General Flavor Theory

"flavor 2019: (still) puzzling and great opportunity”

Gudrun Hiller, TU Dortmund
symmetry, and symmetry-breaking (the same yet not the same)
The Standard Model of Particle Physics

renormalizable QFT in 3+1 Minkowski space w. local symmetry

\[ SU(3)_C \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_C \times U(1)_{em} \]

\[ \mathcal{L}_{SM} = -\frac{1}{4} F^2 + \bar{\psi} i \not{D} \psi + \frac{1}{2} (D \Phi)^2 - \bar{\psi} Y \Phi \psi + \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2 \]

\( \psi \): fermions (quarks and leptons)

\( D_\mu = \partial_\mu - ieA_\mu + \ldots \)

\( F_{\mu\nu} \): gauge bosons \( g^a, \gamma, Z^0, W^\pm \)

\( \Phi \): Higgs doublet

Known fundamental matter comes in generations

\( \psi \rightarrow \psi_i, i = 1, 2, 3, \)

subject to identical gauge transformations. ”universality”, hard-wired.
They are not the same

Fields in representations under the SM $SU(3)_C \times SU(2)_L \times U(1)_Y$

Higgs: $\Phi(1, 2, 1/2)$
hypercharge $Y = Q - T_3$

quarks: $Q_L(3, 2, 1/6)_i, D_R(3, 1, -1/3)_i, U_R(3, 1, 2/3)_i$

leptons: $L_L(1, 2, -1/2)_i, E_R(1, 1, -1)_i$

labelled with increasing mass, distinguished by 'flavor' (mass and mixing, i.e. CKM (quarks), PMNS (leptons))

$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix}, U_R = u_R, c_R, t_R, \quad D_R = d_R, s_R, b_R$

$L_L = \begin{pmatrix} \nu_e \\ e \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}, E_R = e_R, \mu_R, \tau_R$
Flavor in the SM is sourced only by the Yukawa interactions:

\[ \mathcal{L}_{SM} = \sum_{\psi=Q,U,D,L,E} \bar{\psi}_i \mathcal{D} \psi_i - \bar{Q}_L (Y_u)_{ij} \Phi^C U_R - \bar{Q}_L (Y_d)_{ij} \Phi D_R - \bar{L}_L (Y_e)_{ij} \Phi E_R + \mathcal{L}_{higgs} + \mathcal{L}_{gauge}, \]

\[ \Phi^C = i\sigma^2 \Phi^* \]

\( Y_{u,d,e} \): Yukawa matrices (3 x 3, complex)
different Yukawa \( \rightarrow \) different mass from vev \( \langle \Phi \rangle \) etc
off-diagonal entries open up possibility to mix generations
direct link with Higgs physics: \( h \to \psi \bar{\psi} \) probes \( Y_{u,d,e} \), flavor!

Program: determine flavor parameters (in SM)
Quark Spectrum

<table>
<thead>
<tr>
<th>Length [m]</th>
<th>Energy</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>(10^{-18})</td>
<td>(\Lambda_{EWK})</td>
<td>(t)</td>
</tr>
<tr>
<td>(10^{-15})</td>
<td>(\Lambda_{QCD})</td>
<td>(w, z)</td>
</tr>
<tr>
<td>(10^{-12})</td>
<td>(E_{Deuteron})</td>
<td>(b)</td>
</tr>
<tr>
<td>(10^{-9})</td>
<td>(E_{Rydberg})</td>
<td>(\tau, c)</td>
</tr>
<tr>
<td>(10^{-6})</td>
<td>(2) eV</td>
<td>(\mu, s)</td>
</tr>
<tr>
<td></td>
<td>(u, d)</td>
<td>(\text{particle physics})</td>
</tr>
<tr>
<td></td>
<td>(e)</td>
<td>(\text{atomic, nuclear physics})</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
m_u (2 \text{ GeV}) & = 2.8 \pm 0.6 \text{ MeV} \\
m_d (2 \text{ GeV}) & = 5.0 \pm 1.0 \text{ MeV} \\
m_s (2 \text{ GeV}) & = 95 \pm 15 \text{ MeV} \\
m_c (m_c) & = 1.28 \pm 0.05 \text{ GeV} \\
m_b (m_b) & = 4.22 \pm 0.05 \text{ GeV} \\
m_t (m_t) & = 163 \pm 3 \text{ GeV}
\end{align*}
\]

Spectrum spans five orders of magnitude.
Experimentally (if rotated solely to up-sector)

\[
Y_u \sim \begin{pmatrix}
10^{-5} & -0.002 & 0.008 + i 0.003 \\
10^{-6} & 0.007 & -0.04 \\
10^{-8} + i 10^{-7} & 0.0003 & 0.94
\end{pmatrix}
\]

\[
Y_d \sim \text{diag} \left( 10^{-5}, 5 \cdot 10^{-4}, 0.025 \right)
\]

\[
Y_e \sim \text{diag} \left( 10^{-6}, 6 \cdot 10^{-4}, 0.01 \right)
\]

\[
\text{diag} \left( a, b \right) = \begin{pmatrix}
a & 0 \\
0 & b
\end{pmatrix}
\]

Quark mixing is hierarchal, as well as quark and charged lepton masses.

Why? ideas, no “SM” nowhere near, needs BSM to progress
Flavor change

$\psi \rightarrow \psi_i, i = 1, 2, 3$ sounds simple but implies rich phenomenology:
flavor change (within same and other generations), CP violation, meson mixing, ...
SM flavor change only through weak interaction among left-handed fermions:

$V_{ij} = (V_{CKM})_{ij}$. Product of up and down unitary matrices $V = V_u V_d^\dagger$, derived from $Y_{u,d}$ (diagonalization). Not physical each in SM.
Masses from spontaneous breaking of electroweak symmetry
\( \Phi^T(x) \rightarrow 1/\sqrt{2}(0, v + h(x)) \), Higgs vev \( \langle \Phi \rangle = v/\sqrt{2} \simeq 174 \) GeV

\[ \mathcal{L}_{\text{yukawa}}^{\text{SM}} = -\overline{Q}_L Y_u \Phi^C U_R - \overline{Q}_L Y_d \Phi D_R - \overline{L}_L Y_e \Phi E_R \]

Want mass eigenstates rather than gauge eigenstates \( QUDELE \): perform unitary trasfos on quark fields \( Q_L = (U_L, D_L), U_R, D_R \)
\( \tilde{q}_A(\text{mass}) = V_{A,q} q_A(\text{gauge}) \) \quad \text{with} \quad V_{A,q} V_{A,q}^\dagger = 1, \quad A = L, R, q = u, d.

The 4 unitary matrices \( V_{A,q} \) are determined by

\[
\text{diag}(m_u, m_c, m_t) = \langle \Phi \rangle \cdot \text{diag}(y_u, y_c, y_t) = \langle \Phi \rangle \cdot V_{L,u} Y_u V_{R,u}^\dagger \\
\text{diag}(m_d, m_s, m_b) = \langle \Phi \rangle \cdot \text{diag}(y_d, y_s, y_b) = \langle \Phi \rangle \cdot V_{L,d} Y_d V_{R,d}^\dagger
\]

i.e., they diagonalize the Yukawas.
insert unit matrices
\( \mathcal{L}_{SM}^{\text{yukawa}} = -\bar{U}_L \begin{pmatrix} V_{L,u}^\dagger V_{L,u} & Y_u \Phi^C \\ \end{pmatrix} Y_u \Phi^C \begin{pmatrix} V_{R,u}^\dagger V_{R,u} & U_R \end{pmatrix} + \text{down quarks.} \)

then rewrite term and split up
\( \mathcal{L}_{SM}^{\text{up-mass}} = -\bar{U}_L V_{L,u}^\dagger V_{L,u} \begin{pmatrix} V_{L,u} Y_u V_{R,u}^\dagger \Phi^C \\ \end{pmatrix} V_{R,u} U_R = -\bar{U}_L \tilde{m}_{ui} \Phi^C \tilde{U}_R. \)

The tilde basis are mass eigenstates, down quarks analogously.

What else happened under the basis change in \( \mathcal{L}_{SM} \)?

Lets look at the charged currents \( W^\pm \):
\( \bar{U}_L \gamma^\mu W_{\mu}^+ D_L = \bar{U}_L (V_{L,u}^\dagger V_{L,u}) \gamma^\mu W_{\mu}^+ (V_{L,d}^\dagger V_{L,d}) D_L \)
\( = \bar{U}_L \gamma^\mu W_{\mu}^+ V_{L,u} V_{L,d}^\dagger \tilde{D}_L; \quad \text{Since quarks mix, } V_{L,u} \neq V_{L,d}. \)
The charged current interaction gets a flavor structure by $V$

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} \left( \bar{U}_L \gamma^{\mu} W^{\mu}_L + \bar{D}_L \gamma^{\mu} W^{\mu}_L \right).$$

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}, \quad V_{13} = V_{ub} \text{ etc}$$

Via $W$ exchange is the only way to change flavor in the SM. Since CKM is known (more or less precise, see talks), in SM every quark flavor changing process can be predicted! (TH uncertainties play an important role, see talks on hadronic matrix elements). Overconstrain, fits (see talks!)
$V$ is unitary, is in general complex, and induces CP violation. $V$ has 4 physical parameters, 3 angles and 1 phase.

"PDG" parametrization (exact, fully general)

$$V = \begin{pmatrix}
    c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\
    -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\
    s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}
\end{pmatrix}$$

$s_{ij} \equiv \sin \Theta_{ij}$, $c_{ij} \equiv \cos \Theta_{ij}$. $\delta$ is the CP violating phase.

In Nature, $\delta \sim \mathcal{O}(1)$ and $V$ is hierarchical $\Theta_{13} \ll \Theta_{23} \ll \Theta_{12} \ll 1$.

Very different – large mixing angles for leptons (PMNS-Matrix):

$$\Theta_{23} \sim 45^\circ, \Theta_{12} \sim 35^\circ, \Theta_{13} \sim \mathcal{O}(10^\circ) \quad \text{all } \mathcal{O}(1) \text{ – anarchy?}$$
CP is violated!.. together with Quark Flavor

Quark mixing matrix has 1 physical CP violating phase $\delta_{CKM}$.

Verified in $B\bar{B}$ mixing

$\sin 2\beta = 0.672 \pm 0.023$  HFAG Aug 2010

$\delta_{CKM}$ is large, $O(1)$!

CPX also observed in $B$-decay

$A_{CP}(B \rightarrow K^{\pm}\pi^{\mp}) = -0.098 \pm 0.013$  HFAG Aug 2010

$\Gamma(B \rightarrow K^{+}\pi^{-}) \neq \Gamma(\bar{B} \rightarrow K^{-}\pi^{+})$
Charm is the new Beauty

\[ \Delta A_{\pi}^{\text{tagged}} = \left[ -18.2 \pm 3.2 \text{ (stat.)} \pm 0.9 \text{ (syst.)} \right] \times 10^{-4} \]

\[ \Delta A_{\mu}^{\text{tagged}} = \left[ -9 \pm 8 \text{ (stat.)} \pm 5 \text{ (syst.)} \right] \times 10^{-4} \]

- Compatible with previous LHCb results and the WA
- Combination with LHCb Run 1 gives:

\[ \Delta A_{CP} = \left( -15.4 \pm 2.9 \right) \times 10^{-4} \]

\[ CP \text{ violation observed at } 5.3\sigma \]

\[ \Delta A_{CP} = A_{CP}(D^0 \rightarrow K^+ K^-) - A_{CP}(D^0 \rightarrow \pi^+ \pi^-) \]

General Flavor Theory
SSI 2019
The CKM numerics you can memorize

\[ V \text{ is hierarchical } \Theta_{13} \ll \Theta_{23} \ll \Theta_{12} \ll 1. \] Wolfenstein parametrization: expansion in \( \lambda = \sin \Theta_C \sim 0.2, A, \rho, \eta \sim \mathcal{O}(1) \)

\[
V = \begin{pmatrix}
1 - \lambda^2/2 & +\lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \lambda^2/2 & +A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + \mathcal{O}(\lambda^4)
\]

beyond lowest order \( \bar{\rho} = \rho(1 - \lambda^2/2) \) and \( \bar{\eta} = \eta(1 - \lambda^2/2) \)

\[ V_{CKM}V_{CKM}^\dagger = 1 \]

\[ C = (0,0) \quad B = (1,0) \]

\[ V_{ud}V_{ub}^* \quad V_{cd}V_{cb}^* \quad V_{td}V_{tb}^* \]

\[ A = (\bar{\rho}, \bar{\eta}) \]

\[ \gamma \quad \beta \]

[Diagram showing the CKM matrix and its implications, with various parameters and regions highlighted.]
Neutral Currents – a window beyond SM

Neutral current gauge interactions $\gamma, Z, g$ remain unaffected by misalignment between gauge and mass bases in SM because of $\psi \rightarrow \psi_i$ (universality) since they involve the same fields, for instance:

$$\bar{U}_L \gamma^\mu A_\mu U_L = \bar{U}_L (V_{L,u}^\dagger V_{L,u}) \gamma^\mu A_\mu (V_{L,u}^\dagger V_{L,u}) U_L$$

$$= \bar{U}_L \gamma^\mu A_\mu V_{L,u} V_{L,u}^\dagger \tilde{U}_L = \bar{U}_L \gamma^\mu A_\mu \tilde{U}_L$$  nothing has happened!

Imagine a BSM $U(1)'$ with generation-dependent charges $g_i$:

$$\bar{U}_i g_i \gamma^\mu A_\mu U_i = \bar{U}_i \gamma^\mu A_\mu (V_u)_{ij} \cdot g_j (V_u^\dagger)_{jk} \tilde{U}_k$$

Consider 2 generations, $V_u$ orthogonal with mixing angle $\vartheta_u$ between 1st and 2nd generation

$$V_u = \begin{pmatrix} \cos \vartheta_u & \sin \vartheta_u \\ -\sin \vartheta_u & \cos \vartheta_u \end{pmatrix}$$

We obtain FCNC ”flavor changing neutral current” amplitudes

$$\cos \vartheta_u \sin \vartheta_u (g_1 - g_2) \bar{U}_1 \gamma^\mu A_\mu \tilde{U}_2$$
FCNC "flavor changing neutral current" $U_2 \rightarrow U_1$ drop the tilde for mass eigenstates

$$\cos \vartheta_u \sin \vartheta_u (g_1 - g_2) \bar{U}_1 \gamma^\mu A_\mu U_2$$

i) no tree-level FCNC in the SM or other models with universality, where $g_1 = g_2$ etc holds.

individual rotations $\vartheta_u, \vartheta_d$ in SM not physical, only $V = V_{Lu} V_{Ld}^\dagger$, no constraint on $V_{Ru}, V_{Rd}$.

ii) FCNCs have sensitivity to a) BSM physics and b) origins of flavor (up versus down, it could be that mixing comes only from up-sector and $\vartheta_d = 0$)
In SM neutral currents conserve flavor. However, charged currents induce FCNCs through quantum loops.

The upper figure shows an FCNC with flavor number changing in units of one, $\Delta F = 1$, as in decays, meson mixing has $\Delta F = 2$. 
Different sectors/couplings presently probed with FCNCs:

$s \to d$: $K^0 - \bar{K}^0$, $K \to \pi \nu \bar{\nu}$

$c \to u$: $D^0 - \bar{D}^0$, $\Delta A_{CP}$, $D \to \pi(\pi)\mu\mu$, $D \to \rho \gamma$

$b \to d$: $B^0 - \bar{B}^0$, $B \to \rho \gamma$, $b \to d \gamma$, $B \to \pi\mu\mu$

$b \to s$: $B_s - \bar{B}_s$, $b \to s \gamma$, $B \to K_s\pi^0 \gamma$, $b \to sll$, $B \to K(\ast)ll$ (precision, angular analysis, universality), $B_s \to \mu\mu$

$t \to c, u, l \to l'$: not observed

in red: hot topics

"leaving no stone unturned" (see talks & lectures)
Flavor Changing Neutral Currents

Let's discuss a generic SM FCNC $b \rightarrow s$ amplitude

$$
A(b \rightarrow s)_{SM} = V_{ub}V_{us}^{*}A_{u} + V_{cb}V_{cs}^{*}A_{c} + V_{tb}V_{ts}^{*}A_{t}
$$

quantum loop effect induced by weak interaction. $A_{q} = A(m_{q}^{2}/m_{W}^{2})$.  

with CKM unitarity $VV^{\dagger} = 1$, specifically $\sum_{i} V_{ib}V_{is}^{*} = 0$:

$$
A(b \rightarrow s)_{SM} = V_{tb}V_{ts}^{*}(A_{t} - A_{c}) + V_{ub}V_{us}^{*}(A_{u} - A_{c})
$$

$A$ vanishes for trivial CKM matrix or if quarks in loop are degenerate.

$$
A(b \rightarrow s)_{SM} = \lambda^{2} \left( V_{tb}V_{ts}^{*}(A_{t} - A_{c}) + V_{ub}V_{us}^{*}(A_{u} - A_{c}) \right)
$$

amplitude is dominated by first term because of lesser CKM
suppression and because the GIM (Glashow Iliopoulos Maiani) suppression inactive for tops $\frac{m_t^2 - m_c^2}{m_W^2} \sim O(1)$, whereas $\frac{m_u^2 - m_c^2}{m_W^2} \ll 1$.

We probe top properties with rare $b$-decays despite of $m_t \gg m_b$.

CP violation requires interference between the two terms with different phases; for $b \rightarrow s$, this is small, $O(\lambda^2)$.

**Generic SM FCNC** $c \rightarrow u$ amplitude

\[ A(c \rightarrow u)_{SM} = V_{cd}^* V_{ud} A_d + V_{cs}^* V_{us} A_s + V_{cb}^* V_{ub} A_b, \quad A_q = A(m_q^2/m_W^2). \]

\[ A(c \rightarrow u)_{SM} = V_{cd}^* V_{ud}(A_d - A_b) + V_{cs}^* V_{us}(A_s - A_b) \cdot A \text{ is} \]

GIM-suppressed; CP violation is suppressed by $\frac{V_{cb}^* V_{ub}}{V_{cd}^* V_{ud}} \sim \lambda^4$. Very sensitive to corrections beyond the SM. How about

\[ \Delta A^{LHCb}_{CP} \simeq -1.5 \cdot 10^{-3} ? \]
i FCNCs are induced by the weak interaction thru loops.
ii FCNCs require $V \neq 1$.
iii FCNCs vanish for degenerate intermediate quarks. Since mass splitting among up-quarks is larger than for down quarks, GIM suppression is larger with external up-type than down-type quarks.

$$B(b \to s\gamma) = 3 \cdot 10^{-4} \quad (E_\gamma > 1.6 \text{ GeV})$$

$$B(b \to s l^+ l^-) = 4 \cdot 10^{-6} \quad (m_{ll}^2 > 0.04 \text{ GeV}^2)$$

**SM:** $B(t \to cg) \sim 10^{-10}$, $B(t \to c\gamma) \sim 10^{-12}$, $B(t \to cZ) \sim 10^{-13}$, $B(t \to ch) \lesssim 10^{-13}$ Eilam, Hewett, Soni ’91/99

Lepton flavor violation (LFV) in SM arises through finite neutrino masses which is so small that LFV observables are ”null tests”.
We see that 3 mechanisms suppress FCNCs in SM: CKM, GIM and absence at tree level. New physics, which doesn't need to share these features, competes with small SM background!

FCNCs feel physics in the loops from energies much higher than the ones actually involved in the real process.

They are very useful to look for new physics, in fact, we already now a lot about new physics from FCNCs!

<table>
<thead>
<tr>
<th>$\Lambda_{NP}$ [TeV]</th>
<th>$K^0 \bar{K}^0$</th>
<th>$D^0 \bar{D}^0$</th>
<th>$B_d^0 \bar{B}_d^0$</th>
<th>$B_s^0 \bar{B}_s^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2 \cdot 10^5$</td>
<td>$5 \cdot 10^3$</td>
<td>$2 \cdot 10^3$</td>
<td>$3 \cdot 10^2$</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: The lower bounds on the scale of new physics from FCNC mixing data in TeV for arbitrary new physics at 95 % C.L.
Besides statistics, BSM reach is limited by theoretical uncertainties, dominated by hadronic physics.

Use approximate symmetries of SM to improve here: (key in charm, useful in beauty)

- GIM $D \rightarrow \pi \pi \mu^+ \mu^-$
- Isospin, or U-spin $\Delta A_{CP}$
- CP $\Delta A_{CP}$, $B_s$-mixing
- V-A , helicity $P'_5$
- LFV
- universality $R_K$, $R_{K^*}$
Construct EFT $\mathcal{H}_{\text{eff}} = -4 \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i(\mu) O_i(\mu)$ at dim 6

V,A operators $O_9 = \bar{s} \gamma_\mu P_L b \ [\bar{\ell} \gamma_5 \ell]$ , $O'_9 = \bar{s} \gamma_\mu P_R b \ [\bar{\ell} \gamma_\mu \ell]$
$O_{10} = \bar{s} \gamma_\mu P_L b \ [\bar{\ell} \gamma_5 \gamma_5 \ell] , \quad O'_{10} = \bar{s} \gamma_\mu P_R b \ [\bar{\ell} \gamma_\mu \gamma_5 \ell]$

S,P operators $O_S = \bar{s} P_R b \ [\bar{\ell} \ell]$ , $O'_S = \bar{s} P_L b \ [\bar{\ell} \ell]$ , \quad ONLY $O_9, O_{10}$ are SM, all other BSM
$O_P = \bar{s} P_R b \ [\bar{\ell} \gamma_5 \ell] , \quad O'_P = \bar{s} P_L b \ [\bar{\ell} \gamma_5 \ell]$

and tensors $O_T = \bar{s} \sigma_{\mu\nu} b \ [\bar{\ell} \sigma^{\mu\nu} \ell] , \quad O_{T5} = \bar{s} \sigma_{\mu\nu} b \ [\bar{\ell} \sigma^{\mu\nu} \gamma_5 \ell]$

lepton specific $C_i O_i \rightarrow C_i^{\ell} O_i^{\ell}, \ell = e, \mu, \tau$
Lepton Non-universality?

\[
\begin{pmatrix}
\nu_e \\
e
\end{pmatrix},
\begin{pmatrix}
\nu_\mu \\
\mu
\end{pmatrix},
\begin{pmatrix}
\nu_\tau \\
\tau
\end{pmatrix}
\]

Anomalies in semileptonic $B$-meson decays:

\[
R_K = \frac{\mathcal{B}(B \to K\mu\mu)}{\mathcal{B}(B \to K\text{ee})} \quad 2.6\sigma \quad \text{(LHCb’14,19)}
\]

\[
R_{K^*} = \frac{\mathcal{B}(B \to K^{*}\mu\mu)}{\mathcal{B}(B \to K^{*}\text{ee})} \quad 2.6\sigma \quad \text{(LHCb’17)}
\]

\[
R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)} \quad \sim 2.7\sigma \ (D^*), \sim 2\sigma \ (D)
\quad \text{(LHCb’15,B-factories)}
\]
LNU in $b \to s$ FCNCs

\[
R_H = \frac{\mathcal{B}(B \to H_{\mu\mu})}{\mathcal{B}(B \to H_{ee})}, \quad H = K, K^*, X_s, \Phi, \ldots
\]

In models with lepton universality (incl. SM): $R_H = 1 + \text{tiny}$ \cite{GH, Kruger03}

<table>
<thead>
<tr>
<th>LHCb</th>
<th>SM</th>
</tr>
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<tbody>
<tr>
<td>$\mathcal{B}(B \to K_{\mu\mu})_{[1,6]}$</td>
<td>$(1.21 \pm 0.09 \pm 0.07) \cdot 10^{-7}$</td>
</tr>
<tr>
<td>$\mathcal{B}(B \to K_{ee})_{[1,6]}$</td>
<td>$(1.56^{+0.19+0.06}_{-0.15-0.04}) \cdot 10^{-7}$</td>
</tr>
<tr>
<td>$R_K</td>
<td>_{[1,6]}$</td>
</tr>
</tbody>
</table>
\( \psi_i \) may be more different than we thought

**model space 2002**

2002: top-down models  plot from hep-ph/0207121

2018,19: \( U(1) \)-extensions, leptoquarks,...

theory activities how to get these from UV-models 1708.06450, 1708.06350, 1706.05033, 1808.00942 .. see talks during this school!
We are seeing $\sim 2.6\sigma$ hints of new physics in $b \to sll$, LNU between $e$’s and $\mu$’s in both observables $R_K$ and $R_{K^*}$ LHCb ’14, ’17,

$$R_H = \frac{B(\bar{B} \to \bar{H} \mu \mu)}{B(\bar{B} \to \bar{H} e e)}, \text{ same cuts } e \text{ and } \mu, \quad H = K, K^*, X_s, \ldots$$

Lepton-universal models (incl. SM): $R_H = 1 + \text{tiny}$ GH, Krüger, hep-ph/0310219

How can we go on, consolidate and decipher this effect?

1. Which operators are responsible for the deviation? 1411.4773

2. BSM in electrons, or muons, or in both?

3. Side effects from flavor: LFV, $\tau$’s, or $SU(2)$: $\nu$’s 1411.0565, 1412.7164, 1503.01084 Charm and Kaons

4. Collider implications (leptoquarks!)