The Flavor of h (and S?)

Higgs Tasting Workshop 2016

Centro de Ciancias de Benasque Pedro Pascual, Spain
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Plan of Talk

1. Flavor at the LHC
2. The (B)SM flavor of h
3. What if $\text{BR}(h \to \tau\mu) \sim 0.01$?
4. The flavor of S_{750}
5. Conclusions

Flavor at the LHC

Questions for the LHC

- What is the mechanism of electroweak symmetry breaking?
- What separates the electroweak scale from the Planck scale?
- What happened at the electroweak phase transition?
- How was the baryon asymmetry generated?
- What are the dark matter particles?
- What is the solution of the flavor puzzles?

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  One of the topics of this talk

Perhaps an answer from the LHC

- $\sigma(pp \to S)\text{BR}(S \to \gamma\gamma) \sim 5 \text{ fb}, \quad m_S \sim 750 \text{ GeV}$

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- $\sigma(pp \to S)\mathrm{BR}(S \to \gamma\gamma) \sim 5$ fb, $m_S \sim 750$ GeV
  What is the question?

The flavor puzzles

- The SM flavor puzzle:
  Why is there structure in the charged fermion flavor parameters?
  Smallness and hierarchy

- The SM flavor puzzle extended:
  Why is the neutrino flavor structure different?
  Neither smallness nor hierarchy

- The NP flavor puzzle:
  If there is TeV-scale NP, why doesn't it affect FCNC?
  Degeneracy and alignment

Can we make progress?

- NP that couples to quarks/leptons $\Longrightarrow$ New flavor parameters (spectrum, flavor decomposition) that can be measured
- The NP flavor structure could be:
  - MFV
  - Related but not identical to SM
  - Unrelated to SM or even anarchical
- The NP flavor puzzle:
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- $\boxed{h}$ $\Longrightarrow$ The "NP" is already here!
  $Y_{\bar{f}_i f_j}$ are new flavor parameters that can be measured

The (B)SM flavor of h

Dery, Efrati, Hochberg, YN, JHEP1305,039 [arXiv:1302.3229]

Dery, Efrati, Hiller, Hochberg, YN, JHEP1308,006 [arXiv:1304.6727]

Dery, Efrati, YN, Soreq, Susič, PRD90, 115022 [arXiv:1408.1371]

Relevant data

Observable	Experiment
$R_{\gamma\gamma}$	1.14 ± 0.18
R_{ZZ^*}	1.17 ± 0.23
R_{WW^*}	0.99 ± 0.15
$R_{b\bar{b}}$	0.7 ± 0.3
$R_{\tau\tau}$	1.09 ± 0.23
$R_{\mu\mu}$	< 7
R_{ee}	$< 4 \times 10^5$

- $R_f = \frac{\sigma_{\rm prod}{\rm BR}(h\to f)}{[\sigma_{\rm prod}{\rm BR}(h\to f)]^{\rm SM}}$

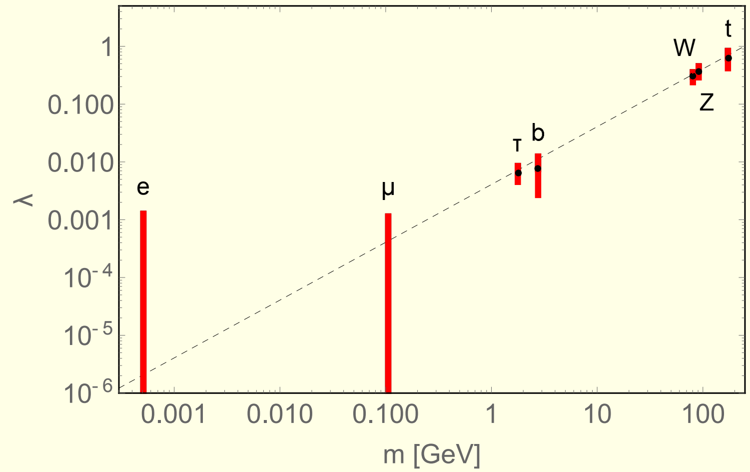
Y^F *vs.* M_F: SM

- $Y^F = \sqrt{2} M_F / v$

  - Proportionality: $y_i \equiv Y^F_{ii} \propto m_i$
  - Factor of proportionality: $y_i / m_i = \sqrt{2}/v$

  - Diagonality: $Y^F_{ij} = 0$ for $i \neq j$

Proportionality?



A. Efrati

- Indication that Y_t, Y_b, Y_τ not far from SM
- $y_3/m_3 \approx \sqrt{2}/v$
- $y_e, y_\mu < y_\tau$
- The beginning of Higgs flavor physics

Diagonality?

- $\mathrm{BR}(t \to ch) \leq 0.0046$ ATLAS, 1509.06047; CMS, 1410.2751
  $\Longrightarrow \sqrt{Y_{tc}^2 + Y_{ct}^2} \leq 0.13$

- $\mathrm{BR}(h \to \tau\mu) \leq 0.015$ CMS, 1502.07400; ATLAS, 1604.07730
  $\Longrightarrow \sqrt{Y_{\tau\mu}^2 + Y_{\mu\tau}^2} \leq 0.004$

Y^F vs. M_F: BSM

- Proportionality and diagonality may be violated at tree level
  - Two (or more) Higgs Doublets
    Without loss of generality, $\{\phi_M, \phi_A\}$ where
    $\langle\phi_M^0\rangle = v/\sqrt{2},\ \langle\phi_A^0\rangle = 0$
    $h = s_{\alpha-\beta}\mathrm{Re}(\phi_M^0) + c_{\alpha-\beta}\mathrm{Re}(\phi_A^0)$
    $\Longrightarrow\ Y_h^E = s_{\alpha-\beta}(\sqrt{2}M_E/v) + c_{\alpha-\beta}Y_A^E$
  - Single Higgs doublet and non-renormalizable terms
    $\frac{1}{\Lambda^2}(\phi^\dagger\phi)\phi\overline{L_L}Z^e E_R$:
    $M_E = \frac{v}{\sqrt{2}}\left(Y^e + \frac{v^2}{2\Lambda^2}Z^e\right), \quad Y^E = Y^e + 3\frac{v^2}{2\Lambda^2}Z^e$
    $\Longrightarrow\ Y^E = (\sqrt{2}M_E/v) + \frac{v^2}{2\Lambda^2}Z^e$

Leptonic observables

Observable ($\ell = e, \mu$)	SM	Test
$R_{\tau^+\tau^-}$	1	Factor
$X_{\ell\ell} = \frac{\mathrm{BR}(h\to\ell^+\ell^-)}{\mathrm{BR}(h\to\tau^+\tau^-)}$	$(m_\ell/m_\tau)^2$	Proportionality
$X_{\ell\tau} = \frac{\mathrm{BR}(h\to\ell^\pm\tau^\mp)}{\mathrm{BR}(h\to\tau^+\tau^-)}$	0	Diagonality

- What can we learn from $R_{\tau\tau},\ X_{\ell\ell},\ X_{\ell\tau}$?

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- What can we learn from $R_{\tau\tau},\ X_{\ell\ell},\ X_{\ell\tau}$?
- ATLAS/CMS:
  - $R_{\tau\tau} = 1.09 \pm 0.23$
  - $X_{\mu\mu} < 12(m_\mu/m_\tau)^2 \sim 0.05, \quad X_{ee} < 7\times 10^5 (m_e/m_\tau)^2 \sim 0.06$
  - $X_{\mu\tau} = 0.14 \pm 0.06 < 0.3$

Flavor models

- 2HDM with Type II NFC
  Solution to the 2HDM flavor puzzle
- SM-EFT with MFV
  Solution to the NP flavor puzzle
- SM-EFT with FN
  Solution to the SM and NP flavor puzzles

Flavor models

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  – Non-universal correction to the diagonal couplings
- SM-EFT with FN
  Solution to the SM and NP flavor puzzles
  – Non-universal correction to the diagonal couplings +
  Off-diagonal couplings

Higgs Physics = new flavor arena

Model	$Y_\tau^2/(2m_\tau^2/v^2)$	$(Y_\mu^2/Y_\tau^2)/(m_\mu^2/m_\tau^2)$	$Y_{\mu\tau}^2/Y_\tau^2$
SM	1	1	0
NFC-II	$(\sin\alpha/\cos\beta)^2$	1	0
MFV*	$1+2av^2/\Lambda^2$	$1-4bm_\tau^2/\Lambda^2$	0
FN	$1+\mathcal{O}(v^2/\Lambda^2)$	$1+\mathcal{O}(v^2/\Lambda^2)$	$\mathcal{O}(\|U_{23}\|^2v^4/\Lambda^4)$
GL	9	$25/9$	$\mathcal{O}(10^{-2})$

Dery, Efrati, Hochberg, YN, JHEP1305,039 [arXiv:1302.3229]

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Measuring Y_{ij} can probe flavor models

$$\boxed{\text{What if BR}(h \to \tau\mu) \sim 0.01?}$$

Exciting $\times$ 3

- $U(1)_\mu \times U(1)_\tau$ broken
  $\Lambda_{\rm LFV} \ll \Lambda_{\rm LNV}$?

- ${\rm BR}(h \to \tau\mu) \not\ll {\rm BR}(h \to \tau\tau)$
  FCNC at tree level?

- $Y_E \not\propto M_E$
  Not the SM Higgs?

The leptonic SM

- Symmetry: local $SU(2)_L \times U(1)_Y$
- Particle content: $3 \times \{L(2)_{-1/2} + E(1)_{-1}\}$
- Spontaneous breaking $\to U(1)_{\rm EM}$ by $\langle \phi(2)_{+1/2} \rangle \neq 0$

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- $\Longrightarrow$ Accidental symmetry: $U(1)_e \times U(1)_\mu \times U(1)_\tau$
- $\boxed{h \to \tau\mu \text{ forbidden}}$

- Accidental symmetries are broken by higher dimension terms (SM=EFT)

$d = 5$ terms

- $\frac{(Y^N)_{ij}}{\Lambda} L_i L_j \phi\phi$
- $M_N = \frac{Y^N v^2}{2\Lambda} \Longrightarrow$ Explain neutrino mass and mixing
- Break $U(1)_e \times U(1)_\mu \times U(1)_\tau$
- Break also total lepton number
- $h \to \tau\mu$ allowed, but...
  - Loop suppression $\sim \alpha_2^2$
  - Mixing suppression $\sim |U_{\mu 3} U_{\tau 3}|^2$
  - GIM suppression $\sim (\Delta m_{23}^2 / m_W^2)^2$
- $\mathrm{BR}(h \to \tau\mu) \sim 10^{-50}$

$d = 6$ terms

- $\frac{1}{\Lambda^2}(\phi^\dagger\phi)\phi\overline{L_i}Z^e_{ij}E_j$
  - $M_E = \frac{v}{\sqrt{2}}\left(Y^e + \frac{v^2}{2\Lambda^2}Z^e\right)$
  - $Y^E_h = Y^e + 3\frac{v^2}{2\Lambda^2}Z^e$
  - $\Longrightarrow\ Y^E_h = (\sqrt{2}M_E/v) + \frac{v^2}{2\Lambda^2}Z^e$
- For $\Lambda/\sqrt{Z^e_{\mu\tau}} \sim$ few TeV: BR$(h \to \tau\mu) \sim 0.01$

- Note: $\frac{1}{\Lambda^2}\phi\overline{\mu_L}X^e_{\mu\tau}\sigma_{\mu\nu}\tau_R F^{\mu\nu} \implies \tau \to \mu\gamma$

The scale of LFV

- $\frac{1}{\Lambda_{\rm LNV}} LL\phi\phi$

  $m_\nu \sim 0.1$ eV $\implies \Lambda_{\rm LNV} \sim 10^{15}$ GeV
  Intriguingly close to $\Lambda_{\rm GUT}$

- $\frac{1}{\Lambda^2_{\rm LFV}} \phi^\dagger \phi L \phi E^c$

  ${\rm BR}(h \to \tau\mu) \sim 0.01 \implies \Lambda_{\rm LFV} \sim 5$ TeV
  New physics should be directly accessible at the LHC!

Reminder: SM-FCNC are loop suppressed

- The gluon and the photon do not mediate FCNC at tree level because massless gauge bosons have flavor-universal and, in particular, flavor diagonal couplings

- Within the SM, the $Z-$boson does not mediate FCNC at tree level because all fermions with the same chirality, color and charge originate in the same $SU(2)_L \times U(1)_Y$ representation

- Within the SM, the $h-$boson does not mediate FCNC at tree level because
  - All SM fermions are chiral $\Longrightarrow$ no bare mass terms
  - The scalar sector has a single Higgs doublet

Loop suppression?

- All models with no bare mass terms and with NFC:
  $h \to \tau\mu$ is loop suppressed

- With loop suppression:
  $(v^2/\Lambda^2)(\alpha_W/4\pi)X_{\mu\tau} \not\ll y_\tau \sim 10^{-2}$
  Very challenging model building

- MSSM - excluded Aloni, YN, Stamou, JHEP 04(2016)162 [1511.00979]

  Brignole, Rossi, NPB701(2004)3; Arana-Catania, Arganda, Herrero, JHEP 09(2013)160

- Models with tree-level-FCNC favored

Not the SM Higgs?

$Y^h_{\mu\tau} \neq 0$ at tree level:

- Single Higgs doublet and vector-like leptons
  Strongly disfavored by the $\tau \to \mu\mu\mu$ bound

  Efrati, YN, Stamou, work in progress

  Dorsner et al., 1502.07784

- Multi-Higgs doublet models
  Not easy to combine with flavor models

Vector-like leptons

- In all models of vector-like leptons, there are unavoidable tree level contributions to $Z \to \tau\mu$ and $\tau \to \mu\mu\mu$
- For each type of vector-like leptons, there is a parameter-independent relation:

$$\boxed{\frac{\mathrm{BR}(h\to\tau\mu)/\mathrm{BR}(h\to\tau\tau)}{\mathrm{BR}(Z\to\tau\mu)/\frac{1}{3}\mathrm{BR}(Z\to\nu\bar{\nu})} = \frac{1}{2}}$$

Efrati, YN, Stamou, work in progress

- Experiment: $\frac{\mathrm{BR}(Z\to\tau\mu)}{\frac{1}{3}\mathrm{BR}(Z\to\nu\bar{\nu})} < 1.8 \times 10^{-4}$
  $\Longrightarrow \quad \mathrm{BR}(h \to \tau\mu) < 2 \times 10^{-5}$
- Still, possible to account for $\mathrm{BR}(h \to \tau\mu) \sim 0.01$ with fine-tuned cancelations
- Strongly disfavored

2HDM

- Without loss of generality, use the basis $\{\phi_M, \phi_A\}$ where $\langle\phi_M^0\rangle = v/\sqrt{2},\ \langle\phi_A^0\rangle = 0$
- $h = s_{\alpha-\beta}\mathrm{Re}(\phi_M^0) + c_{\alpha-\beta}\mathrm{Re}(\phi_A^0)$
  $\Longrightarrow\ Y_h^E = s_{\alpha-\beta}(\sqrt{2}M_E/v) + c_{\alpha-\beta}Y_A^E$
- Note: Y_A^E arbitrary
- With $c_{\alpha-\beta}(Y_A^E)_{\mu\tau} \lll s_{\alpha-\beta}(\sqrt{2}m_\tau/v)$:
  $\mathrm{BR}(h\to\tau\mu) \lll \mathrm{BR}(h\to\tau\tau)$
- With all other $(Y_A^F)_{ij}=0$, no phenomenological problems
- 2HDM: the favored option
- Inconsistent with motivated flavor models

What if S_{750} is really there?

2HDM, KS

- If S is part of 2HDM and produced by $q\bar{q} \to S$:
  $\Longrightarrow K-\bar{K}$ and $D-\bar{D}$ mixing constrain $Y_{Sq\bar{q}} < 0.5$
  $\Longrightarrow \frac{\Gamma(S\to\gamma\gamma)/M_S}{(\alpha/4\pi)^2} \gg 1$ is typically required
  Avoided if $Y_{Sq\bar{q}}$ is $U(2)$-symmetric

  Aloni, Blum, Dery, Efrati, YN, 1512.05778

- If S is part of 2HDM and $\text{BR}(h \to \tau\mu) \sim 0.01$
  $\Longrightarrow$ Lower bound on $\Gamma(S \to \tau\mu)$

  Bizot, Davidson, Frigerio, Kneur, 1512.08508; Efrati, Kamenik, YN, work in progress

- If S a QCD-bound state of $XX^\dagger$ with $X(3,1)_{+4/3}$
  $\Longrightarrow$ Antisymmetric Xu_iu_j couplings

  Kats, Strassler, 1602.08819

Conclusions

$h \to \mu\tau$

If $\mathrm{BR}(h \to \tau\mu) \sim 0.01$:

- SM, NFC, MLFV* - excluded
- New physics at the TeV scale
- Most likely, FCNC at tree level
- Most likely, extra scalar doublets
- Challenge to present explanations of the flavor puzzles

h Physics = New Flavor Arena

Measure:

- Third generation couplings: Y_t, Y_b, Y_τ
- Second generation couplings: Y_c, Y_s, Y_μ
- Flavor violating couplings: $Y_{\mu\tau}$, $Y_{e\tau}$, Y_{ct}, Y_{ut}

Test:

- MFV
- FN
- NFC
- ...

S Physics

Search for:

- $WW,\ ZZ,\ Z\gamma,\ hh$
- $t\bar{t},\ b\bar{b},\ q\bar{q},\ \tau^+\tau^-, \ldots$
- $\tau\mu, \ldots$

Test:

- ???

2HDM and Flavor Models

- Are there viable and natural flavor models that have
  - $Y_{\mu\tau} \sim 0.01$ but $Y_{e\mu} \lesssim 10^{-6}$?
- Natural Flavor Conservation (NFC)
  - Impossible ($Y_{\mu\tau} = 0$)
- Minimal Lepton Flavor Violation (MLFV)
  - Y^E-spurion: Impossible ($Y_{\mu\tau} = 0$)
  - Y^E, Y^N, M^N-spurions: Possible with fine-tuning
- Froggatt-Nielsen (FN):
  - $Y_{e\mu}/Y_{\mu\tau} \sim |U_{e2}/U_{\mu 3}|(m_\mu/m_\tau) \sim 0.05 \Longrightarrow$ too large
  - Possible with supersymmetry and holomorphic zeros

Dery, Efrati, YN, Soreq, Susič, PRD90, 115022 [arXiv:1408.1371]

Natural Flavor Conservation (NFC)

- A solution to the 2HDM flavor puzzle
- NFC $\equiv$ Each fermion sector (U, D, E) couples to a single Higgs doublet
- Type II: $\overline{Q}Y^U U\phi_2 + \overline{Q}Y^D D\phi_1 + \overline{L}Y^E E\phi_1$
- $\boxed{Y_h^E = (\sin\alpha/\cos\beta)(\sqrt{2}M_E/v)}$
- Proportionality and diagonality maintained, but with a different factor of proportionality

Minimal Flavor Violation (MFV)

- A solution to the NP flavor puzzle
- SM: When $Y^F = 0 \Longrightarrow$ A large global symmetry
  $SU(3)_Q \times SU(3)_U \times SU(3)_D \times SU(3)_L \times SU(3)_E$
- MFV $\equiv$ The only NP breaking of the $SU(3)^5$ symmetry:
  $Y^U(3,\bar{3},0,0,0),\ Y^D(3,0,\bar{3},0,0),\ Y^E(0,0,0,3,\bar{3})$
- Example: $\frac{1}{\Lambda^2}(\phi^\dagger\phi)\overline{L_{Li}}Z^e_{ij}\phi E_{Rj}$
- $\boxed{Z^e = (a + bY^{E\dagger}Y^E)Y^E}$
- Proportionality violated, diagonality maintained

The Froggatt-Nielsen mechanism (FN)

- A solution to both the SM and the NP flavor puzzles
- A $U(1)_H$ symmetry broken by a small spurion $\epsilon_H(-1) \ll 1$
- Example: $\frac{1}{\Lambda^2}(\phi^\dagger\phi)\overline{L_{Li}}Z^e_{ij}\phi E_{Rj}$
- $\boxed{Z^e_{ij} = \mathcal{O}(y_j|U_{ij}|)}$
- Proportionality and diagonality violated

Recent related work

- Blankenburg, Ellis, Isidori, Phys. Lett. B712, 386 (2012)
- Bhattacharyya, Leser, Pas, Phys. Rev D86, 036009 (2012)
- Harnik, Kopp, Zupan, JHEP 1303, 026 (2013)
- Davidson, Verdier, Phys. Rev. D80, 111701 (2012)
- Celis, Cirigliano, Passemar, Phys. Rev. D89, 013008 (2014)
- Falkowski, Straub, Vicente, JHEP 1405, 092 (2014)
- Delaunay *et al.*, Phys. Rev. D89, 033014 (2014)
- Gorbahn, Haisch, JHEP 1406, 033 (2014)
- Kagan *et al.*, arXiv:1406.1722
- Crivellin, D'Ambrosio, Heeck, arXiv: 1501.00993