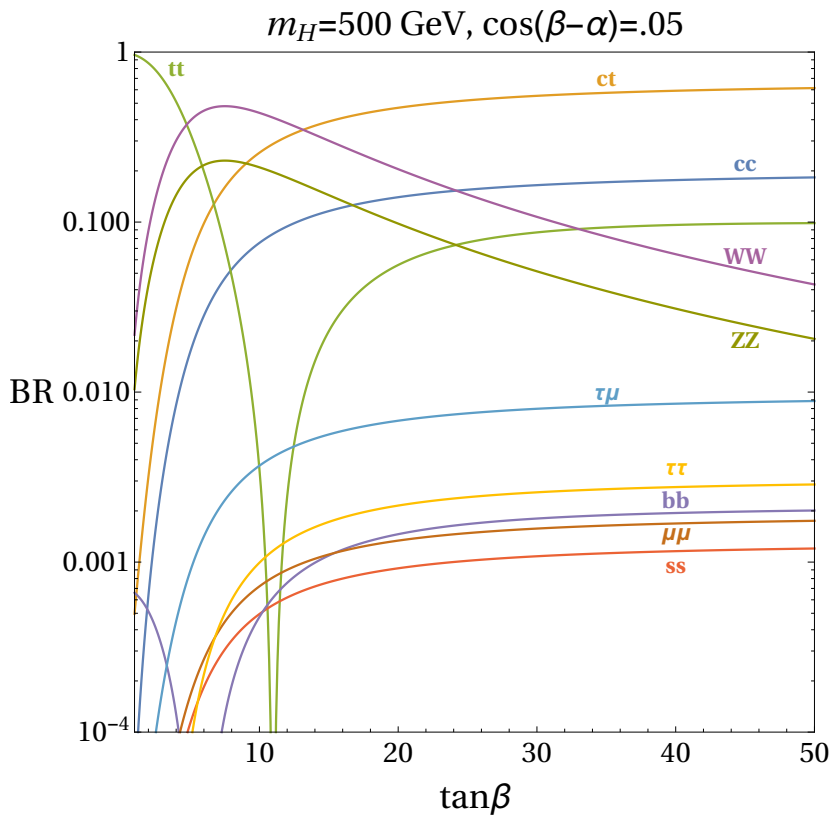
	W,Z κ_V^H	up quarks κ_t^H, κ_c^H, κ_u^H	down quarks κ_b^H, κ_s^H, κ_d^H	leptons κ_τ^H, κ_μ^H, κ_e^H
2HDM type 1	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\,\frac{s_\alpha}{c_\beta}$	$\frac{1}{t_\beta}\,\frac{s_\alpha}{c_\beta}$	$\frac{1}{t_\beta}\,\frac{s_\alpha}{c_\beta}$
2HDM type 2	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\,\frac{s_\alpha}{c_\beta}$	$t_\beta\,\frac{c_\alpha}{s_\beta}$	$t_\beta\,\frac{c_\alpha}{s_\beta}$
flavorful 2HDM	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\,\frac{s_\alpha}{c_\beta}$, $t_\beta\,\frac{c_\alpha}{s_\beta}$, $t_\beta\,\frac{c_\alpha}{s_\beta}$	$\frac{1}{t_\beta}\,\frac{s_\alpha}{c_\beta}$, $t_\beta\,\frac{c_\alpha}{s_\beta}$, $t_\beta\,\frac{c_\alpha}{s_\beta}$	$\frac{1}{t_\beta}\,\frac{s_\alpha}{c_\beta}$, $t_\beta\,\frac{c_\alpha}{s_\beta}$, $t_\beta\,\frac{c_\alpha}{s_\beta}$

(in the flavorful 2HDM there are additional corrections of the order of $O(m_c/m_t)$, $O(m_s/m_b)$, $O(m_\mu/m_\tau)$)

Heavy Higgs Production and Decays

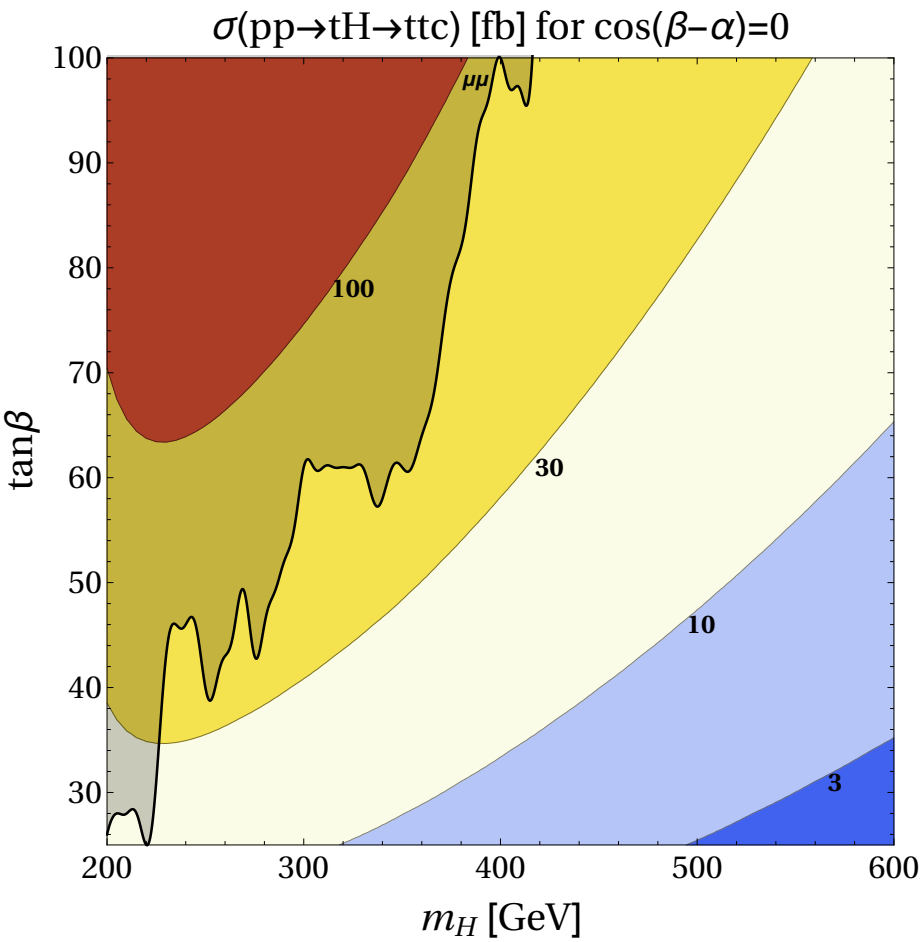
most important production and decay modes involve 2nd gen. fermions





WA, Eby, Gori, Lotito, Martone, Tuckler 1610.02398

Interesting Collider Signatures



current most stringent constraint:
di-muon resonance searches
$pp \to H/A \to \mu^+\mu^-$
(gray shaded region)

Interesting signatures include:

same sign tops
$pp \to tH/A \to tt\bar{c}$

di-jet resonances that are produced in association with a top
$pp \to tH/A \to tc\bar{c}$
$pp \to tH^{\pm} \to tcs$

flavor violating heavy Higgses
$pp \to H/A \to \tau\mu$

WA, Eby, Gori, Lotito, Martone, Tuckler 1610.02398

Conclusions

- Beyond the Standard Model physics can lead to flavor and CP violating Higgs couplings

  $\rightarrow$ strong indirect constraints from low energy observables

Conclusions

- Beyond the Standard Model physics can lead to flavor and CP violating Higgs couplings

  $\rightarrow$ strong indirect constraints from low energy observables

- Flavor violating Higgs decays involving taus at an observable level can be easily viable if a second source of electro-weak symmetry breaking is present

  $\rightarrow$ a flavorful 2HDM with non-standard low energy and collider signatures