The Flavor of Higgs

39th Johns Hopkins Workshop
Theory challenges in the LHC era

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Plan of Talk

1. Flavor at the LHC
2. The SM flavor of h
3. The BSM flavor of h
4. $h \to \tau\mu$: Experiment
5. What if $\mathrm{BR}(h \to \tau\mu) \sim 0.01$?
6. 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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  The topic of this talk

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
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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 SM flavor of h

Y^F *vs.* M_F: SM

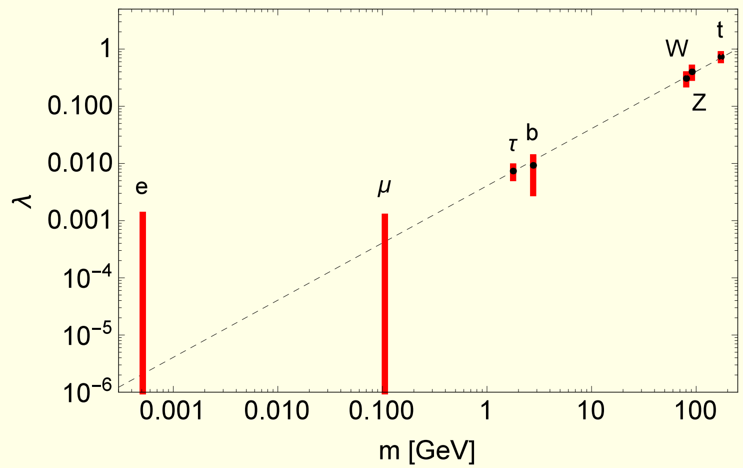
- $Y^F = \sqrt{2} M_F / v$
  - Proportionality: $y_i \equiv Y^F_{ii} \propto m_i$
  - Factor of proportionality: $y_i / m_i = \sqrt{2}/v$
  - Diagonality: $Y^F_{ij} = 0$ for $i \neq j$

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}	$< 4 \times 10^5$

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

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?

- $\mathrm{BR}(t \to ch) \le 0.006$ ATLAS, 1403.6293; CMS, 1410.2751
  $\Longrightarrow \sqrt{Y_{tc}^2 + Y_{ct}^2} \le 0.14$

- $\mathrm{BR}(h \to \tau\mu) \le 0.015$ CMS, 1502.07400; ATLAS, HIGG-2014-08
  $\Longrightarrow \sqrt{Y_{\tau\mu}^2 + Y_{\mu\tau}^2} \le 0.004$

The BSM 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]

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:
  - $R_{\tau\tau} = 1.09 \pm 0.23$
  - $X_{\mu\mu} < 12(m_\mu/m_\tau)^2 \sim 0.05, \quad X_{ee} < 7\times10^5(m_e/m_\tau)^2 \sim 0.06$
  - $X_{\mu\tau} = 0.14 \pm 0.06 < 0.3$

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

Flavor models

- 2HDM with Type II NFC
  - Universal correction to the diagonal couplings
- SM-EFT with MFV
  - Non-universal correction to the diagonal couplings
- SM-EFT with FN
  - 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	$1+\mathcal{O}(v^2/\Lambda^2)$	$1+\mathcal{O}(v^2/\Lambda^2)$	$\mathcal{O}(\lvert U_{23}\rvert^2v^4/\Lambda^4)$
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

$h \to \tau\mu$: Experiment

Shikma Bressler, Avital Dery, Aielet Efrati, PRD 90 (2014) 015025 [1405.3229]

Experimental results

- CMS $h \to \mu\tau_e,\ h \to \mu\tau_h$ [1502.07400]:
  - $\text{BR}(h \to \tau\mu) < 1.51 \times 10^{-2}$
  - $\text{BR}(h \to \tau\mu) = (0.84^{+0.39}_{-0.37}) \times 10^{-2}$

- ATLAS $h \to \mu\tau_h$ [HIGG-2014-08]:
  - $\text{BR}(h \to \tau\mu) < 1.85 \times 10^{-2}$
  - $\text{BR}(h \to \tau\mu) = (0.77 \pm 0.62) \times 10^{-2}$

- ATLAS $e \leftrightarrow \mu$ asymmetry:
  - $\text{BR}(h \to \tau\mu) < \ldots$ – Soon to appear

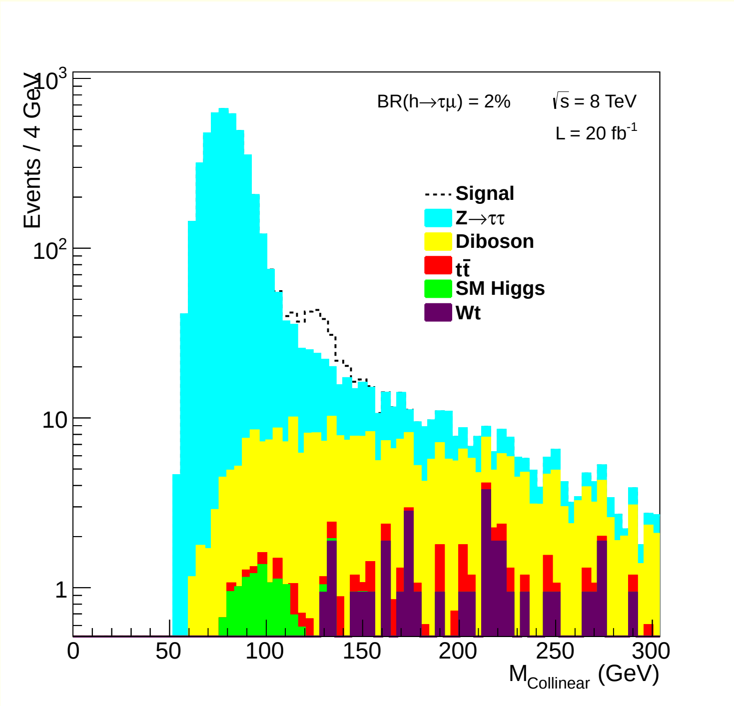
The problem

- Consider the following signal processes:
  - $h \to \tau^{\pm}\mu^{\mp}$ followed by $\tau^{\pm} \to e^{\pm}\nu\bar{\nu}$
  - $h \to \tau^{\pm}e^{\mp}$ followed by $\tau^{\pm} \to \mu^{\pm}\nu\bar{\nu}$
- The signal: $\boxed{\mu^{\pm}e^{\mp}\not{E}_T}$
- SM background:

  (i) $Z \to \tau^{+}\tau^{-} \to \mu^{\pm}e^{\mp}\not{E}_T$

  (ii) $W^{+}W^{-} \to \mu^{\pm}e^{\mp}\not{E}_T$
- Problem: signal lies in transitional region between (i) and (ii)
- Extrapolations from outside Higgs window inadequate; Monte-Carlo uncertain

Background and signal



Simulated background+signal

The theoretical input

- The SM gauge interactions are lepton flavor universal
- m_e, m_μ are negligible in the relevant processes
- $\Longrightarrow$ SM processes symmetric under $e \leftrightarrow \mu$

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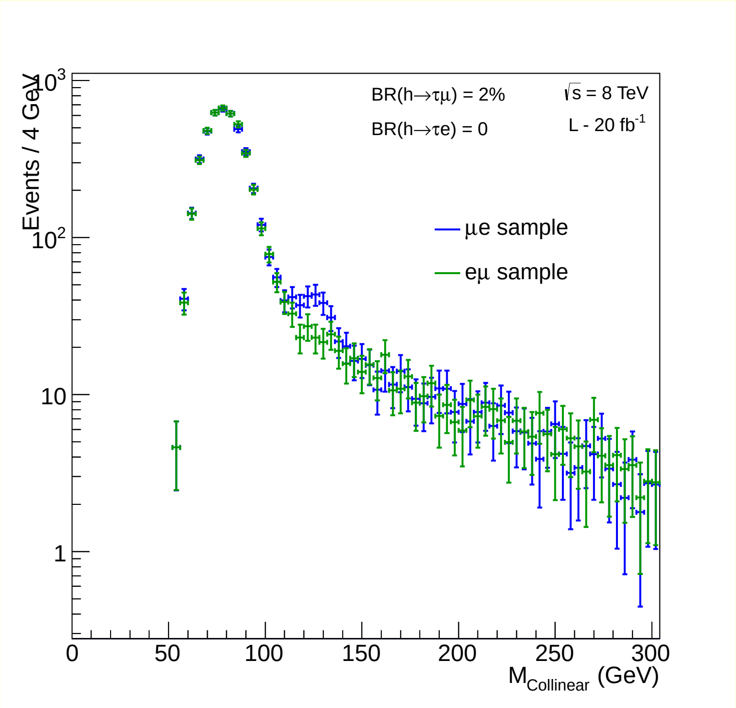
- Yukawa interactions are not universal
- $\mathrm{BR}(h \to \tau\mu) \neq \mathrm{BR}(h \to \tau e)$ – possible
- In fact, the bounds from $\mu \to e\gamma$ imply that $\mathrm{BR}_{\tau\mu}$ and $\mathrm{BR}_{\tau e}$ cannot be simultaneously close to the respective upper bounds
- $\Longrightarrow$ $\mathrm{BR}(h \to \tau\mu) \neq \mathrm{BR}(h \to \tau e)$ breaks the $e \leftrightarrow \mu$ symmetry

The method

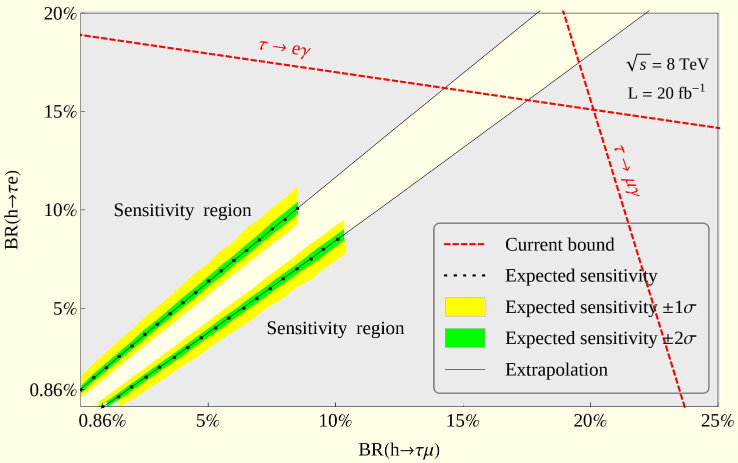
- Divide the data to two mutually exclusive samples:
  - (μe) data sample: $p_T^\mu > p_T^e$
  - $(e\mu)$ data sample: $p_T^e > p_T^\mu$
- SM background: divided equally between the two samples
- $h \to \tau^\pm \mu^\mp$ events are mostly in the (μe) sample; $h \to \tau^\pm e^\mp$ events are mostly in the $(e\mu)$ sample
- Subtracting $(\mu e) - (e\mu)$ provides a measurement of $\mathrm{BR}_{\tau\mu} - \mathrm{BR}_{\tau e}$
- For $\mathrm{BR}_{\tau e} = 0$, the $(e\mu)$ sample provides the SM background

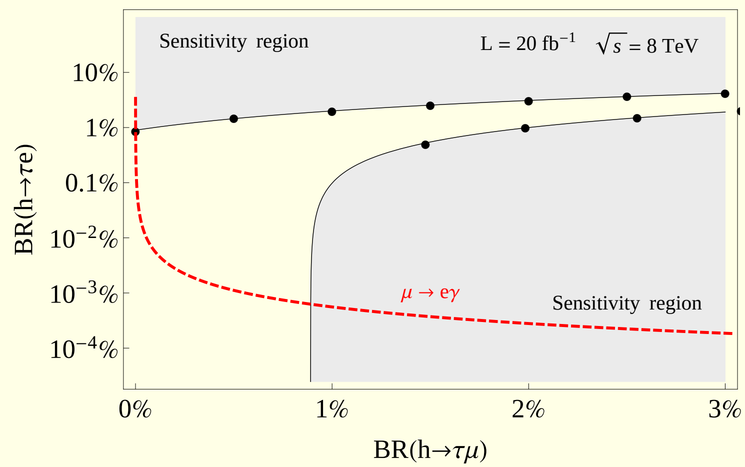
Data driven background estimate



(μe) and $(e\mu)$ distributions

The sensitivity





1405.4545

- With one rate negligibly small, and with 20 fb^{-1} of collected data: 3σ sensitivity for discovering $\text{BR}_{\tau\mu}$ (or $\text{BR}_{\tau e}$) $\simeq 0.9\%$.

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

Exciting $\times$ 3

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

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

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

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 $\Lambda_{\rm GUT}$

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

  $\mathrm{BR}(h \to \tau\mu) \sim 0.01 \implies \Lambda_{\rm LFV} \sim 5$ 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 - strongly disfavored Aloni, YN, Stamou, work in progress

  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

2HDM

- 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):
  - $Y_{e\mu}/Y_{\mu\tau} \sim |U_{e2}/U_{\mu3}|(m_\mu/m_\tau) \sim 0.05 \Longrightarrow$ too large
  - Possible with supersymmetry and holomorphic zeros

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

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

Test:

- MFV
- FN
- NFC
- ...

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

$h \to \mu\tau$ in EFT

- SM: Forbidden by the accidental $U(1)_\mu \times U(1)_\tau$
- $d = 5$ terms $\frac{(Y^N)_{ij}}{\Lambda} L_i L_j \phi\phi$: Allowed, but $\Longrightarrow$
  - Loop suppression $\sim \alpha_2^2$
  - Mixing suppression $\sim |U_{\mu 3} U_{\tau 3}|^2$
  - GIM suppression $\sim (\Delta m_{23}^2 / m_W^2)^2$
- $d = 6$ terms $\frac{1}{\Lambda^2}(\phi^\dagger \phi)\phi \overline{\mu_L} Z^e_{\mu\tau} \tau_R$:
  The leading contribution –
  $M_E = \frac{v}{\sqrt{2}}\left(Y^e + \frac{v^2}{2\Lambda^2} Z^e\right), \quad Y_h^E = Y^e + 3\frac{v^2}{2\Lambda^2} Z^e$
  $\Longrightarrow \; Y_h^E = (\sqrt{2} M_E / v) + \frac{v^2}{2\Lambda^2} Z^e$
- Note: $\frac{1}{\Lambda^2}\phi \overline{\mu_L} X^e_{\mu\tau} \sigma_{\mu\nu} \tau_R F^{\mu\nu} \;\Longrightarrow\; \tau \to \mu\gamma$