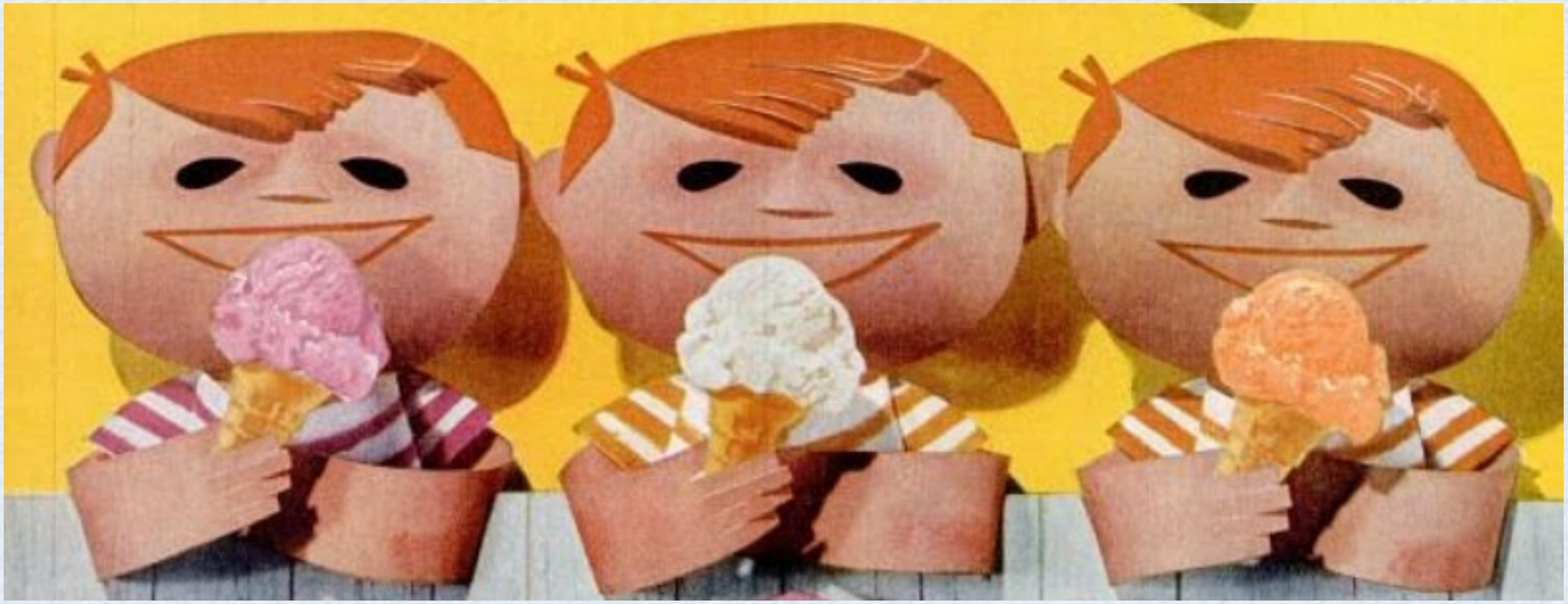
Flavor Violating Higgs Decays

Yotam Soreq

Higgs Couplings 2016, SLAC, Nov 11, 2016

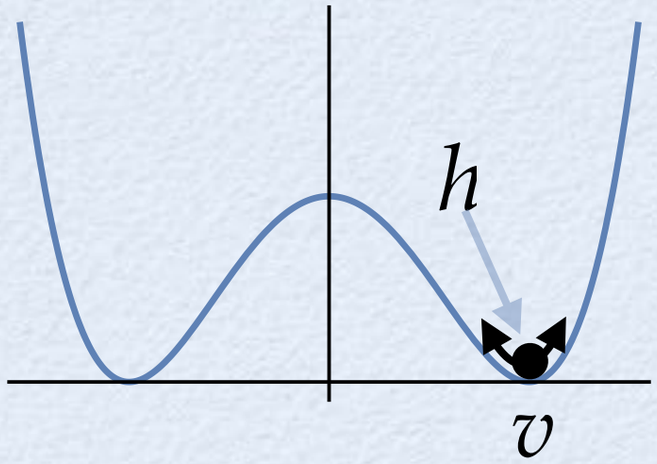

H



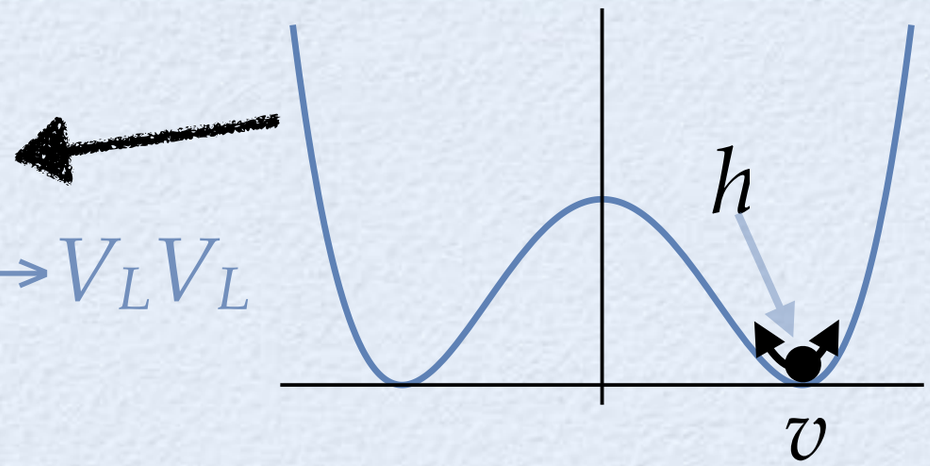
OUTLINE

- introduction
- probing Higgs flavor violating couplings
- model building
- summary

HIGGS IN THE STANDARD MODEL



HIGGS IN THE STANDARD MODEL



unitarize: $V_L V_L \rightarrow V_L V_L$

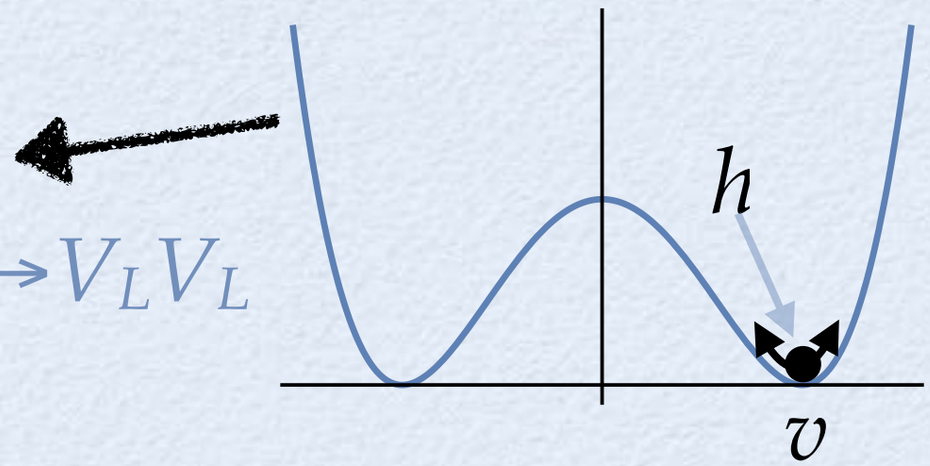
$m_{W,Z} \neq 0$

tested by:

direct - $h \rightarrow WW^*, ZZ^*$

indirect - Electroweak precision

HIGGS IN THE STANDARD MODEL



unitarize: $V_L V_L \rightarrow V_L V_L$

$m_{W,Z} \neq 0$

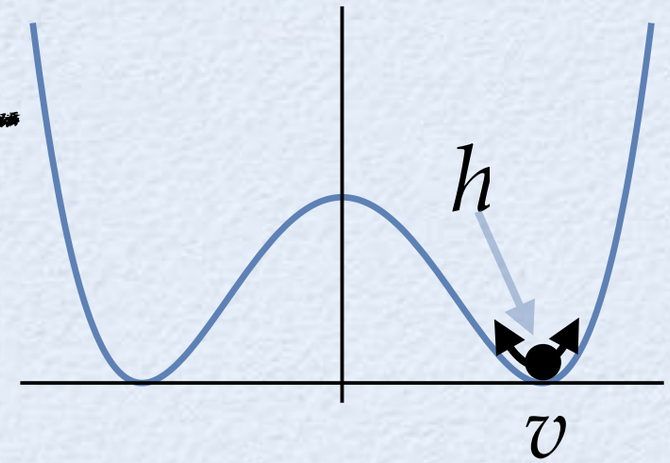
tested by:

direct - $h \rightarrow WW^*, ZZ^*$

indirect - Electroweak precision

the Higgs is the main source of Electroweak symmetry breaking

HIGGS IN THE STANDARD MODEL



unitarize: $V_L V_L \to V_L V_L$

$m_{W,Z} \neq 0$

tested by:

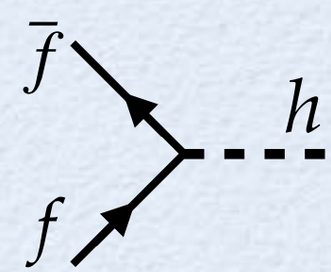
direct - $h \to WW^*, ZZ^*$

indirect - Electroweak precision

the Higgs is the main source of Electroweak symmetry breaking

unitarize: $f\bar{f} \to V_L V_L$

$m_f \neq 0$



$y_f \propto m_f$

much less is known

INTRODUCTION

Standard Model

$$y_f^{\mathrm{SM}} = \frac{m_f}{v}$$

- non-universal and hierarchical
- diagonal
- flavor violating Higgs decays are suppressed by loop, mixing (CKM/PMNS) and GIM

INTRODUCTION

Standard Model

$$y_f^{\rm SM} = \frac{m_f}{v}$$

- non-universal and hierarchical
- diagonal
- flavor violating Higgs decays are suppressed by loop, mixing (CKM/PMNS) and GIM

off diagonal Yukawa → new physics

INTRODUCTION

Standard Model

$$y_f^{\rm SM} = \frac{m_f}{v}$$

- non-universal and hierarchical
- diagonal
- flavor violating Higgs decays are suppressed by loop, mixing (CKM/PMNS) and GIM

off diagonal Yukawa ⇒ new physics

if at the TeV scale

⇒ NP flavor structure cannot be anarchic
need to be aligned with the SM (or universal)

probing Higgs flavor violating couplings

EXPERIMENTAL PROBES

- Higgs data:
  - **dedicated searches:** $h \to b\bar{b}$, $h \to \tau\mu$, $h \to M\gamma$, $t \to hj$, $t\bar{t}h$ (mostly 3rd generation)
  - **indirect constraints:** total width, global fit, kinematical distributions
- **low energy process:** $\mu \to e\gamma$, meson mixing…

Lepton sector

CMS:

$BR(h \to e\mu)_8 < 0.036\%$

$BR(h \to e\tau)_8 < 0.70\%$

$BR(h \to \mu\tau)_8 < 0.89 \pm 0.39\%$

$BR(h \to \mu\tau)_{13} < 1.20\%$ (1.62% expected)

ATLAS:

$BR(h \to e\tau)_8 < 1.04\%$

$BR(h \to \mu\tau)_8 < 0.53 \pm 0.51\%$

Lepton sector

CMS:

$BR(h\to e\mu)_8<0.036\%$

$BR(h\to e\tau)_8<0.70\%$

$BR(h\to \mu\tau)_8<0.89\pm0.39\%$

$BR(h\to \mu\tau)_{13}<1.20\%$(1.62% expected)

ATLAS:

$BR(h\to e\tau)_8<1.04\%$

$BR(h\to \mu\tau)_8<0.53\pm0.51\%$

$$Y^\ell = \begin{pmatrix} y_e & y_{e\mu} & y_{e\tau} \\ y_{\mu e} & y_\mu & y_{\mu\tau} \\ y_{\tau e} & y_{\tau\mu} & y_\tau \end{pmatrix} <$$

	0.54	2.4
0.54		3.2
2.4	3.2	

$\times 10^{-3}$

direct searches

3.6×10^{-6} $(\mu\to e\gamma)$

$(|y_{\tau e}\, y_{\mu\tau}|^2+|y_{e\tau}\, y_{\tau\mu}|^2)^{1/4}< 3.4\times 10^{-4}$ $(\mu\to e\gamma)$

Up Quark Sector

ATLAS: $BR(t \to hj)_8 < 0.46\%$

CMS: $BR(t \to hj)_8 < 0.56\%$

UP QUARK SECTOR

ATLAS: BR($t \to hj$)$_8$<0.46%

CMS: BR($t \to hj$)$_8$<0.56%

$$Y^u = \begin{pmatrix} y_u & y_{uc} & y_{ut} \\ y_{cu} & y_c & y_{ct} \\ y_{tu} & y_{tc} & y_t \end{pmatrix} <$$

	7×10^{-5}	0.13
7×10^{-5}		0.13
0.13	0.13	

D^0-$\bar{D}^0$ mixing

Harnik, Kopp, Zupan- 1209.1397
Blankenburg, Ellis, Isidori- 1202.5704

$t \to hj$: decay and th production

Greljo, Kamenik, Koop 1404.1278

UP QUARK SECTOR

ATLAS: BR($t \to hj$)$_8$<0.46%

CMS: BR($t \to hj$)$_8$<0.56%

$$Y^u = \begin{pmatrix} y_u & y_{uc} & y_{ut} \\ y_{cu} & y_c & y_{ct} \\ y_{tu} & y_{tc} & y_t \end{pmatrix} <$$

	7×10^{-5}	0.13
7×10^{-5}		0.13
0.13	0.13	

D^0-$\bar{D}^0$ mixing

Harnik, Kopp, Zupan- 1209.1397
Blankenburg, Ellis, Isidori- 1202.5704

$t \to hj$: decay and th production

Greljo, Kamenik, Koop 1404.1278

- bounds from meson mixing may be relaxed in models where the Higgs is part of flavor multiplet
- direct probing of $y_{cu,uc}$: $h \to D^* \gamma$ - weak sensitivity

Kagan et al- 1406.1722

DOWN QUARK SECTOR

K^0-$\bar{K}^0$ mixing

Re (Im)

$$Y^d = \begin{pmatrix} y_d & y_{ds} & y_{db} \\ y_{sd} & y_s & y_{sb} \\ y_{bd} & y_{bs} & y_b \end{pmatrix} <$$

	2.4(0.17)×10^{-5}	1.5 ×10^{-4}
2.4(0.17)×10^{-5}		1.3 ×10^{-3}
1.5 ×10^{-4}	1.3 ×10^{-3}	

B_d-$\bar{B}_d$ mixing B_s-$\bar{B}_s$ mixing

Harnik, Kopp, Zupan- 1209.1397
Blankenburg, Ellis, Isidori- 1202.5704

- bounds from meson mixing may be relaxed in models where the Higgs is part of flavor multiplet
- direct probing of $y_{bd,db}$, $y_{bs,sb}$, $y_{ds,sd}$: $h \to K^*\gamma, B_s^*\gamma, B_d^*\gamma$ - weak sensitivity

Kagan et al- 1406.1722

model building for flavor changing Higgs couplings

MODEL BUILDING - EFT

$$\lambda^f_{ij}\bar{\psi}^i_R\psi^j_L H + \frac{\lambda'^f_{ij}}{\Lambda^2}\bar{\psi}^i_R\psi^j_L H(H^\dagger H)$$

MODEL BUILDING - EFT

$$\lambda^f_{ij}\bar{\psi}^i_R\psi^j_L H + \frac{\lambda'^f_{ij}}{\Lambda^2}\bar{\psi}^i_R\psi^j_L H(H^\dagger H)$$

$$\hat{\lambda}^f = V^f_L \lambda'^f V^{f\dagger}_R$$

$$Y^f_{ij} = \frac{\sqrt{2}m^f_i}{v}\delta_{ij} + \frac{v^2}{\Lambda^2}\hat{\lambda}^f_{ij} = \frac{\sqrt{2}m^f_i}{v}\delta_{ij} + 0.01\left(\frac{\hat{\lambda}^f_{ij}}{0.17}\right)\left(\frac{\mathrm{TeV}}{\Lambda}\right)^2$$

MODEL BUILDING - EFT

$$\lambda^f_{ij}\bar{\psi}^i_R\psi^j_L H + \frac{\lambda'^f_{ij}}{\Lambda^2}\bar{\psi}^i_R\psi^j_L H(H^\dagger H)$$

$$\hat{\lambda}^f = V^f_L \lambda'^f V^{f\dagger}_R$$

$$Y^f_{ij} = \frac{\sqrt{2}m^f_i}{v}\delta_{ij} + \frac{v^2}{\Lambda^2}\hat{\lambda}^f_{ij} = \frac{\sqrt{2}m^f_i}{v}\delta_{ij} + 0.01\left(\frac{\hat{\lambda}^f_{ij}}{0.17}\right)\left(\frac{\mathrm{TeV}}{\Lambda}\right)^2$$

$$\mathrm{BR}(h\to\tau\mu) \simeq 0.8\%\left(\frac{\mathrm{TeV}}{\Lambda}\right)^4\left(\left|\frac{\hat{\lambda}^e_{\mu\tau}}{0.35}\right|^2 + \left|\frac{\hat{\lambda}^e_{\tau\mu}}{0.35}\right|^2\right)$$

$$\mathrm{BR}(t\to ch) \simeq 0.4\%\left(\frac{\mathrm{TeV}}{\Lambda}\right)^4\left(\left|\frac{\hat{\lambda}^u_{tc}}{1.5}\right|^2 + \left|\frac{\hat{\lambda}^u_{ct}}{1.5}\right|^2\right)$$

MODEL BUILDING - EFT

loop generated dipole operators

$$\frac{\lambda'^{f}_{ij}}{\Lambda^2}\bar{\psi}^i_R\psi^j_L H(H^\dagger H)$$

$$\frac{c^f_{ij}}{\Lambda^2}\bar{\psi}^i_R\sigma_{\mu\nu}\psi^j_L H F^{\mu\nu}$$

similar flavor structure

MODEL BUILDING - EFT

$$\frac{\lambda'^{f}_{ij}}{\Lambda^2}\bar{\psi}^i_R\psi^j_L H(H^\dagger H)$$

loop generated dipole operators

$$\frac{c^{f}_{ij}}{\Lambda^2}\bar{\psi}^i_R\sigma_{\mu\nu}\psi^j_L H F^{\mu\nu}$$

similar flavor structure

$h \to \bar{\psi}^i\psi^j$ correlate $\psi^i \to \psi^j\gamma$

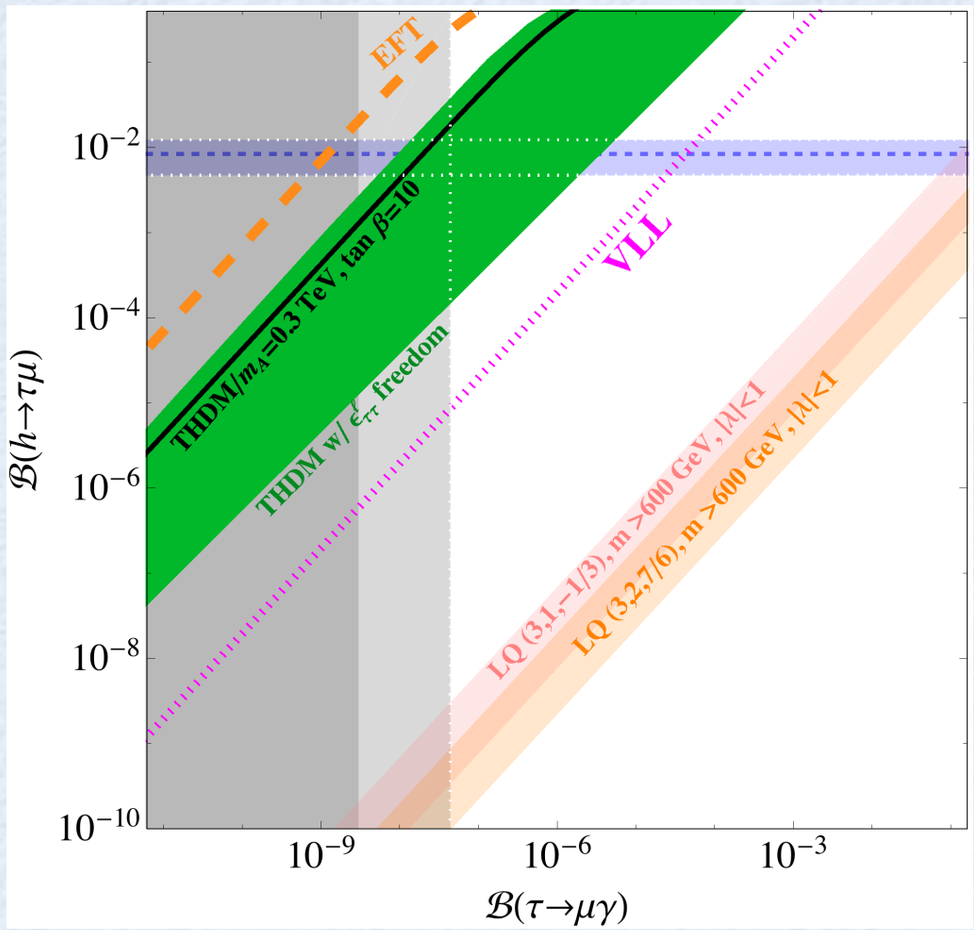
naive: $c \sim \lambda\, e/16\pi^2$

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

Altmannshofer et al 1507.07927
Dorsner et al- 1502.07784

MODEL BUILDING - EFT

BR($h \to \tau\mu$)



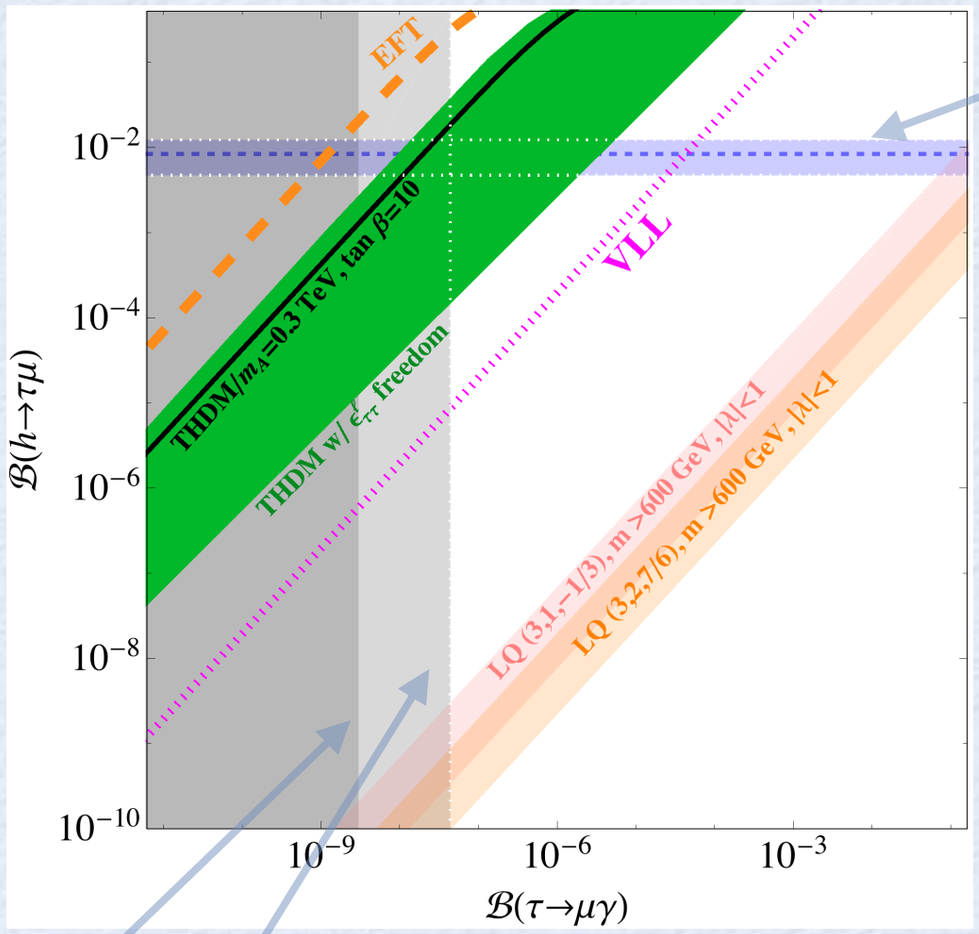
BR($\tau \to \mu\gamma$)

Dorsner et al- 1502.07784

MODEL BUILDING - EFT

CMS run 1

BR($h \to \tau\mu$)



projection

current bound (*BABAR*)

BR($\tau \to \mu\gamma$)

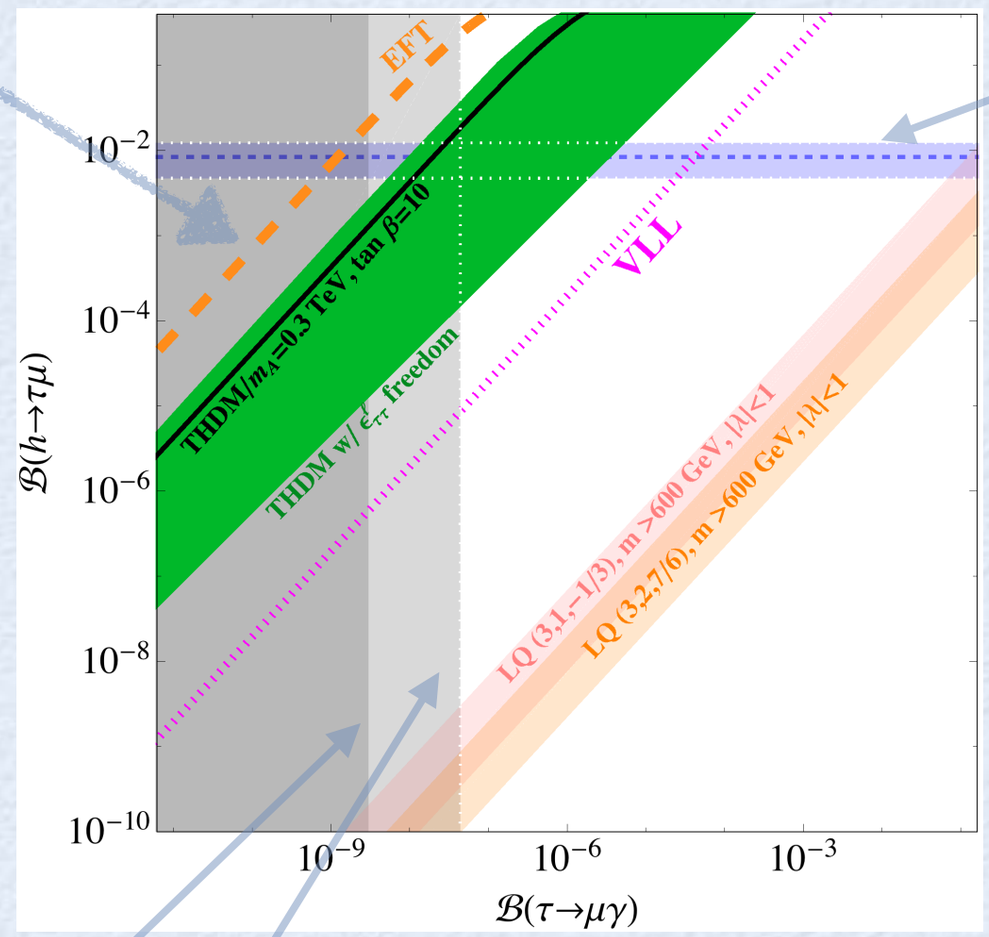
Dorsner et al- 1502.07784

MODEL BUILDING - EFT

$$\frac{\lambda'^{f}_{ij}}{\Lambda^2}\bar{\psi}^i_R\psi^j_L H(H^\dagger H)$$

CMS run 1

BR($h\to\tau\mu$)



$$\frac{c^{f}_{ij}}{\Lambda^2}\bar{\psi}^i_R\sigma_{\mu\nu}\psi^j_L H F^{\mu\nu}$$

projection

current bound (*BABAR*)

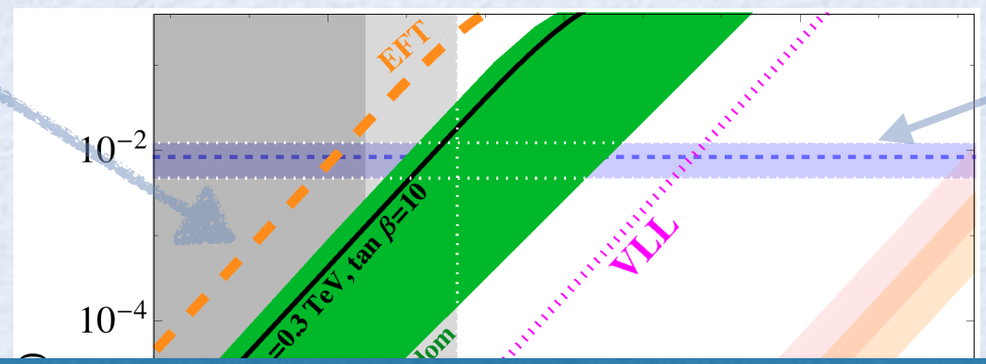
BR($\tau\to\mu\gamma$)

Dorsner et al- 1502.07784

MODEL BUILDING - EFT

$$\frac{\lambda'^{f}_{ij}}{\Lambda^2}\bar{\psi}^i_R\psi^j_L H(H^\dagger H)$$

CMS run 1



BR($h\to\tau\mu$)

$\tau\to\mu\gamma$ constrain can be avoid by:

- tuning (MSSM example: Aloni, Nir, Stamou - 1511.00979)
- first two generations (e and μ) receive their masses from additional source of EWSB ($h\to\tau\mu$: Altmannshofer et al 1507.07927, Yukawa less: Ghosh et al 1508.01501)

projection

current bound (*BABAR*)

BR($\tau\to\mu\gamma$)

Dorsner et al- 1502.07784

MODEL BUILDING

how can we have both

$$\mathrm{BR}(t \to ch) \sim 4 \times 10^{-3}$$

$$\mathrm{BR}(h \to \tau\mu) \sim 10^{-2}$$

?

MODEL BUILDING

how can we have both

$$\mathrm{BR}(t \to ch) \sim 4 \times 10^{-3}$$
$$\mathrm{BR}(h \to \tau\mu) \sim 10^{-2}$$

?

new physics at the TeV scale

non trivial flavor structure

MODEL BUILDING

how can we have both

$$\mathrm{BR}(t \to ch) \sim 4 \times 10^{-3}$$
$$\mathrm{BR}(h \to \tau\mu) \sim 10^{-2}$$

?

new physics at the TeV scale

non trivial flavor structure

SM-EFT with flavor models

Minimal Flavor Violation (MFV)
solves the NP flavor puzzle

Froggatt-Nielsen (FN)
solves both SM and NP flavor puzzles

MINIMAL FLAVOR VIOLATION

up sector:

$$\lambda'^u = Y^u_{\rm SM}\left(A^u + B^u Y^u_{\rm SM} Y^{u\dagger}_{\rm SM} + C^u Y^d_{\rm SM} Y^{d\dagger}_{\rm SM}\right)$$

$$\frac{Y_{ct}}{Y_{tt}} = \frac{C^u y_b^2\ V_{cb}V^*_{tb}}{A^u + B^u y_t^2 + C^u y_b^2 |V_{tb}|^2} \lesssim V_{cb}$$

maximal $t \to ch$ rate small by order of magnitude than current bounds

lepton sector:

$$\frac{Y_{\mu\tau}}{Y_{\tau\tau}} = \frac{C^\nu y_3^2\ U_{\mu 3}U^*_{\tau 3}}{A^\nu + B^\nu y_\tau^2 + C^\nu y_3^2 |U_{\tau 3}|^2} \lesssim U_{\mu 3}/U_{\tau 3},$$

small rates

from $\mu \to e\,\gamma$: $|Y_{\mu\tau}| \lesssim 10^{-4}$

Dery, Efrati, Nir, YS, Susic - 1408.1371

FROGGATT-NIELSEN

Approximate U(1)'s symmetries → Yukawa are suppressed by different powers of the breaking parameters

$$\epsilon_i \simeq \lambda = 0.2$$

Consider two possibilities

- SM + nonrenormalizable terms
- Supersymmetric model + nonrenormalizable terms

FROGGATT-NIELSEN

SM + nonrenormalizable terms:

$$\mathcal{L}_Y = -\lambda^u_{ij} Q_i \bar{U}_j \phi - \frac{\lambda'^u_{ij}}{\Lambda^2} Q_i \bar{U}_j \phi \left(\phi^\dagger \phi\right) + \text{h.c.}$$

$$Y^u_{ij} = \frac{\sqrt{2} m^u_i}{v} \delta_{ij} + \frac{v^2}{\Lambda^2} (V^u_L \lambda'^u V^{u\dagger}_R)_{ij}$$

$(\phi^\dagger \phi)$ does not carry a FN charge

λ and λ' have the same parametric structure

$$Y_{tc} \sim \frac{v^2}{\Lambda^2} \lambda \lesssim 10^{-3} \ll 0.14$$

$\epsilon_i \simeq \lambda = 0.2$

current bound

FCNC bounds (charm mixing) $\frac{v^2}{\Lambda^2} \lesssim 10^{-2}$

FROGGATT-NIELSEN

Supersymmetric model + nonrenormalizable terms:

$$\mathcal{L}_Y = \lambda^u_{ij} Q_i \bar{U}_j \phi_u + \frac{\lambda'^u_{ij}}{\Lambda^2} Q_i \bar{U}_j \phi_u \left(\phi_u \phi_d\right)$$

$$(Y^u_h)_{ij} = \frac{c_\alpha}{s_\beta} \frac{m^u_i}{v} \delta_{ij} + \frac{v^2 c_{\alpha+\beta} s_\beta}{2\sqrt{2}\Lambda^2} (V^u_L \lambda'^u V^{u\dagger}_R)_{ij}$$

If $(\phi_u \phi_d)$ carry a FN charge → λ and λ' have different parametric structure

Use "holomorphic zeros" to align the new sources of flavor violation and avoid FCNC bounds

Leurer, Nir, Seiberg
hep-ph/9310320

FROGGATT-NIELSEN

Supersymmetric model + nonrenormalizable terms:

$$\mathcal{L}_Y = \lambda^u_{ij} Q_i \bar{U}_j \phi_u + \frac{\lambda'^u_{ij}}{\Lambda^2} Q_i \bar{U}_j \phi_u \left(\phi_u \phi_d\right)$$

$$\Rightarrow \quad (Y^u_h)_{ij} = \frac{c_\alpha}{s_\beta} \frac{m^u_i}{v} \delta_{ij} + \frac{v^2 c_{\alpha+\beta} s_\beta}{2\sqrt{2}\Lambda^2} (V^u_L \lambda'^u V^{u\dagger}_R)_{ij}$$

Approximate U(1)×U(1) FN symmetry:

$$\hat{\lambda}^u \sim \frac{1}{\lambda} \begin{pmatrix} \lambda^{15} & \lambda^{12} & \lambda^{13} \\ \lambda^8 & \lambda^5 & \lambda^6 \\ \lambda^4 & \lambda^1 & \lambda^2 \end{pmatrix}, \quad \hat{\lambda}^d = 0, \quad \hat{\lambda}^e \sim \frac{1}{\lambda} \begin{pmatrix} \lambda^8 & 0 & 0 \\ 0 & \lambda^5 & \lambda^3 \\ 0 & \lambda^5 & \lambda^3 \end{pmatrix}$$

safe from meson mixing and $\mu \to e\,\gamma$

$$\Rightarrow \quad Y_{tc} \sim \frac{v^2}{\Lambda^2} \sim 0.1 \quad Y_{\mu\tau} \sim \frac{v^2}{\Lambda^2} \lambda^2 \sim 0.004$$

SUMMARY

- the Higgs flavor violating couplings to leptons and to top can be directly probed at the sub percent level
- low energy processes constrain the other flavor violating Higgs couplings to the per-mil level
- visible signals $t \to hj$ and $h \to \tau\mu$ require non trivial flavor structure. Additional sub-dominant source of EWSB can be used to relax low energy constraints.

BACKUP SLIDES