FLAVOR THEORY 2020 and OUTLOOK

Having fun with leptons: B-anomalies and more

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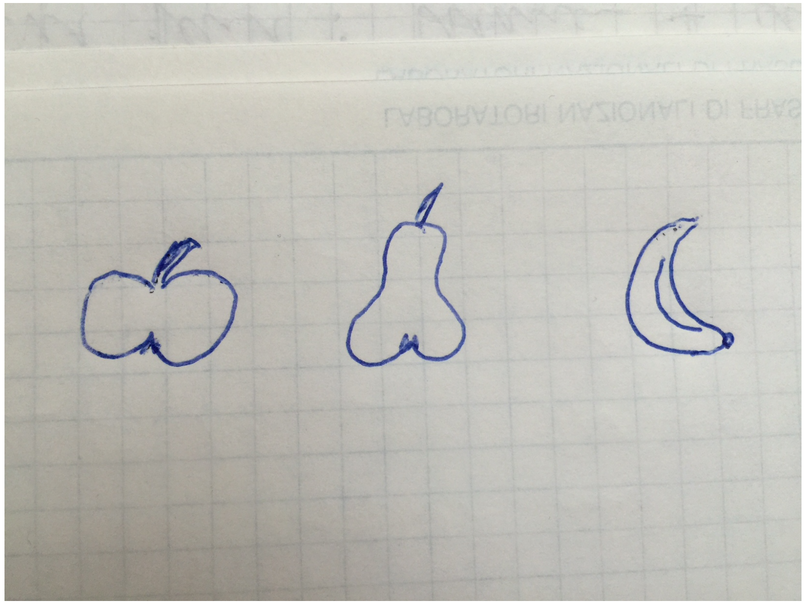
Supported by DFG research Unit FOR 1873 and Federal Ministry for Education and Research (BMBF)



the same, yet not the same

Yukawa coupling Y to Higgs in $\mathcal{L}_{SM} = -\bar{\psi} Y \psi H + ...$ is a 3×3 matrix.

$$
\begin{aligned}
Y_u &\sim \begin{pmatrix} 10^{-5} & -0.002 & 0.008 + i\,0.003 \\ 10^{-6} & 0.007 & -0.04 \\ 10^{-8} + i\,10^{-7} & 0.0003 & 0.94 \end{pmatrix} \\
Y_d &\sim \text{diag}\left(10^{-5}, 5 \cdot 10^{-4}, 0.025\right) \\
Y_e &\sim \text{diag}\left(10^{-6}, 6 \cdot 10^{-4}, 0.01\right)
\end{aligned}
$$

very peculiar structure versus universality in gauge interactions

$\psi \to \psi_i,\ i = 1, 2, 3$

..... the flavor puzzle starts into yet another season in 2020 plus. Merlo

– angular distributions $b \to s\mu\mu$, $b \to s\gamma$ ”the global fit” Neshatpour

– R_{K,K^*} $b \to s\mu\mu$ vs $b \to see$

– R_{D,D^*} $b \to c\tau\nu$ vs $b \to c\mu\nu$

– $Br(K_L \to \pi^0 \nu\bar{\nu})$ Soni

– $(g-2)$ of muon and electron Giusti

common denominator: ”something (in low energy measurements) with leptons”

”anomalies” require improved data – more statistics, cross checks, control measurements, e.g. $b \to see$ angular distributions, more universality ratios R_{XYZ}.

from theory:

– SM background control; preciser hadronic matrix elements Giusti, Witzel; preciser parametric input, CKM, masses Bona

– interpretation, model-independently (fits, SMEFT) Neshatpour, Silva, Sumensari

– BSM models, collider searches Becirevic, Mukherjee

test the SM

probe new physics models

progress towards/give feedback on flavor puzzle

the present flavor anomalies give directions for all of these.

moving on with lepton universality tests and more

– testing lepton universality and charged lepton flavor conservation with dineutrino modes

– explaining $(g-2)_{e,\mu}$ with lepton universal BSM

universality tests with $q \to q' \nu \bar{\nu}$

Leading semileptonic 4-fermion operators at scale above m_W (SMEFT) contributing to dineutrino modes $q \to q' \nu \bar{\nu}$

$$\mathcal{L}_{\text{eff}} \supset \frac{C_{\ell q}^{(1)}}{v^2} \bar{Q} \gamma_\mu Q \, \bar{L} \gamma^\mu L + \frac{C_{\ell q}^{(3)}}{v^2} \bar{Q} \gamma_\mu \tau^a Q \, \bar{L} \gamma^\mu \tau^a L + \frac{C_{\ell u}}{v^2} \bar{U} \gamma_\mu U \, \bar{L} \gamma^\mu L + \frac{C_{\ell d}}{v^2} \bar{D} \gamma_\mu D \, \bar{L} \gamma^\mu L \, . \quad (1)$$

$SU(2)_L \times U(1)_Y$ gauge invariance links up and down quarks, $Q = (u, d)$ and left-handed neutrinos and charged leptons $L = (\nu, \ell)$.

$$C_L{}^U = K_L{}^D = C_{\ell q}^{(1)} + C_{\ell q}^{(3)} \, , \quad C_R^U = K_R^U = C_{\ell u} \, , C_L^D = K_L^U = C_{\ell q}^{(1)} - C_{\ell q}^{(3)} \, , \quad C_R^D = K_R^D = C_{\ell d} \, .$$

contribution to $c \to u \nu \bar{\nu}$ (C_L^U) identical to $s \to d \ell \bar{\ell}$ (K_L^D) etc

L,R denotes left or right handed quark currents; only SM-like neutrinos.

Since the neutrino flavors are not tagged, the branching ratio, say for charm, is obtained by an incoherent sum

$$\mathcal{B}\left(c \to u\,\nu\bar{\nu}\right) = \sum_{i,j} \mathcal{B}\left(c \to u\,\nu_i\bar{\nu}_j\right)$$

in terms of Wilson coefficients

$$\mathcal{B}\,(c \to u\,\nu\bar{\nu}) = \sum_{i,j} \mathcal{B}\,(c \to u\,\nu_i\bar{\nu}_j) \propto \sum_{i,j} |\mathcal{C}_L^{Uij}|^2 + |\mathcal{C}_R^{Uij}|^2$$

which can be written as a trace

$$\mathcal{B}\,(c \to u\,\nu\bar{\nu}) \propto \sum_{i,j} |\mathcal{C}_L^{Uij}|^2 + |\mathcal{C}_R^{Uij}|^2 = tr\Big[\mathcal{C}_L^U\,\mathcal{C}_L^{U\dagger} + \mathcal{C}_R^U\,\mathcal{C}_R^{U\dagger}\Big]$$

and apparently PMNS rotations W between gauge and mass eigenstates drop out due to unitarity.

Using SMEFT $SU(2)_L \times U(1)_Y$ gauge invariance follows

$\mathcal{C}_L^U = W^\dagger\,\mathcal{K}_L^D\,W + \mathcal{O}(\lambda), \quad \mathcal{C}_R^U = W^\dagger\,\mathcal{K}_R^U\,W$ and

$$\mathcal{B}\,(c \to u\,\nu\bar{\nu}) \propto \sum_{\nu=i,j} \left(|\mathcal{C}_L^{Uij}|^2 + |\mathcal{C}_R^{Uij}|^2 \right) = tr\left[\mathcal{C}_L^U\,\mathcal{C}_L^{U\dagger} + \mathcal{C}_R^U\,\mathcal{C}_R^{U\dagger} \right]$$

$$= tr\left[\mathcal{K}_L^D \mathcal{K}_L^{D\dagger} + \mathcal{K}_R^U \mathcal{K}_R^{U\dagger} \right] + \mathcal{O}(\lambda) = \sum_{\ell=i,j} \left(|\mathcal{K}_L^{Dij}|^2 + |\mathcal{K}_R^{Uij}|^2 \right) + \mathcal{O}(\lambda)\,,$$

$\mathcal{K}_L^{Dij}$ mass eigenstates charged leptons in $s \to d\ell^{i+}\ell^{j-}$
$\mathcal{K}_R^{Uij}$ mass eigenstates charged leptons in $c \to u\ell^{i+}\ell^{j-}$

lhs: neutrino branching ratio, rhs: couplings to charged leptons

$$\mathcal{B}\,(c \to u\,\nu\bar{\nu}) \propto \sum_{\nu=i,j} \left(|\mathcal{C}_L^{U\,ij}|^2 + |\mathcal{C}_R^{U\,ij}|^2\right) = tr\Big[\mathcal{C}_L^U\,\mathcal{C}_L^{U\dagger} + \mathcal{C}_R^U\,\mathcal{C}_R^{U\dagger}\Big]$$

$$= tr\left[\mathcal{K}_L^D \mathcal{K}_L^{D\dagger} + \mathcal{K}_R^U \mathcal{K}_R^{U\dagger}\right] + \mathcal{O}(\lambda) = \sum_{\ell=i,j} \left(|\mathcal{K}_L^{D ij}|^2 + |\mathcal{K}_R^{U ij}|^2\right) + \mathcal{O}(\lambda)\ ,$$

we obtain upper limits on dineutrino branching ratios from upper limits of charged dilepton modes 2007.05001 depending on scenarios

i) $\mathcal{K}_{L,R}^{ij} \propto \delta_{ij}$, that is, *lepton-universality* (LU).

ii) $\mathcal{K}_{L,R}^{ij}$ are diagonal, that is, *charged lepton flavor conservation* (cLFC)

iii) $\mathcal{K}_{L,R}^{ij}$ arbitrary.

universality tests with $q \to q'\nu\bar\nu$

		ee	$\mu\mu$	$\tau\tau$	$e\mu$	$e\tau$	$\mu\tau$
$s \to d$	$\lvert\bar{\mathcal{K}}_L^{D\ell\ell'}\rvert$	3.5	1.9	6.7	1.8	5.0	5.3
$c \to u$	$\lvert\bar{\mathcal{K}}_R^{U\ell\ell'}\rvert$	2.9	1.6	5.6	1.5	4.2	4.3

Upper limits on $|\Delta s| = |\Delta d| = 1$ and $|\Delta c| = |\Delta u| = 1$ leptonic couplings $\bar{\mathcal{K}}_{L,R}$ from high–p_T Fuentes-Martin et al 2020 ,Angelescu et al 2020. LFV-bounds are quoted as charge-averaged, $\sqrt{|\bar{\mathcal{K}}^{\ell^+\ell'^-}|^2 + |\bar{\mathcal{K}}^{\ell^-\ell'^+}|^2}$.

$$\mathcal{B}\,(c \to u\,\nu\bar\nu) \propto 3\,R^{\mu\mu} \lesssim 18\,, \quad \text{(LU)} \tag{2}$$

$$\mathcal{B}\,(c \to u\,\nu\bar\nu) \propto R^{ee} + R^{\mu\mu} + R^{\tau\tau} \lesssim 103\,, \quad \text{(cLFC)} \tag{3}$$

$$\mathcal{B}\,(c \to u\,\nu\bar\nu) \propto R^{ee} + R^{\mu\mu} + R^{\tau\tau} + 2(R^{e\mu} + R^{e\tau} + R^{\mu\tau}) \lesssim 294. \tag{4}$$

dimuons are the most stringent ones and provide the LU-limit. Lepton flavor limit is violated if measured branching ratio is too large! Upper limits data-driven, and evolve with charged lepton data.

$h_c \to F$	$\mathcal{B}^{\rm max}_{\rm LU}$ $[10^{-7}]$	$\mathcal{B}^{\rm max}_{\rm cLFC}$ $[10^{-6}]$	$\mathcal{B}^{\rm max}$ $[10^{-6}]$
$D^0 \to \pi^0$	3.2	1.8	5.2
$D^+ \to \pi^+$	13	7.4	21
$D_s^+ \to K^+$	2.4	1.4	3.9
$D^0 \to \pi^0\pi^0$	1.5	0.9	2.5
$D^0 \to \pi^+\pi^-$	1.5	0.9	2.4
$D^0 \to K^+K^-$	0.02	0.01	0.03
$\Lambda_c^+ \to p^+$	9.7	5.6	16
$\Xi_c^+ \to \Sigma^+$	19	11	31
$D^0 \to X_u$	6.3	3.6	10
$D^+ \to X_u$	16	9.2	26
$D_s^+ \to X_u$	7.7	4.4	13

Model-independent upper limits on $\mathcal{B}^{\rm max}_{\rm LU}$, $\mathcal{B}^{\rm max}_{\rm cLFC}$, $\mathcal{B}^{\rm max}$ from (2), (3) and (4), respectively. 2007.05001

In reach of Belle II, BES III and high-luminosity Z-factories.

branching ratio	$D^0 \to \pi^+\pi^-\mu^+\mu^-$	$D^0 \to K^+K^-\mu^+\mu^-$	$D^0 \to \pi^+\pi^-e^+e^-$	$D^0 \to K^+K^-e^+e^-$
LHCb 17	$(9.64 \pm 1.20) \times 10^{-7}$	$(1.54 \pm 0.33) \times 10^{-7}$	–	–
BESIII 18	–	–	$< 0.7 \times 10^{-5}$	$< 1.1 \times 10^{-5}$
resonant	$\sim 1 \times 10^{-6}$	$\sim 1 \times 10^{-7}$	$\sim 10^{-6}$	$\sim 10^{-7}$
non-resonant	$10^{-10} - 10^{-9}$	$\mathcal{O}(10^{-10})$	$10^{-10} - 10^{-9}$	$\mathcal{O}(10^{-10})$

$$R^D_{P_1P_2} = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} d\mathcal{B}/dq^2(D \to P_1P_2\mu^+\mu^-)}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} d\mathcal{B}/dq^2(D \to P_1P_2e^+e^-)}$$ with same cuts $q^2_{\rm min} \geq 4m^2_\mu$

full q^2	SM	BSM	LQ	hi q^2 SM	LQs	lo q^2 SM	BSM
$R^D_{\pi\pi}$	$1.00 \pm \mathcal{O}(\%)$	0.85 ...0.99	SM-like	$1.00 \pm \mathcal{O}(\%)$	0.7 ...4.4		
R^D_{KK}	$1.00 \pm \mathcal{O}(\%)$	SM-like	SM-like	NA	NA	$0.83 \pm \mathcal{O}(\%)$	0.60..0.87

O(1)BSM effects in $R^D_{\pi\pi}$ above Φ; small BSM effects in R^D_{KK} below η.

Naive ratios $\bar{R}^{D\,exp}_{\pi^+\pi^-} \gtrsim 0.1$, $\bar{R}^{D\,exp}_{K^+K^-} \gtrsim 0.01$ based on different cuts and about one order of magnitude away from SM, are model-dependent.

The benefits of doing the same with different leptons

Anomalous magnetic moments of electron and muon simultaneously

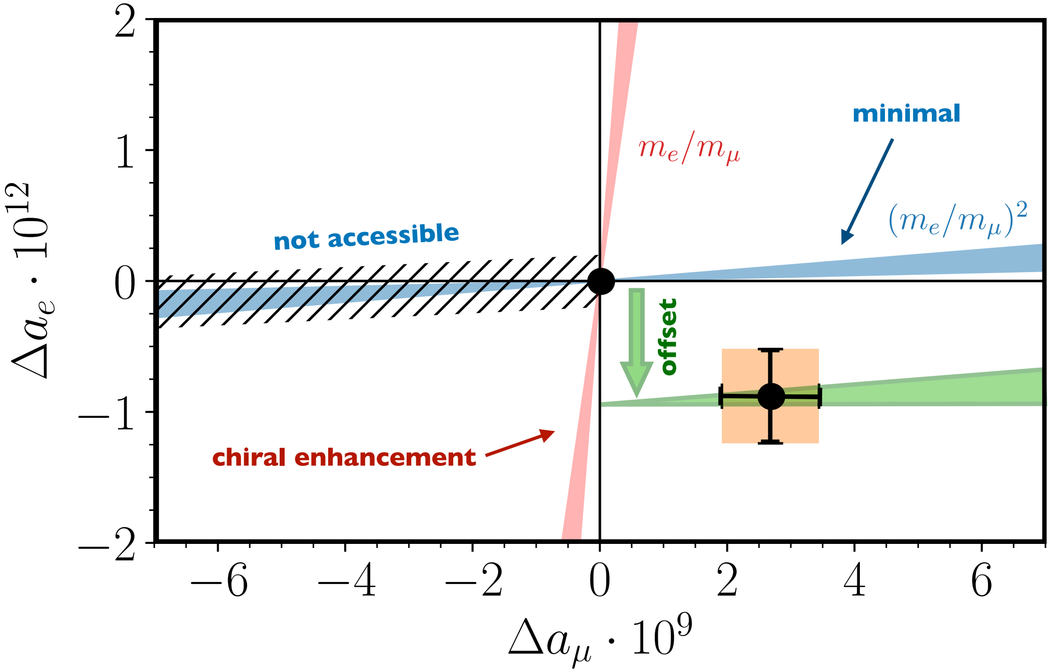
Marciano, Davoudiasl, Hoferichter, Crivellin, Gardner, ...

GH, Hormigos-Feliu, Litim, Steudtner

$$\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 268(63)(43) \cdot 10^{-11} \quad (3.5\sigma)$$

$$\Delta a_e \equiv a_e^{\text{exp}} - a_e^{\text{SM}} = -88(28)(23) \cdot 10^{-14} \quad (2.4\sigma)$$

$\frac{\Delta a_e}{\Delta a_\mu} \neq \frac{m_e^2}{m_\mu^2}$ neither sign nor size, flavor interesting!

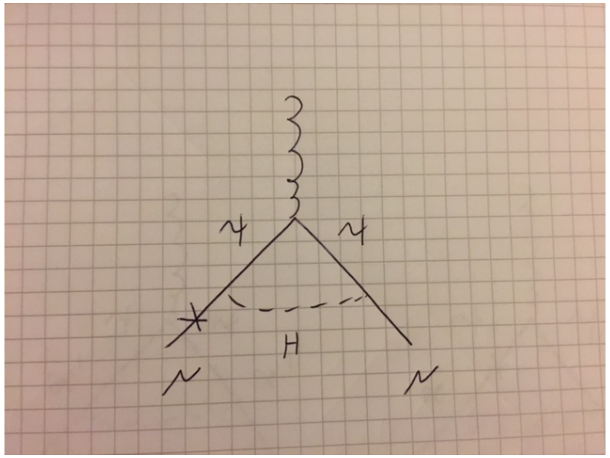


Leading contributions to $\Delta a_{e,\mu}$ from MFV (blue band) and chiral enhancement (red band), which, in combination (green band), explain the electron and muon data (cross) simultaneously.

no lepton universality breaking or flavor violation *required*

Consider vector-like leptons with mixed Yukawas for Δa_μ: $\kappa \bar{L} H \psi$

Giudice, Wise, Ligeti, ..

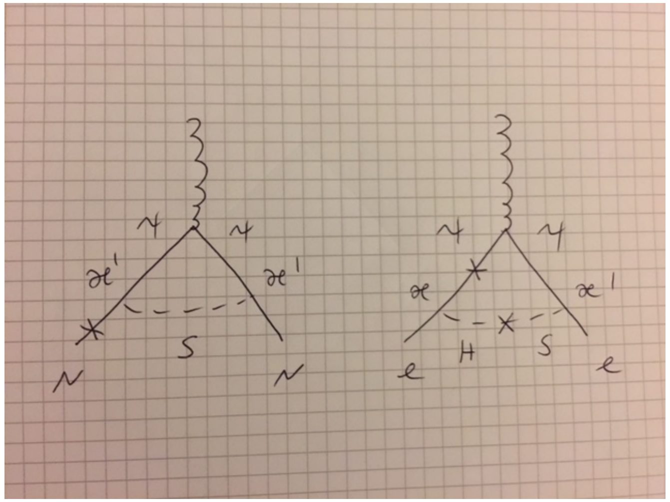


problems: Δa_e unaccounted, $Z\ell\ell$ bounds and LFV (fermions mix)

$(g-2)_{e,\mu}$ **together**

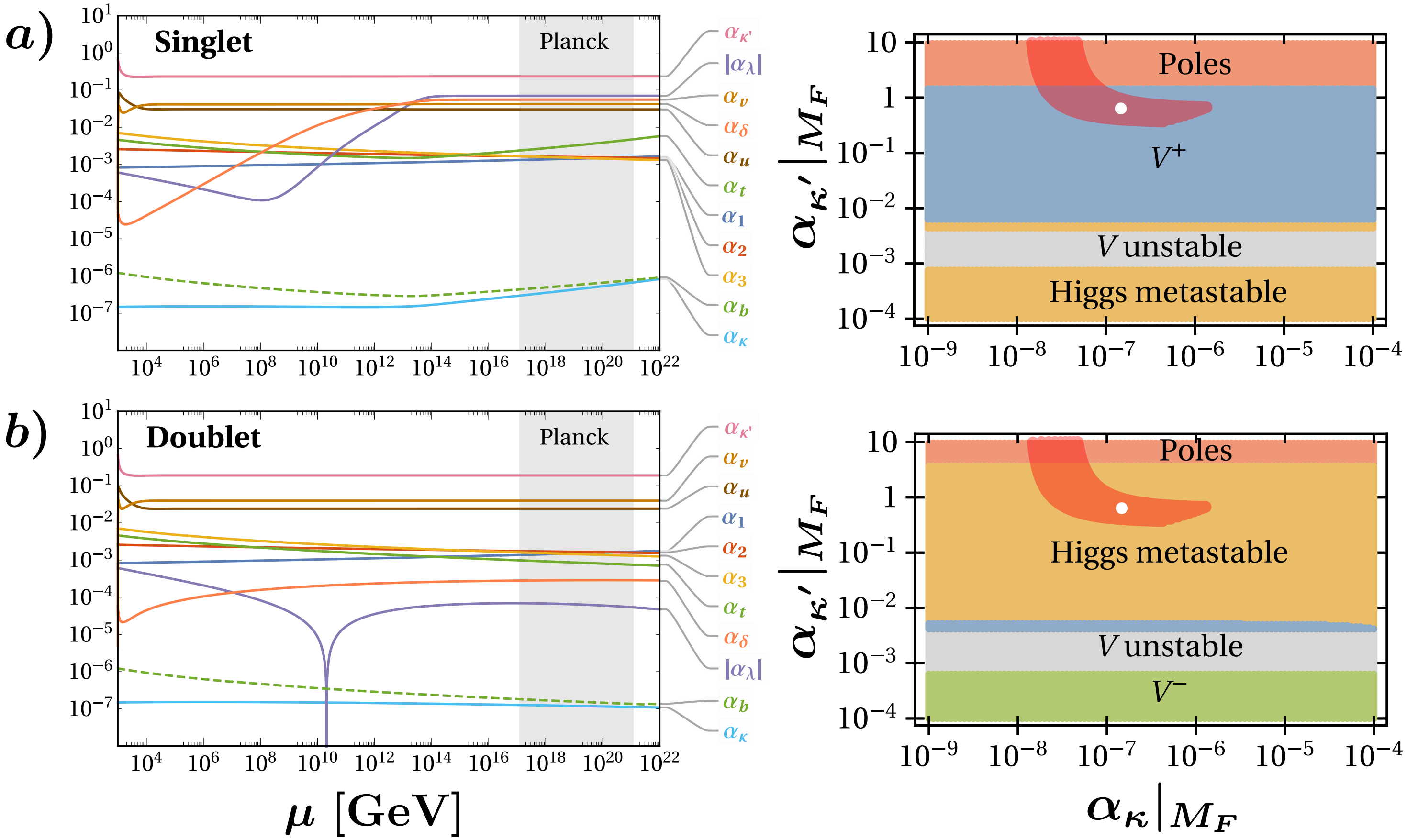
Straight-forward explanation with enlarged BSM-flavor sector (VLLs and scalar singlets with Higgs portal) $\kappa \bar{L} H \psi + \kappa' E S \psi + \delta S^\dagger S H^\dagger H$

$\Delta a_\mu \sim \frac{m_\mu^2}{M_\psi^2} \frac{\kappa'^2}{16\pi^2}$ (quadratic), $\Delta a_e \sim \frac{m_e}{M_\psi} \frac{\kappa \kappa' \delta}{16\pi^2}$ (linear)



Flavor scalar sector instrumental – appears "for free" in asymptotically safe model building, where couplings stay safe (no poles, instabilities) up to the Planck scale and beyond 1910.14062 and wip

model building with Planck safety



right plots: TeV-BSM parameters with Planck features and red banana: $g-2$, V^+: universal groundstate, V^-: vacuum singles out electrons– spontaneous breakdown of universality

Summary

- Current anomalies $R_K, R_{K^*}, R_D, R_{D^*}$ in semileptonic B-meson decays hint at violation of lepton-universality – and therefore breakdown of standard model.
  Huge impact on model-building already (leptoquarks, Z')

- Future data – LNU updates and others $R_\Phi, R_{Xs}..., B \to K^* ee$ – from LHCb and from Belle II are eagerly awaited.

- LNU tests in charm decays are already happening ($R^D_{\pi\pi} \gtrsim 0.1$). Tests with $D \to \pi\ell\ell$ promising, huge BSM effects possible.

- New ideas for LNU and cLFC tests with dineutrino modes suitable for Belle II, BES III and Z-factory.

- SM deviations in AMMs of electron (2.4 σ) and muon (3.5 σ) suggest flavor and Higgs portal. Explanation with enlarged BSM-flavor sector for free in asymptoticaly safe model building.

- Flavor broader and more exciting than ever –stay tuned