Flavor Physics

Lake Louise Winter Institute 2017

Chateau Lake Louise, Canada
February 24, 2017

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Plan of Talk

1. Introduction
   - Answers from the B factories
   - Questions to the LHC
   - The flavor puzzles
2. The flavor of h
   - The SM flavor of h
   - The BSM flavor of h
   - What if $\text{BR}(h \to \tau\mu) \sim 0.01$?
3. $R[D^{(*)}]$
4. Conclusions

Answers from the B factories

A brief history of experimental CPV

- 1964 – 2000
  - $|\varepsilon| = (2.228 \pm 0.011) \times 10^{-3}$; $\mathcal{R}e(\varepsilon'/\varepsilon) = (1.65 \pm 0.26) \times 10^{-3}$

A brief history of experimental CPV

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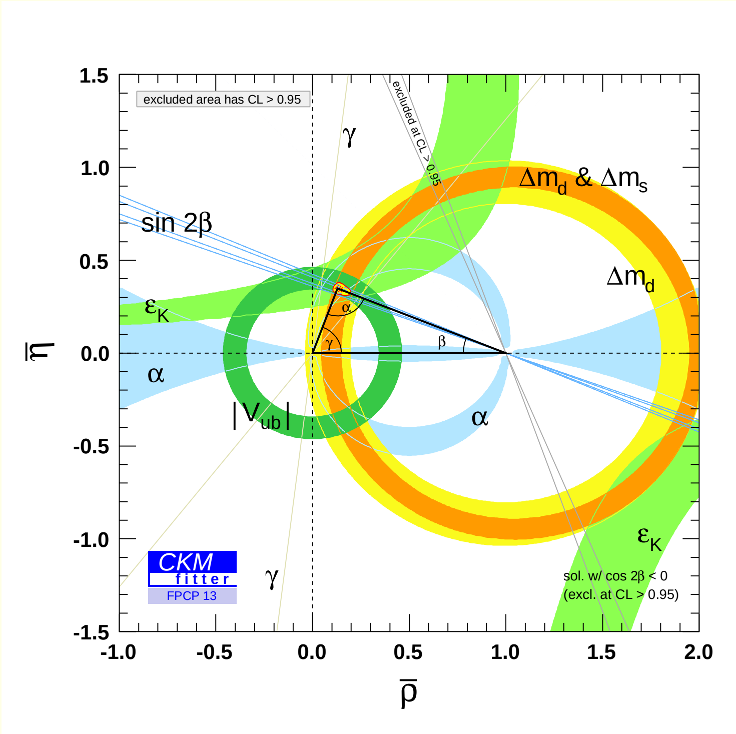
- 2000 – 2016, 5σ
  - $S_{\psi K^0} = +0.691 \pm 0.017$
  - $S_{D^{(*)}_{CP}h} = +0.63 \pm 0.11$
  - $S_{\phi K_S} = +0.74 \pm 0.12$, $S_{\eta' K_S} = +0.63 \pm 0.06$, $S_{f_0 K_S} = +0.69 \pm 0.11$
  - $S_{K^+K^-K_S} = +0.68 \pm 0.10$
  - $S_{\pi^+\pi^-} = -0.66 \pm 0.06$, $C_{\pi^+\pi^-} = -0.31 \pm 0.05$
  - $S_{\psi\pi^0} = -0.93 \pm 0.15$, $S_{DD} = -0.98 \pm 0.17$, $S_{D^*D^*} = -0.71 \pm 0.09$
  - $\mathcal{A}_{K^\mp\pi^\pm} = -0.082 \pm 0.006$, $\mathcal{A}_{B_s \to K^-\pi^+} = +0.26 \pm 0.04$
  - $\mathcal{A}_{D_+K^\pm} = +0.195 \pm 0.027$, $\mathcal{A}_{K^+K^-\pi^\pm} = -0.118 \pm 0.022$

Testing CKM – Take I

- Assume CKM matrix is the only source of FV and CPV
  $\Longrightarrow$ Four CKM parameters: λ, A, ρ, η
- λ known from $K \to \pi\ell\nu$
  A known from $b \to c\ell\nu$
- Many observables are $f(\rho, \eta)$:
  - $b \to u\ell\nu \implies \propto |V_{ub}/V_{cb}|^2 \propto \rho^2 + \eta^2$
  - $\Delta m_{B_d}/\Delta m_{B_s} \implies \propto |V_{td}/V_{ts}|^2 \propto (1-\rho)^2 + \eta^2$
  - $S_{\psi K_S} \implies \frac{2\eta(1-\rho)}{(1-\rho)^2+\eta^2}$
  - $S_{\rho\rho}$
  - $\mathcal{A}_{DK}$
  - ϵ_K

Answers from the B-factories - I



CKMFitter

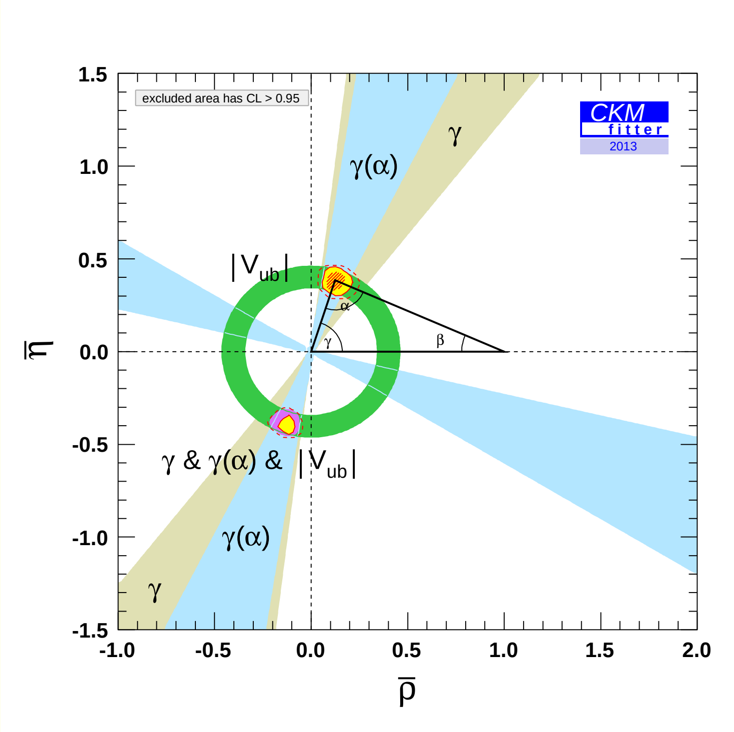
Very likely, the CKM mechanism dominates FV and CPV

Testing CKM - take II

- Allow arbitrary new physics in $B^0-\overline{B}^0$ mixing:
  $\Longrightarrow h_d e^{2i\sigma_d} = A^{\rm NP}(B^0\to\overline{B})/A^{\rm SM}(B^0\to\overline{B})$
- Consider only tree decays and $B^0-\overline{B}^0$ mixing:
  $|V_{ub}/V_{cb}|$, $\mathcal{A}_{DK}$, $S_{\psi K}$, $S_{\rho\rho}$, Δm_{B_d}, $\mathcal{A}_{\rm SL}^d$
- Fit to the four parameters: ρ,η (CKM), h_d,σ_d (NP)

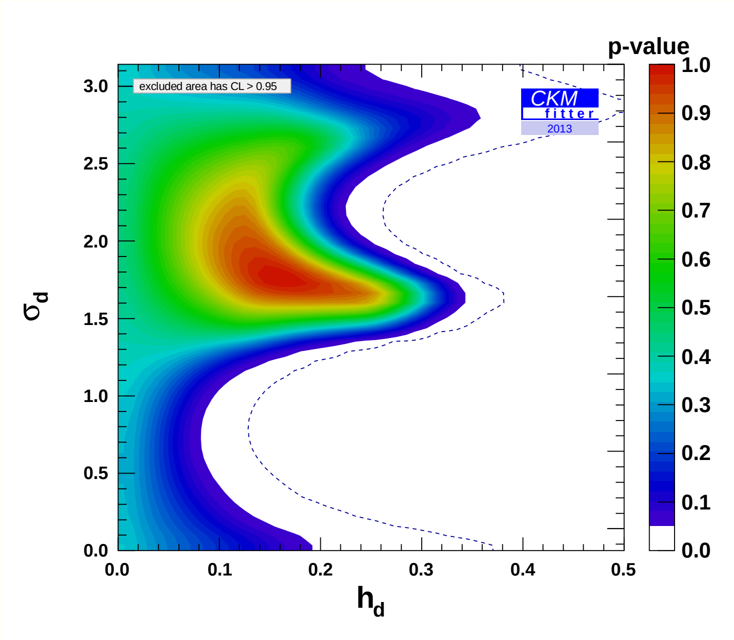
- Find whether $\eta=0$ is allowed
  If not $\Longrightarrow$ The KM mechanism is at work
- Find whether $h_d \gtrsim 1$ is allowed
  If not $\Longrightarrow$ The CKM mechanism is dominant

Answers from the B-factories - II



- $\eta \neq 0 \Longrightarrow$ The KM mechanism is at work

Answers from the B-factories - III



- $h \lesssim 0.4 \Longrightarrow$ The KM mechanism dominates CPV
- $hs_{2\sigma_d} \lesssim 0.2 \Longrightarrow$ The CKM mechanism dominates FV
- NP contributions to the observed FCNC are small ($s \leftrightarrow d$, $c \leftrightarrow u$, $b \leftrightarrow d$, $b \leftrightarrow s$)
- So what remains to be understood?

Questions for 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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- What is the solution of the flavor puzzles?
  One of the topics 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
- The NP flavor puzzle:
  With ATLAS/CMS we are likely to understand how it is solved
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  Progress possible if structure not MFV but related to SM
- $\boxed{h}$ $\Longrightarrow$ The "NP" is already here!
  $Y_{\bar{f}_i f_j}$ are new flavor parameters that can be measured

The SM flavor of h

Relevant data

Observable	Experiment
$\mu_{\gamma\gamma}$	1.14 ± 0.14
μ_{ZZ^*}	1.17 ± 0.23
μ_{WW^*}	0.99 ± 0.15
$\mu_{b\bar{b}}$	0.7 ± 0.3
$\mu_{\tau\tau}$	1.09 ± 0.23
$\mu_{\mu\mu}$	< 7
μ_{ee}	$< 4 \times 10^5$

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

More relevant data

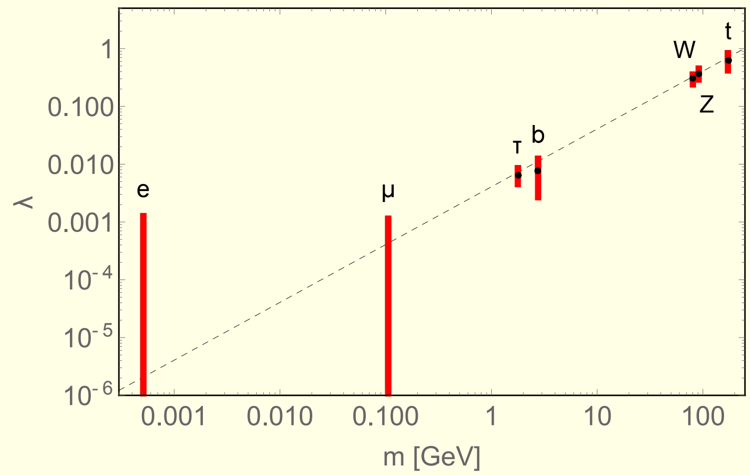
- $\text{BR}(t \to ch) \leq 4.0 \times 10^{-3}$ CMS, 1610.04857; ATLAS, 1509.06047
- $\text{BR}(t \to uh) \leq 4.5 \times 10^{-3}$ ATLAS, 1509.06047; CMS, 1610.04857

- $\text{BR}(h \to \tau\mu) \leq 1.2 \times 10^{-2}$ CMS-PAS-HIG-16-005; ATLAS, 1604.07730
- $\text{BR}(h \to \tau e) \leq 6.9 \times 10^{-3}$ CMS, 1607.03561; ATLAS, 1604.07730
- $\text{BR}(h \to \mu e) \leq 3.5 \times 10^{-4}$ CMS, 1607.03561

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

- $y_e, y_\mu < y_\tau$: supports proportionality
- For y_t, y_b, y_τ: $y_3/m_3 \approx \sqrt{2}/v$
- The beginning of Higgs flavor physics

Diagonality?

- $\sqrt{Y_{tc}^2 + Y_{ct}^2} \leq 0.12$
- $\sqrt{Y_{tu}^2 + Y_{ut}^2} \leq 0.13$

- $\sqrt{Y_{\tau\mu}^2 + Y_{\mu\tau}^2} \leq 3.1 \times 10^{-3}$
- $\sqrt{Y_{\tau e}^2 + Y_{e\tau}^2} \leq 2.4 \times 10^{-3}$
- $\sqrt{Y_{\mu e}^2 + Y_{e\mu}^2} \leq 5.3 \times 10^{-4}$

- No evidence for flavor changing Higgs couplings

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
$\mu_{\tau^+\tau^-}$	1	Factor
$X_{\ell\ell} = \frac{\text{BR}(h\to\ell^+\ell^-)}{\text{BR}(h\to\tau^+\tau^-)}$	$(m_\ell/m_\tau)^2$	Proportionality
$X_{\ell\tau} = \frac{\text{BR}(h\to\ell^\pm\tau^\mp)}{\text{BR}(h\to\tau^+\tau^-)}$	0	Diagonality

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

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- What can we learn from $\mu_{\tau\tau}$, $X_{\ell\ell}$, $X_{\ell\tau}$?
- ATLAS/CMS:
  - $\mu_{\tau\tau} = 1.09 \pm 0.23$
  - $X_{\mu\mu} < 12(m_\mu/m_\tau)^2 \sim 0.05, \quad X_{ee} < 7\times10^5(m_e/m_\tau)^2 \sim 0.06$
  - $X_{\mu\tau} = 0.087 \pm 0.045 < 0.2$

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

- 2HDM with Type II NFC
  Solution to the 2HDM flavor puzzle
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- 2HDM with Type II NFC
  Solution to the 2HDM flavor puzzle
  - Universal correction to the diagonal couplings
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  Solution to the NP flavor puzzle
  - Non-universal correction to the diagonal couplings
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  Solution to the 2HDM flavor puzzle
  - Universal correction to the diagonal couplings
- SM-EFT with MFV
  Solution to the NP flavor puzzle
  - 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	$\mathcal{O}(10^{-2})$

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Measuring Y_{ij} can probe flavor models

$$\boxed{h \to \tau\mu}$$

Relevant data

- $\mathrm{BR}(h \to \tau\mu) = (8.9^{+3.9}_{-3.7}) \times 10^{-3}$ CMS, 1502.07400
- $\mathrm{BR}(h \to \tau\mu) = (-7.6^{+8.1}_{-8.4}) \times 10^{-3}$ CMS, CMS-PAS-HIG-16-005
- $\mathrm{BR}(h \to \tau\mu) = (5.3 \pm 5.1) \times 10^{-3}$ ATLAS, 1604.07730

- Average: $\mathrm{BR}(h \to \tau\mu) = (5.5 \pm 2.8) \times 10^{-3}$

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- Average: $\mathrm{BR}(h \to \tau\mu) = (5.5 \pm 2.8) \times 10^{-3}$
- What if $\mathrm{BR}(h \to \tau\mu) \sim 0.005$?

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 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

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

- 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

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

  $m_\nu \sim 0.1\ \text{eV} \implies \Lambda_{\rm LNV} \sim 10^{15}\ \text{GeV}$

  Intriguingly close to $\Lambda_{\rm GUT}$

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

  $\text{BR}(h \to \tau\mu) \sim 0.01 \implies \Lambda_{\rm LFV} \sim 5\ \text{TeV}$

  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 $\mathrm{BR}(h \to \tau\mu) \sim 0.005$ 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

$$\boxed{R[D^{(*)}]}$$

NP in flavor?

- Most tensions either disappeared or below 3σ or involve large hadronic uncertainties:
  - Lepton universality in $B \to D^{(*)}\tau\nu$
  - Lepton universality in $B \to K\ell^+\ell^-$
  - Angular distribution in $B \to K^*\ell^+\ell^-$
  - CP violation in $D \to K^+K^-, \pi^+\pi^-$
  - CP violation in $B_{d,s} \to \ell\nu X$

The $R[D^{(*)}]$ puzzle

- $R[D^{(*)}] \equiv \Gamma(B \to D^{(*)}\tau\nu)/\Gamma(B \to D^{(*)}\ell\nu), \quad (\ell = e, \mu)$
- BaBar, Belle, LHCb:
  $R(D) = 0.403 \pm 0.047, \quad R(D^*) = 0.310 \pm 0.017, \quad \rho = -0.23$
- The SM:
  $R(D) = 0.300 \pm 0.008, \quad R(D^*) = 0.252 \pm 0.003$
- 3.9σ deviation from the SM

The $R[D^{(*)}]$ solutions

- 30% corrections to SM $b \to c$ tree-level decay
  $\Longrightarrow$ Most likely, NP contributes at tree level as well
- Seven possibilities:
  - Vector-bosons:
    $W'_\mu(1,3)_0$, $U_\mu(3,1)_{+2/3}$, $X_\mu(3,3)_{+2/3}$, $V_\mu(3,2)_{-5/6}$
  - Scalars:
    $S(3,1)_{-1/3}$, $T(3,3)_{-1/3}$, $D(3,2)_{+7/6}$
- In all cases, quark doublets are involved
  $\Longrightarrow$ NP in FCNC

The $R[D^{(*)}]$-related phenomenology

- $t \to c\tau^+\tau^-$
- $b \to s\tau^+\tau^-$
- $B_c \to \tau\nu$
- $\Lambda_b \to \Lambda_c\tau\nu$
- $b\bar{b}/c\bar{c} \to \tau^+\tau^-$
- $\Upsilon, \psi \to \tau^+\tau^-$ Aloni, Efrati, YN, work in progress

Conclusions

Lessons from flavor factories

- The KM phase is different from zero (SM violates CP)
- The KM mechanism is the dominant source of the CP violation observed in meson decays
- Complete alternatives to the KM mechanism are excluded (Superweak, Approximate CP)
- The CKM mechanism is the dominant source of the flavor violation observed in meson decays
- NP contributions to the observed FCNC are small ($s \leftrightarrow d$, $c \leftrightarrow u$, $b \leftrightarrow d$, $b \leftrightarrow s$)

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:

- SM
- MFV
- FN
- NFC
- ...

$h \to \mu\tau$

If $\mathrm{BR}(h \to \tau\mu) \sim 0.005$:

- 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

$R[D^{(*)}]$

If $R[D^{(*)}]$ deviates by $\mathcal{O}(30\%)$ from SM:

- SM, 2HDM+NFC excluded
- New physics at TeV scale
- Most likely, extra bosons
- Search for additional effects of FCNC and/or lepton non-universality

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