The Flavor of *h*

PACTS 2018
20 June 2018

Yossi Nir (Weizmann Institute)

Based on…

- Dery, Efrati, Hochberg, YN, JHEP 1305, 039
  - What if $BR(h \to \mu\mu)/BR(h \to \tau\tau) \neq m_\mu^2/m_\tau^2$?
- Dery, Efrati, Hiller, Hochberg, YN, JHEP 1308, 006
  - Higgs couplings to fermions: 2HDM with MFV
- Dery, Efrati, YN, Soreq, Susič, PRD90, 115022
  - Model building for flavor changing Higgs couplings
- Aloni, YN, Stamou, JHEP 1604, 162
  - Large $BR(h \to \tau\mu)$ in the MSSM?
- Dery, YN, JHEP 1704, 003
  - FN-2HDM: Two Higgs doublet models with Froggatt-Nielsen symmetry
- Dery, Frugiuele, YN, JHEP 1804, 044
  - Large Higgs-electron Yukawa coupling in 2HDM

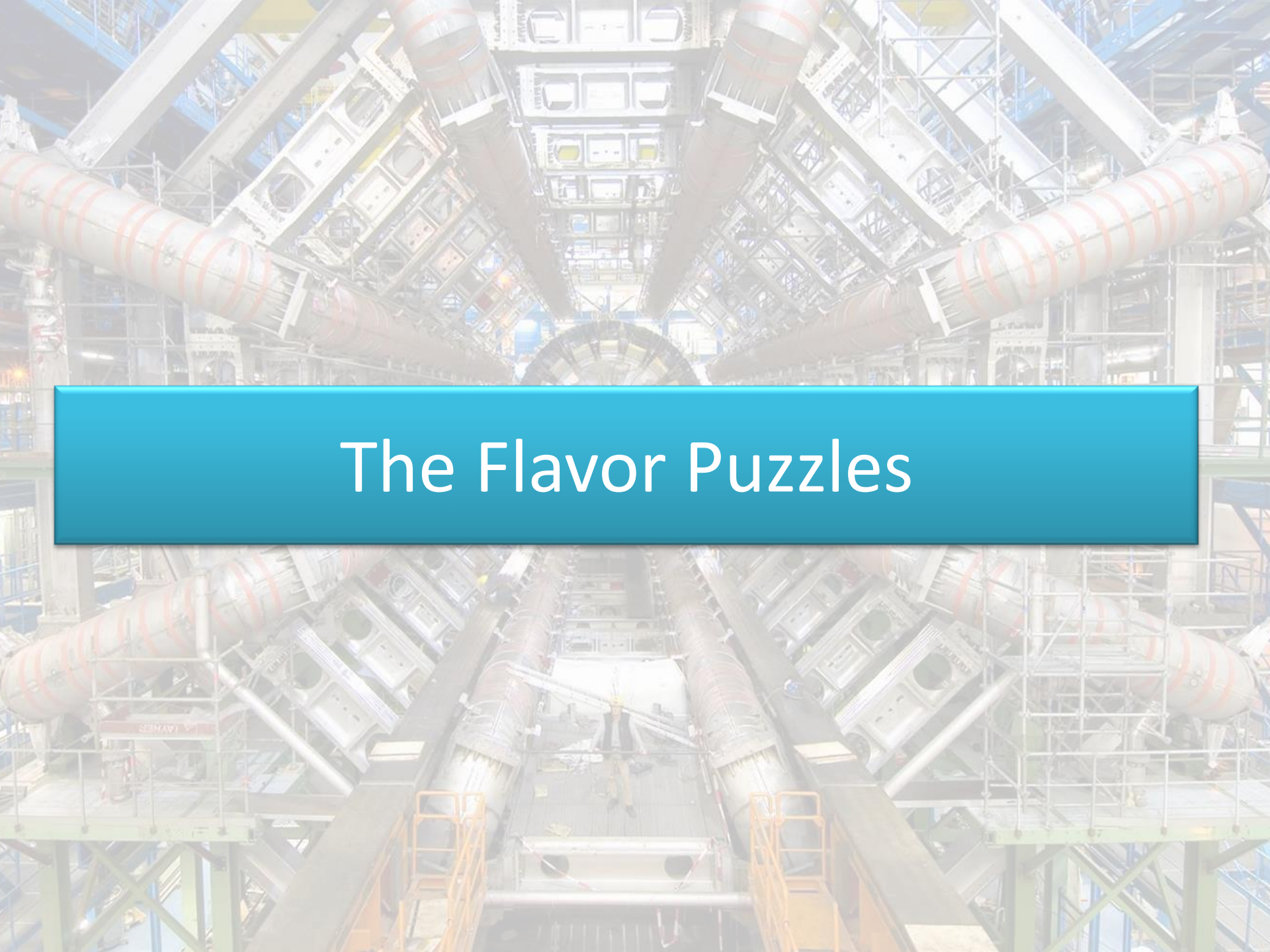
Plan of Talk

The flavor puzzles

The SM flavor of h

The BSM flavor of h

What if $\kappa_e \gg 1$?



The Flavor Puzzles

The Flavor Puzzles

SM

- Why is there structure in the charged fermion flavor parameters?
- Smallness and hierarchy

ν

- Why is the neutrino flavor structure different?
- Neither smallness nor hierarchy

NP

- 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 → New flavor parameters (spectrum, flavor decomposition) that can be measured
- The NP flavor structure can be
  - MFV
  - Related but not identical to SM
  - Unrelated to SM or even anarchical
- The NP flavor puzzle:

  With ATLAS/CMS we are likely to understand how it is solved
- The SM flavor puzzle:

  Progress possible if structure not MFV but related to SM

- h →The "NP" is already here!

  Y_{ij} are new flavor parameters that can be measured

Higgs Data

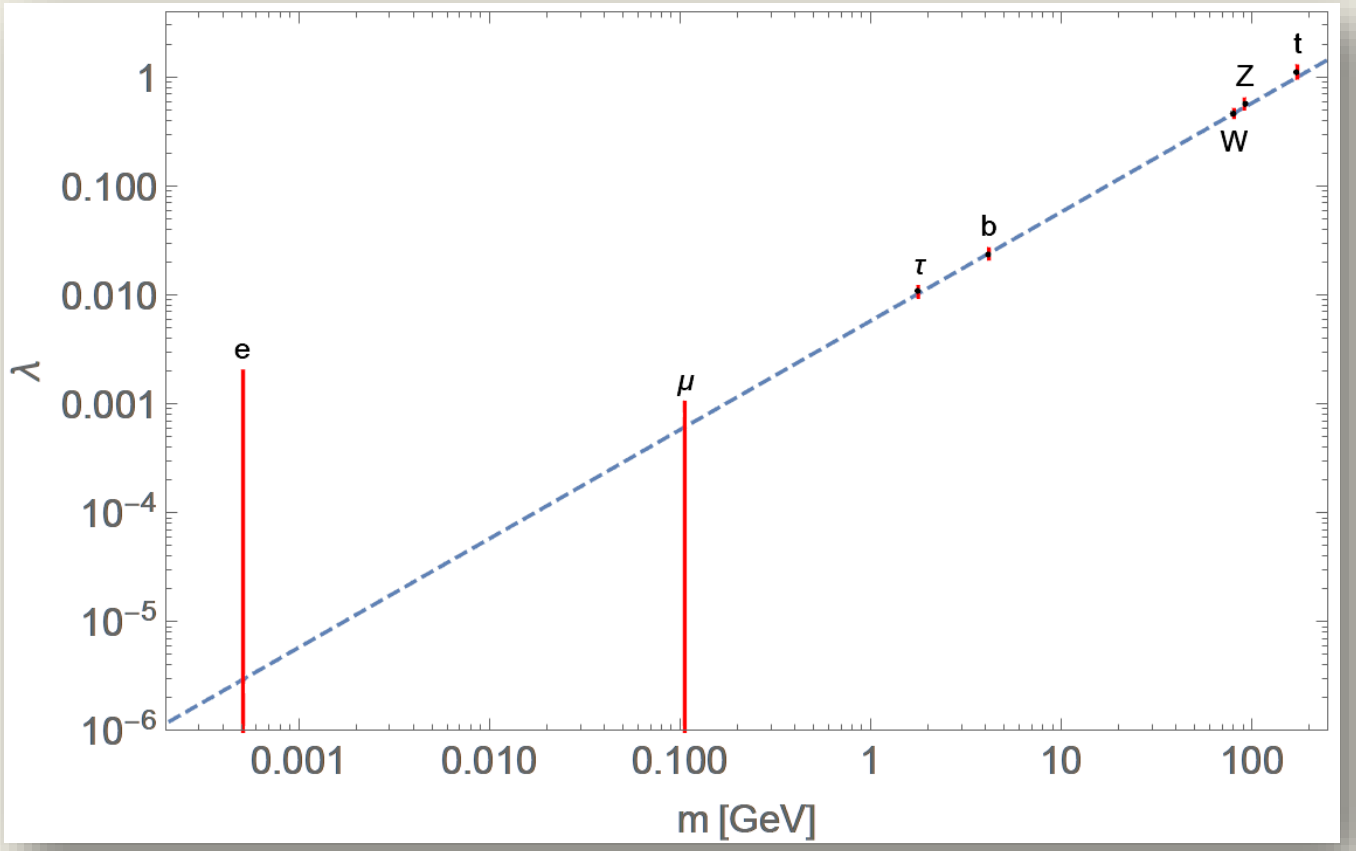
Observable	Experiment
$\mu_{\gamma\gamma}$	1.14 ± 0.14
μ_{ZZ^*}	1.17 ± 0.23
μ_{WW^*}	0.99 ± 0.15
$\mu_{b\bar{b}}$	0.98 ± 0.20
$\mu_{\tau\tau}$	1.09 ± 0.23
μ_{tth}	1.29 ± 0.18
$\mu_{\mu\mu}$	< 2.8
μ_{ee}	$< 4 \times 10^5$

The SM flavor of *h*

SM: $Y_F = (\sqrt{2}/v) M_F$

- Proportionality
  - $y_i/y_j = m_i/m_j \quad (y_i \equiv Y_{ii})$
- Factor of proportionality
  - $y_i/m_i = \sqrt{2}/v$
- Diagonality
  - $Y_{ij} = 0$ for $i \neq j$

Proportionality?



Diagonality?

Observable	Experiment	$Y_{ij} \leq$
$\mathrm{BR}(t \to ch)$	$\leq 2.2 \times 10^{-3}$	9.0×10^{-2}
$\mathrm{BR}(t \to uh)$	$\leq 2.4 \times 10^{-3}$	9.4×10^{-2}
$\mathrm{BR}(h \to \tau\mu)$	$\leq 2.5 \times 10^{-3}$	1.4×10^{-3}
$\mathrm{BR}(h \to \tau e)$	$\leq 6.1 \times 10^{-3}$	2.3×10^{-3}
$\mathrm{BR}(h \to \mu e)$	$\leq 3.4 \times 10^{-4}$	6.0×10^{-4}

Higgs Flavor Tests

- $y_e, y_\mu < y_\tau$
- y_t, y_b, y_τ not far from SM

  $y_{3rd}/m_{3rd} \sim \sqrt{2}/v$
- $\frac{y_{tq}}{y_t} < 0.1, \quad \frac{y_{\tau l}}{y_\tau} < 0.1, \quad \frac{y_{\mu e}}{y_\mu} < 0.1$

- The beginning of Higgs flavor physics

The BSM flavor of *h*

BSM: $Y_F \neq (\sqrt{2}/v)M_F$?

With new physics, it can be that:

- Factor of proportionality is different
  - $y_i/m_i \neq \sqrt{2}/v$
- Proportionality is violated
  - $y_i/y_j \neq m_i/m_j$
- *h* has off-diagonal couplings
  - $Y_{ij} \neq 0$ for $i \neq j$

Solutions to flavor puzzles

- Natural Flavor Conservation (NFC)
  - Solution to the 2HDM flavor puzzle
  - Universal correction to diagonal couplings
- Minimal Flavor Violation (MFV)
  - Solution to the NP flavor puzzle
  - Non-universal correction to diagonal couplings
- Froggatt-Nielsen mechanism (FN)
  - Solution to the SM and NP flavor puzzles
  - Non-universal correction to diagonal couplings + off-diagonal couplings

h-testing flavor models

- SM-EFT

Model	$\frac{Y_\tau^2}{2m_\tau^2/v^2}$	$\frac{Y_\mu^2/Y_\tau^2}{m_\mu^2/m_\tau^2}$	$\frac{Y_{\mu\tau}^2}{Y_\tau^2}$
SM	1	1	0
MFV*	$1+\mathcal{O}(v^2/\Lambda^2)$	$1+\mathcal{O}(m_\tau^2/\Lambda^2)$	0
FN	$1+\mathcal{O}(v^2/\Lambda^2)$	$1+\mathcal{O}(v^2/\Lambda^2)$	$\mathcal{O}(\lvert U_{\mu 3}\rvert^2 v^4/\Lambda^4)$
GL	9	$25/9$	$\mathcal{O}(10^{-2})$

FN-2HDM

- Yukawa couplings:
  - Approximate NFC type II or IV
- Scalar potential:
  - Approximate PQ symmetry
- Both approximations broken by small parameter:
  - $\epsilon_{PQ} = \epsilon_{FN}^{|H(\phi_1) - H(\phi_2)|}$
- Strongest constraint from $\mu \to e\gamma$:
  - $\epsilon_{PQ} < 10^{-3}$

h-testing flavor models

- 2HDM

Model	$\frac{Y_\mu/Y_\tau}{m_\mu/m_\tau}$	$Y_{\mu\tau}$	$\frac{Y_c/Y_t}{m_c/m_t}$	Y_{ct}
NFC	1	0	1	0
MFV	$1+\mathcal{O}(y_\tau^2)$	0	$1+\mathcal{O}(y_t^2)$	$\mathcal{O}(y_t y_b^2 V_{cb} V_{tb}^*)$
FN	$1+\mathcal{O}(\epsilon_{\rm PQ})$	$\mathcal{O}(y_\tau U_{\mu 3}\epsilon_{\rm PQ})$	$1+\mathcal{O}(\epsilon_{\rm PQ})$	$\mathcal{O}(y_t V_{cb}\epsilon_{\rm PQ})$


What if $\kappa_e \gg 1$?

κ_f in general 2HDM

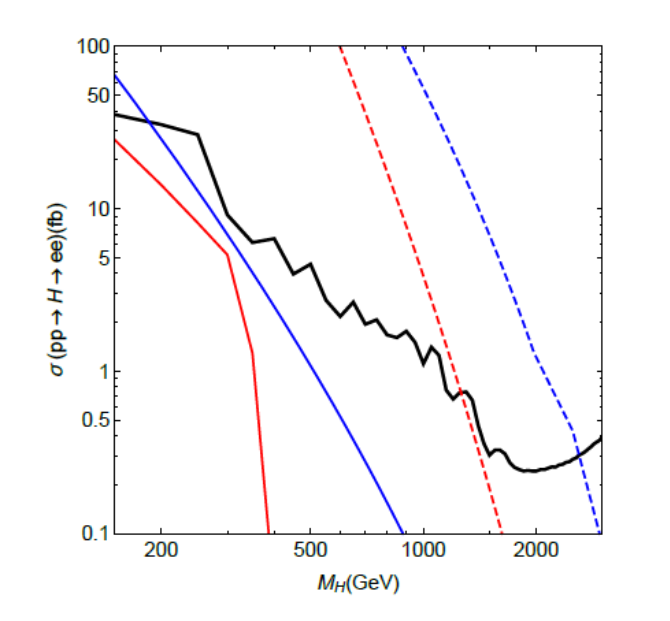
- Without loss of generality, choose a basis where $(Y^2)_{ii} = 0$
- If $(Y^2)_{ii} = (Y^2)_{jj} = 0$:
  - $\kappa_i = \kappa_j$
  - Couplings to $A, H, H^{\pm}$ related
- If $(Y^2)_{ii} = 0, (Y^1)_{jj} = 0$:
  - $\kappa_V = (1 + \kappa_i \kappa_j)/(\kappa_i + \kappa_j)$
  - Couplings to $A, H, H^{\pm}$ related
- Many implications for 2HDM where one of the doublets couples to only the third generation, or to only the first generation, etc.

The scalar spectrum with $\kappa_f \gg 1$

- With hard breaking of Z_2:
  - $v^2 \ll m_A^2 \ll \frac{v^2 \kappa_f}{\sqrt{1-\kappa_V^2}}$ possible
- Otherwise:
  - $m_A \sim v$

$\kappa_e \gg 1$

- The scalar potential and the Yukawa couplings must be CP conserving to excellent approximation, $O(10^{-2}/\kappa_e)$
- LHC searches for e^+e^- resonances are excellent probe



$\kappa_e = 500, m_H = m_A$

Region above black curve excluded

Blue: $Y^2_{u,d,e}$=0, $Y^1_{t,b,\tau,c,s,\mu}$=0

Red: $Y_t^{A,H}$ =0

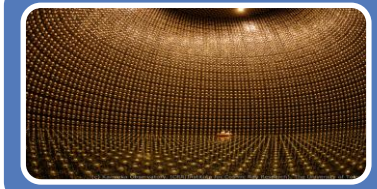
Flavored Conclusions

Quarks: smallness, hierarchy

$\Longrightarrow$ Approximate symmetry?

Squarks: degeneracy, alignment

$\Longrightarrow$ Flavor paradise, but where are they?



Neutrinos: anarchy $\Longrightarrow$ Knowing more does not necessarily mean understanding better

Higgs: diagonality? proportionality?

$\Longrightarrow$ a new opportunity for flavor