The Flavor of Higgs

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Plan of Talk

1. Introduction:
   The flavor puzzles
2. $h \to \ell_i^+ \ell_j^-$:
   Future lessons — Dery, Efrati, Hochberg, YN, 1302.3229
3. $t \to hq,\ h \to \tau\ell$:
   Model building — Dery, Efrati, YN, Soreq, Susič, in progress
4. $h \to \tau^\pm \ell^\mp$:
   Experiment — Bressler, Dery, Efrati, 1405.3229

Introduction

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 (10^{-11} second after the big bang)?
- What are the dark matter particles?
- How was the baryon asymmetry generated?
- What is the solution of the flavor puzzles?

The flavor puzzles

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

- The SM flavor puzzle extended:
  Why is the neutrino flavor structure different?

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

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:
  With ATLAS/CMS we will surely understand how it is solved
- The SM 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

$h \to \ell_i^+ \ell_j^-$: Future Lessons

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

Avital Dery, Aielet Efrati, Gudrun Hiller, Yonit Hochberg, YN, JHEP1308,006 [arXiv:1304.6727]

Relevant data

Observable	Experiment
$R_{\gamma\gamma}$	1.1 ± 0.2
R_{ZZ^*}	1.1 ± 0.2
R_{WW^*}	0.8 ± 0.2
$R_{b\bar{b}}$	0.7 ± 0.4
$R_{\tau\tau}$	0.94 ± 0.23

- $R_f = \frac{\sigma_{\rm prod}{\rm BR}(h\to f)}{[\sigma_{\rm prod}{\rm BR}(h\to f)]^{\rm SM}}$
- Indication that Y_t, Y_b, Y_τ not far from SM
- The beginning of Higgs flavor physics

Observables

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

- What can we learn from $R_{\tau\tau},\ X_{\mu\mu},\ X_{\tau\mu}$?
- Interplay of flavor with electroweak symmetry breaking

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- What can we learn from $R_{\tau\tau},\ X_{\mu\mu},\ X_{\tau\mu}$?
- Interplay of flavor with electroweak symmetry breaking
- ATLAS/CMS: $R_{\tau\tau} = 0.94 \pm 0.23, \quad R_{\mu\mu} < 7.4$
  $(\Longrightarrow\ X_{\mu\mu}/(m_\mu/m_\tau)^2 \lesssim 15)$

MHDM with NFC

- Only one Higgs doublet couples to the charged lepton sector ϕ_ℓ
- $\phi_h = V_{h\ell}\phi_\ell + \cdots$

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$$\Downarrow$$

- $Y_\tau = \frac{V_{h\ell}v}{\langle\phi_l\rangle}\ \frac{\sqrt{2}m_\tau}{v}$
  2HDM type II: $Y_\tau = -\frac{\sin\alpha}{\cos\beta}\ \frac{\sqrt{2}m_\tau}{v}$
- $\frac{Y_\mu}{Y_\tau} = \frac{m_\mu}{m_\tau}$
- $Y_{\mu\tau} = Y_{\tau\mu} = 0$

1HDM with MLFV

- $\lambda_{ij}\bar{L}_i\phi E_j + \frac{\lambda'_{ij}}{\Lambda^2}(\phi^\dagger\phi)\bar{L}_i\phi E_j + \cdots$
- MFV: $\lambda' = a\lambda + b\lambda\lambda^\dagger\lambda + \cdots$

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- MFV: $\lambda' = a\lambda + b\lambda\lambda^\dagger\lambda + \cdots$

$$\Downarrow$$

- $Y_\tau = \left(1 + \frac{av^2}{\Lambda^2}\right) \ \frac{\sqrt{2} m_\tau}{v}$
- $\frac{Y_\mu}{Y_\tau} = \left[1 - \frac{2b(m_\tau^2 - m_\mu^2)}{\Lambda^2}\right] \ \frac{m_\mu}{m_\tau}$
- $Y_{\mu\tau} = Y_{\tau\mu} = 0$

1HDM with FN

- $\lambda_{ij}\bar{L}_i\phi E_j + \frac{\lambda'_{ij}}{\Lambda^2}(\phi^\dagger\phi)\bar{L}_i\phi E_j + \cdots$
- FN: $\lambda'_{ij} = \mathcal{O}(1) \times \lambda_{ij}$

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- $\lambda_{ij} \bar{L}_i \phi E_j + \frac{\lambda'_{ij}}{\Lambda^2} (\phi^\dagger \phi) \bar{L}_i \phi E_j + \cdots$
- FN: $\lambda'_{ij} = \mathcal{O}(1) \times \lambda_{ij}$

$$\Downarrow$$

- $Y_\tau = \left[1 + \mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)\right] \; \frac{\sqrt{2} m_\tau}{v}$
- $\frac{Y_\mu}{Y_\tau} = \left[1 + \mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)\right] \; \frac{m_\mu}{m_\tau}$
- $Y_{\mu\tau} = \mathcal{O}\left(\frac{|U_{23}| v m_\tau}{\Lambda^2}\right), \quad Y_{\tau\mu} = \mathcal{O}\left(\frac{v m_\tau}{|U_{23}| \Lambda^2}\right)$

Summary: $h\ell\ell$, theoretically

Model	$R_{\tau^+\tau^-}$	$X_{\mu^+\mu^-}/(m_\mu^2/m_\tau^2)$	$X_{\tau\mu}$
SM	1	1	0
NFC	$(V_{h\ell}v/v_\ell)^2$	1	0
MSSM	$(\sin\alpha/\cos\beta)^2$	1	0
MFV	$1+2av^2/\Lambda^2$	$1-4bm_\tau^2/\Lambda^2$	0
FN	$1+\mathcal{O}(v^2/\Lambda^2)$	$1+\mathcal{O}(v^2/\Lambda^2)$	$\mathcal{O}(\|U_{23}\|m_\tau v/\Lambda^2)$

$Y_{tq}, Y_{\tau\ell}$: Model building

Avital Dery, Aielet Efrati, YN, Yotam Soreq, Vasja Susič, work in progress

The goal

- Experimentally, the best direct probes of FC Higgs couplings:
  - $t \to hq$ $(q = c, u)$
  - $h \to \tau\ell$ $(\ell = \mu, e)$

- Are there viable and natural flavor models that have
  - $\sqrt{|Y_{tq}|^2 + |Y_{qt}|^2} \sim 0.17$
  - $\sqrt{|Y_{\tau\ell}|^2 + |Y_{\ell\tau}|^2} \sim 0.02$
  - All other couplings within FCNC bounds

MFV

- MQFV:
  - $\frac{Y_{ct}}{Y_{tt}} = \frac{C^u y_b^2 V_{cb} V_{tb}^*}{A^u + B^u y_t^2 + C^u y_b^2 |V_{tb}|^2} \lesssim V_{cb}$
  - No problem with FCNC ($D^0 - \overline{D}^0$ mixing)

- MLFV:
  - If Y^e the only spurion:
    no LFV Higgs couplings
  - If Y^e, Y^ν the only spurions ($M^N = \mathbf{1}$):
    The bounds from $\mu \to e\gamma$ on $|Y_{e\mu}|$ implies $|Y_{\mu\tau}| \lesssim 10^{-4}$
  - With Y^e, Y^ν, M^N spurions + accidental cancelations:
    Possible to have $|Y_{\mu\tau}| \sim 10^{-2}$ and $|Y_{e\mu}| \lesssim 10^{-6}$

FN

- SM with non-renormalizable terms:
  - $\lambda^u_{ij}\bar{Q}_i\tilde{\phi}U_j + \lambda^d_{ij}\bar{Q}_i\phi D_j + \lambda^e_{ij}\bar{L}_i\phi E_j$
    $+\frac{\lambda'^u_{ij}}{\Lambda^2}(\phi^\dagger\phi)\bar{Q}_i\tilde{\phi}U_j + \frac{\lambda'^d_{ij}}{\Lambda^2}(\phi^\dagger\phi)\bar{Q}_i\phi D_j + \frac{\lambda'^e_{ij}}{\Lambda^2}(\phi^\dagger\phi)\bar{L}_i\phi E_j$
  - FN: $\lambda'^f_{ij} = \mathcal{O}(1) \times \lambda^f_{ij}$
  - $Y_{ct} \sim 0.17$ or $Y_{\ell\tau} \sim 0.02$ lead to violating FCNC bounds
- MSSM with non-renormalizable terms:
  - $\lambda^u_{ij}Q_i\phi_u\bar{U}_j + \lambda^d_{ij}Q_i\phi_d\bar{D}_j + \lambda^e_{ij}L_i\phi_d\bar{E}_j$
    $+\frac{\lambda'^u_{ij}}{\Lambda^2}(\phi_u\phi_d)Q_i\phi_u\bar{U}_j + \frac{\lambda'^d_{ij}}{\Lambda^2}(\phi_u\phi_d)Q_i\phi_d\bar{D}_j + \frac{\lambda'^e_{ij}}{\Lambda^2}(\phi_u\phi_d)L_i\phi_d\bar{E}_j$
  - If $(\phi_u\phi_d)$ carries FN charge, $\lambda'^f_{ij} \neq \mathcal{O}(1) \times \lambda^f_{ij}$
  - Holomorphic zeros might appear in λ^f and λ'^f
  - We constructed viable supersymmetric $U(1) \times U(1)$ models that saturate the $Y_{ct}, Y_{\mu\tau}$ bounds

$h \to \tau^{\pm}\ell^{\mp}$: Experiment

Shikma Bressler, Avital Dery, Aielet Efrati, arXiv:1405.4545

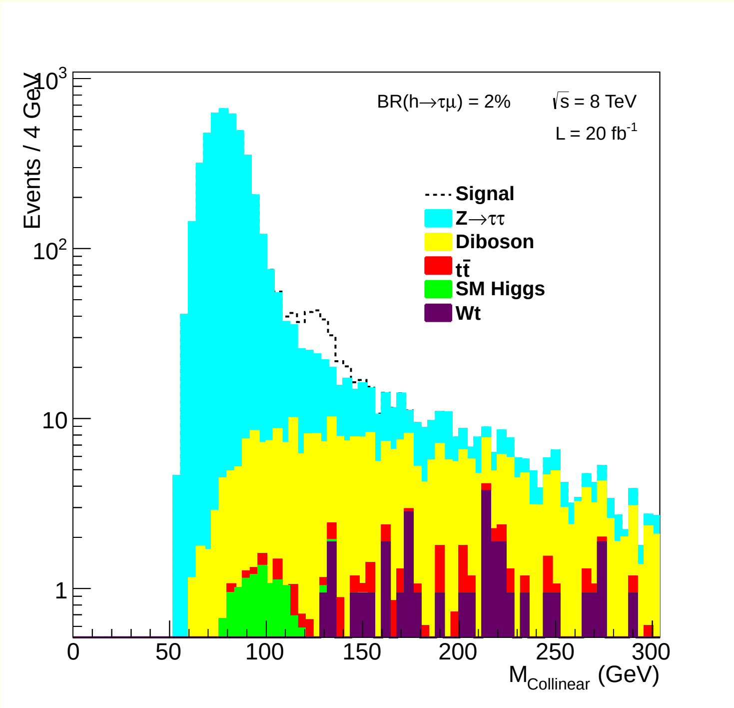
The background

- 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 $\tau^{\pm} \to \mu^{\pm}\nu\bar{\nu}$
- 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
- But: SM processes approximately symmetric under $e \leftrightarrow \mu$; $\mathrm{BR}(h \to \tau\mu) \neq \mathrm{BR}(h \to \tau e)$ breaks this symmetry

The method

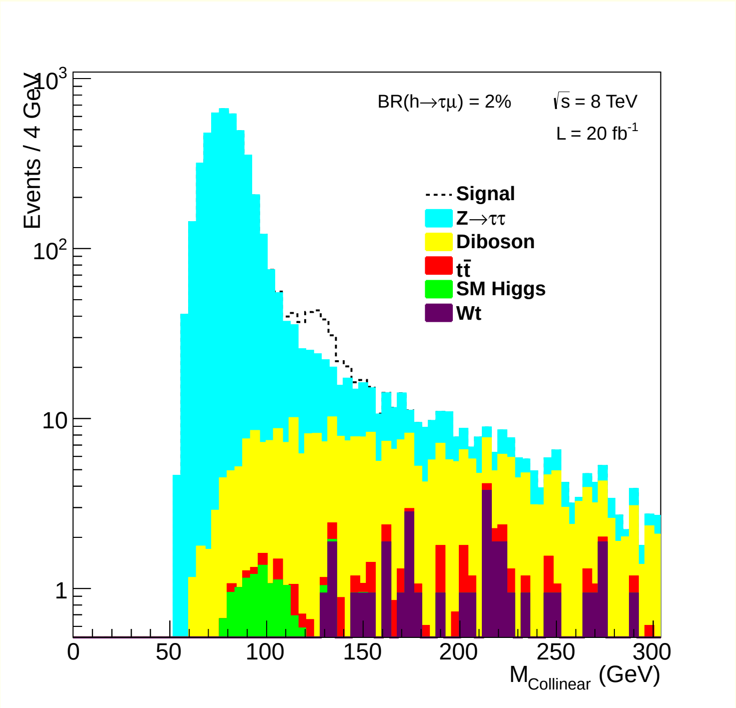
- Divide the data to two mutually exclusive samples:
  - μe data sample: $p_T^\mu > p_T^e$
  - $e\mu$ data sample: $p_T^e > p_T^\mu$
- SM background: divided equally between the two samples
- $h \to \tau^\pm \mu^\mp$ events are mostly in the μe sample
- For $\mathrm{BR}(h \to \tau^\pm e^\mp) = 0$, the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

Data driven background estimate



Simulated background+signal

Data driven background estimate



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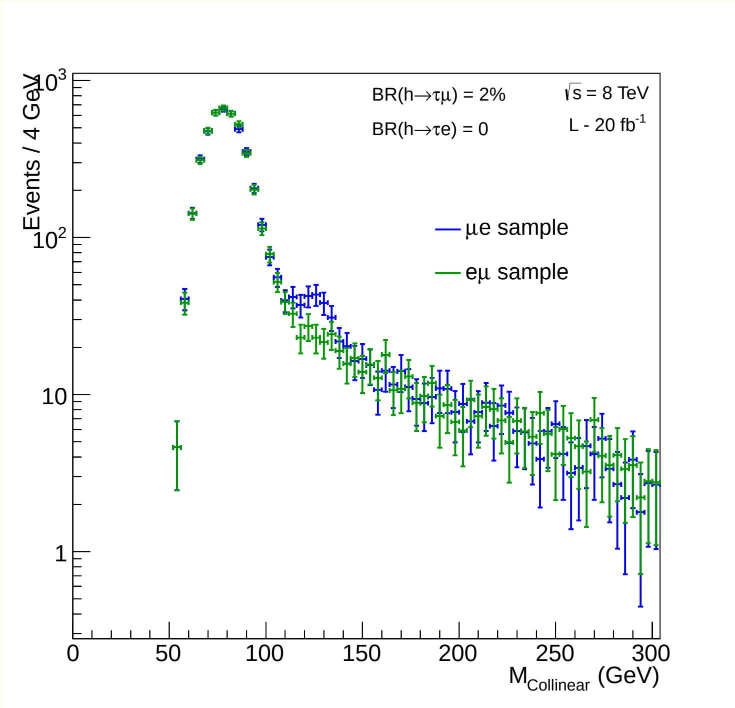
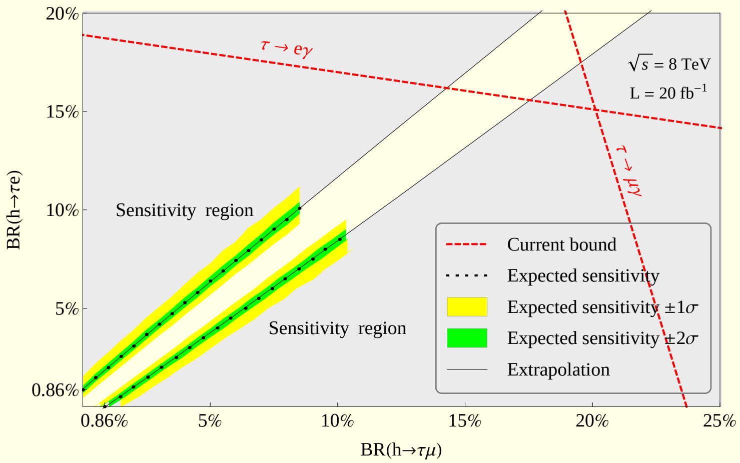
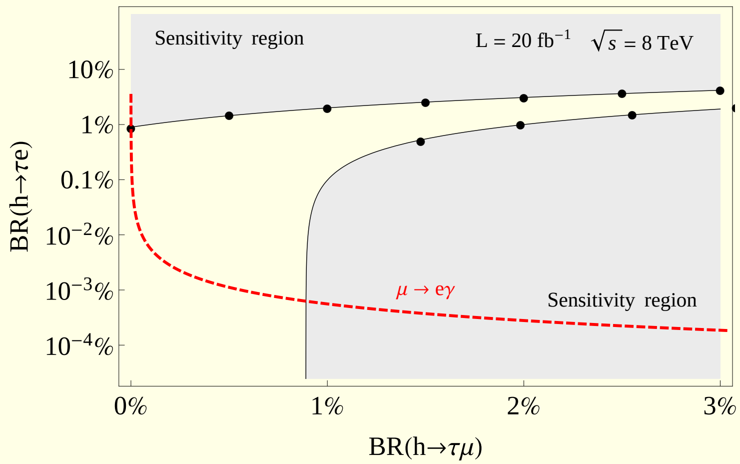


μe and $e\mu$ distributions

[Bressler, Dery, Efrati, 1405.4545]

The sensitivity





1405.4545

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

Conclusions

Recent related work

- Blankenburg, Ellis, Isidori, Phys. Lett. B712, 386 (2012)
- Harnik, Kopp, Zupan, JHEP 1303, 026 (2013)
- Davidson, Verdier, Phys. Rev. D80, 111701 (2012)
- Celis, Cirigliano, Passemar, Phys. Rev. D89, 013008 (2014)

h Physics = New Flavor Arena

Measure:

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

Test:

- MFV
- FN
- NFC
- ...