Flavor and lepton universality violation phenomena in F-theory inspired GUTs

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Outline

- Intro & Motivation
- Non-universal $U(1)$'s from F-theory
- Models without exotics
- Models with VL exotics
- Summary

Intro & motivation

R_K anomalies

⋆ Experimental hints of odd behaviour in the way B-**meson decays** into K mesons [Phys.Rev.Lett. 113 (2014)151601], [JHEP 08 (2017) 055], [Phys. Rev. Lett. 122, 191801 (2019)]

⋆ Important observables are ratios of the form

$$R_K \equiv \frac{\mathbf{BR}(B^+ \to K^+\mu^+\mu^-)}{\mathbf{BR}(B^+ \to K^+e^+e^-)} \, , \quad R_{K^*} \equiv \frac{\mathbf{BR}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathbf{BR}(B^0 \to K^{*0}e^+e^-)}$$

⋆ According to the SM, charged leptons have identical EW interaction strengths:

$$\textbf{lepton universality} \implies R_K^{SM} \approx 1$$

⋆ **LHCb 2021 update:** [arXiv:2103.11769]

↘ ↙

$$\boxed{R_K^{LHCb} = 0.846^{+0.044}_{-0.041}}$$

⋆ The results suggest a 3.1σ deviation of the SM predictions

$\implies$ ...evidence of **lepton universality violation.**

Theoretical explanations

⋆ Explanation of the results requires **New Physics (NP)** beyond the SM.

⋆ NP contributions in to $b \to s l \bar{l}$ transition.

Effective Field theories $\longrightarrow$

SM & BSM contributions parametrized in terms of the effective Hamiltonian:

$$H_{eff}^{b\to sll} = -\frac{4G_F}{\sqrt{2}}\frac{e^2}{16\pi^2}(V_{tb}V_{ts}^*) \times \sum_{k=9,10}\left(C_k^{ll}\mathcal{O}_k^{ll} + C_k^{\prime ll}\mathcal{O}_k^{\prime ll}\right)$$

$\mathcal{O}_k^{ll}$: fermion operators

C_k^{ll}, $C_k^{\prime ll}$ are Wilson coefficients.

$\Downarrow$

[Updated Global Fit: 2103.13370]

[G.D'Amico et al. ,1704.05438]

$\longleftarrow$ Popular candidate models :

- **Leptoquarks**
- **Non-universal** $Z^{'}$
- Vector-like (VL) exotics
- Composite Higgs model
- MSSM+RPV

$\Downarrow$

Extra gauge bosons, VL exotics, Leptoquarks usually appear in **String Theory** inspired models.

$\Downarrow$

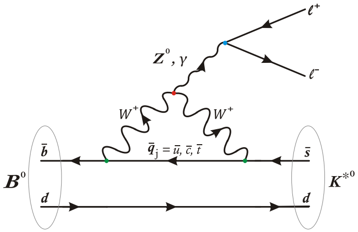
We will investigate the properties of non universal $U(1)$'s in F-theory inspired GUTs

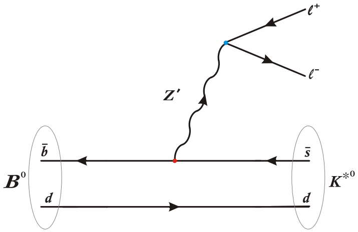
[King, Leontaris, M.Romao]
[AK, Leontaris, Tavellaris,Vlachos]

Non-universal Z'

In the SM, $b \to s l \bar{l}$ processes are suppressed ↘

In the presence of a Z' gauge boson **tree-level** contributions may occur ↙





⋆ A new Z' gauge boson will be related with **an extra $U(1)'$ symmetry**

⋆ Neutral current $\longrightarrow$ $J^\mu = \bar{f}_L \gamma^\mu Q'_{f_L} f_L + \bar{f}_R \gamma^\mu Q'_{f_R} f_R$ with $Q'_{f_L} \equiv V_{f_L} q'_{f_L} V^\dagger_{f_L}$, $Q'_{f_R} \equiv V_{f_R} q'_{f_R} V^\dagger_{f_R}$ where q' are diagonal 'charge' matrices.

[P. Langacker, 0801.1345]

⋆ If the quarks/leptons have non-universal charges under the extra $U(1)'$ then Q's are non-diagonal $\Longrightarrow$ FCNC's appear in the theory.

[P. Langacker & M. Plumacher]

Flavor violation constraints

⋆ While in the SM flavor violation processes are suppressed, in non-universal Z' models substantially larger tree-level contributions may be allowed.

⋆ An explanation of the R_K-anomalies has to be consistent with tight flavor violation constraints:

- Neutral **meson mixing**: $(\mathbf{B}-\bar{\mathbf{B}})$, $(\mathbf{K}-\bar{\mathbf{K}})$, $(D-\bar{D})$
- Leptonic Meson Decays : $P^0 \to l_i \bar{l}_j$
- **Three body lepton decays**: $l_i \to l_j l_k \bar{l}_j$ (like $\mu^- \to \mathbf{e}^- \ \mathbf{e}^- \ \mathbf{e}^+$)
- Radiative decays of the form: $l_i \to l_j \gamma$ (like $\mu \to \mathbf{e}\ \gamma$)

$\Longrightarrow$ *Minimal requirement...* Z' couplings to 1^{st} and 2^{rd} Quarks families are universal in order to avoid the tight bounds from $(K-\bar{K})$ mix effects

$[PDG] \to \Delta M_K^{exp} \simeq 3.482 \times 10^{-15}\ GeV$

Non-universal $U(1)$'s from F-theory

F-theory

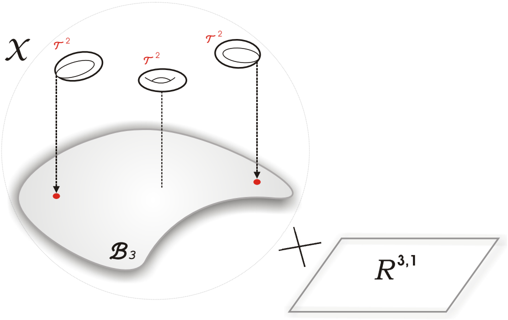
⋆ **'Geometrisation' of Type II-B superstring** *[Vafa 1996]*

• Take the 6-d compact space to be CY 3-fold base B_3.

• Associate a torus with modulus $\tau = C_0 + \imath/g_s$ at each point of B_3.

$$\Downarrow$$

Internal space elliptically fibered **CY** 4-fold $\mathcal{X}$ over B_3



↪ F-theory defined on the background $\mathcal{R}^{3,1} \times \mathcal{X}$ ↩

Singularities

⋆ Fibration is described by the Weierstraß Equation (WE)

$$y^2 = x^3 + f(z)\,x + g(z)$$

x, y, z complex coordinates of B_3.
$f(z)$, $g(z) \longmapsto 8\,\&\,12$ degree polynomials in z.

⋆ For each point of B_3, (WE) describes a torus labeled by z.

⋆ The fiber degenerates at the zeros of the discriminant

$$\Delta = 4\,f^3 + 27\,g^2$$

$$\Downarrow$$

$\Delta = 0 \implies$ singularity of internal mainfold

Singularities and Symmetry

⋆ Type of singularity is specified by the vanishing order of f(z), g(z) polynomials and the discriminant Δ

⋆ Singularities are classified in terms of $\mathcal{ADE}$ Lie groups. [*Kodaira 1968*]

⋆ Gauge degrees of freedom on 7-branes realized in terms of $\mathcal{ADE}$ singularities, in codim-1 in the base B_3: divisor S_{GUT}

$$\boxed{\mathcal{X}\text{-Singularities} \longrightarrow \text{Gauge Symmetry}}$$

⋆ The maximum symmetry enhancement is $E_8 \supset E_6, SO(10), SU(5)$.

⋆ Tate's description emphasizes the local properties of the singularities. [*Tate 1975*]

Example: Tate's Equation for $SU(5)$:

$$y^2 = x^3 + b_0 z^5 + b_2 x z^3 + b_3 y z^2 + b_4 x^2 z + b_5 x y$$

A Class of ‘semi-local’ constructions

⋆ F-GUTs embedded in maximal exceptional group: $E_8 \to \mathbf{G_{GUT}} \times \mathcal{C}$

Present choice: embedding of SM in minimal GUT $\longrightarrow$ SU(5):

$$\begin{aligned} E_8 &\to SU(5) \times SU(5)_\perp \to \mathcal{C} = SU(5)_\perp \\ &\to SU(5) \times U(1)^4 \end{aligned}$$

⋆ *Spectral Cover description*: $SU(5)_\perp \to$ described by the 5^{th} degree polynomial:

$$C_5 = \sum_{k=0}^{5} b_k s^{5-k} = b_5 + b_4 s + b_3 s^2 + b_2 s^3 + b_1 s^4 + b_0 s^5$$

⋆ The five roots $t_{i=1,2,3,4,5}$ of C_5 identified as the Cartan roots of $SU(5)_\perp$

⋆ For $SU(N)$ groups: $\Sigma t_i = 0 \Longrightarrow b_1 = 0$

⋆ $t(b_k)$ solutions undergoes monodromies: *Simplest case* $\to$ Z_2 monodromy $\Rightarrow t_1 \longleftrightarrow t_2$

$\Updownarrow$

reduces $U(1)^4 \to U(1)^3$

Assumed Model: SU(5) *with* $t_1 \leftrightarrow t_2$ *monodromy*

⋆ A non-universal $U(1)'$ should be consistenly embedded in the covering group E_8

⋆ choosing a convenient basis for $U(1)_i$'s ⊥ to $SU(5)$:

$$
\begin{aligned}
E_8 &\rightarrow E_6 \times U(1)_\perp^2 & (1)\\
&\rightarrow SO(10) \times U(1)_\psi \times U(1)_\perp^2 & (2)\\
&\rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi \times U(1)_\perp^2 . & (3)
\end{aligned}
$$

Unbroken generators after *imposing a* Z_2 *monodromy* :

$$
\begin{aligned}
Q_\chi &\propto diag[-1,-1,-1,-1,4] \ \in E_6\\
Q_\psi &\propto \mathrm{diag}[1,1,1,-3,0] \ \in \mathrm{E}_6\\
Q_\perp &\propto \mathrm{diag}[1,1,-2,0,0] & (4)
\end{aligned}
$$

⋆ $U(1)'$ must be a combination of unbroken generators:

$$Q' = c_1 Q_\chi + c_2 Q_\psi + c_3 Q_\perp$$

⋆ Q' must respect anomaly cancellation conditions

⋆ c_i - coefficients subject to normalization condition: $\sum_{i=1,2,3} c_i^2 = 1$

General properties of an F-theory $SU(5) \times U(1)'$ model

Matter Curve	Q'	N_Y	M	SM Content
$\Sigma_{10_{1,\pm t_1}}$	$\frac{10\sqrt{3}c_1+5\sqrt{6}c_2+3\sqrt{10}c_3}{60}$	$-N$	m_1	$m_1 Q + (m_1+N)u^c + (m_1-N)e^c$
$\Sigma_{10_{2,\pm t_3}}$	$\frac{-20\sqrt{3}c_1+5\sqrt{6}c_2+3\sqrt{10}c_3}{60}$	N_7	m_2	$m_2 Q + (m_2-N_7)u^c + (m_2+N_7)e^c$
$\Sigma_{10_{3,\pm t_4}}$	$\frac{\sqrt{10}c_3-5\sqrt{6}c_2}{20}$	N_8	m_3	$m_3 Q + (m_3-N_8)u^c + (m_3+N_8)e^c$
$\Sigma_{10_{4,\pm t_5}}$	$-\sqrt{\frac{2}{5}}c_3$	N_9	m_4	$m_4 Q + (m_4-N_9)u^c + (m_4+N_9)e^c$
$\Sigma_{5_{1,(\pm 2t_1)}}$	$-\frac{c_1}{\sqrt{3}}-\frac{c_2}{\sqrt{6}}-\frac{c_3}{\sqrt{10}}$	N	M_1	$M_1\overline{d^c} + (M_1+N)\overline{L}$
$\Sigma_{5_{2,\pm(t_1+t_3)}}$	$\frac{5\sqrt{3}c_1-5\sqrt{6}c_2-3\sqrt{10}c_3}{30}$	$-N$	M_2	$M_2\overline{d^c} + (M_2-N)\overline{L}$
$\Sigma_{5_{3,\pm(t_1+t_4)}}$	$-\frac{c_1}{2\sqrt{3}}+\frac{c_2}{\sqrt{6}}-\frac{c_3}{\sqrt{10}}$	$-N$	M_3	$M_3\overline{d^c} + (M_3-N)\overline{L}$
$\Sigma_{5_{4,\pm(t_1+t_5)}}$	$\frac{-10\sqrt{3}c_1-5\sqrt{6}c_2+9\sqrt{10}c_3}{60}$	$-N$	M_4	$M_4\overline{d^c} + (M_4-N)\overline{L}$
$\Sigma_{5_{5,\pm(t_3+t_4)}}$	$\frac{c_1}{\sqrt{3}}+\frac{c_2}{\sqrt{6}}-\frac{c_3}{\sqrt{10}}$	N_7+N_8	M_5	$M_5\overline{d^c} + (M_5+N_7+N_8)\overline{L}$
$\Sigma_{5_{6,\pm(t_3+t_5)}}$	$\frac{20\sqrt{3}c_1-5\sqrt{6}c_2+9\sqrt{10}c_3}{60}$	N_7+N_9	M_6	$M_6\overline{d^c} + (M_6+N_7+N_9)\overline{L}$
$\Sigma_{5_{7,\pm(t_4+t_5)}}$	$\frac{5\sqrt{6}c_2+3\sqrt{10}c_3}{20}$	N_8+N_9	M_7	$M_7\overline{d^c} + (M_7+N_8+N_9)\overline{L}$

Table: Matter curves along with their $U(1)'$ charges, flux data and the corresponding SM content. Note that $N = N_7 + N_8 + N_9$.

⋆ The precise spectrum is specified by the flux integers: M_i, m_j, N_k .

⋆ c_i coefficients can be derived by applying Anomaly Cancellation + the condition: $\sum_{i=1,2,3} c_i^2 = 1$

Models without exotics

⋆ Fluxes are subject to phenomenological constraints:

- Chirality $\longrightarrow$ $\sum_i m_i = -\sum_j M_j = 3$
- Ensure a tree-level top coupling $\longrightarrow$ $m_1 = 1,\ m_1 + N \geq 1,\ M_1 + N \geq 1$
- Doublet-triplet splitting $\longrightarrow$ $|N_7| + |N_8| + |N_9| \neq 0$
- **Absence of exotics** $\longrightarrow m_i \geq 0\ ,\ -M_j \geq 0$

⋆ Scan the flux parameter space for combinations of m_i, M_j and N_k which respect all the above MSSM-conditions ... $\Longrightarrow$ **54 solutions** (flux range $[-3, 3]$)

Model	m_1	m_2	m_3	m_4	M_1	M_2	M_3	M_4	M_5	M_6	M_7	N_7	N_8	N_9	$\mathbf{c_1}$	$\mathbf{c_2}$	$\mathbf{c_3}$
A	1	2	0	0	0	0	0	0	-1	-1	-1	1	0	0	0	$-\frac{1}{2}\sqrt{\frac{3}{2}}$	$\frac{1}{2}\sqrt{\frac{5}{2}}$
B	1	0	1	1	0	-1	0	0	-1	0	-1	0	1	0	$-\frac{\sqrt{5}}{3}$	$\frac{1}{6}\sqrt{\frac{5}{2}}$	$-\frac{1}{2}\sqrt{\frac{3}{2}}$
C	1	0	0	2	0	0	-1	0	0	-1	-1	0	0	1	$-\frac{\sqrt{5}}{6}$	$\frac{7}{12}\sqrt{\frac{5}{2}}$	$-\frac{1}{4\sqrt{6}}$
D	1	1	0	1	0	0	0	0	-1	-1	-1	0	0	1	$\frac{1}{2}\sqrt{\frac{5}{6}}$	$\frac{5}{8}\sqrt{\frac{5}{3}}$	$-\frac{3}{8}$

Table: 'MSSM'-spectrum flux solutions along with the corresponding c_i 's .

⋆ All the 'MSSM' solutions fall in to four classes of models, namely A, B, C and D.

Models without exotics

⋆ The various models inside a class are differ on how the SM fields distributed on the matter curves

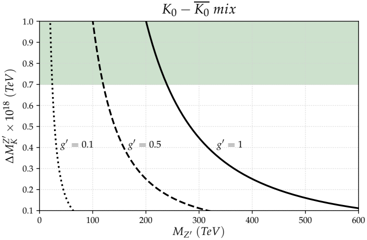
Curve	Model **B**		Model **C**		Model **D**	
	$\sqrt{15}Q'$	SM	$\sqrt{15}Q'$	SM	$\sqrt{10}Q'$	SM
10_1	-1	$Q+2u^c$	1/4	$Q+2u^c$	3/4	$Q+2u^c$
10_2	3/2	-	3/2	-	-1/2	$Q+u^c+e^c$
10_3	-1	$Q+2e^c$	-9/4	-	-7/4	-
10_4	3/2	$Q+u^c+e^c$	1/4	$2Q+u^c+3e^c$	3/4	$Q+2e^c$
5_1	2	H_u	-1/2	H_u	-3/2	H_u
$\bar{5}_2$	1/2	d^c+2L	7/4	L	1/4	L
$\bar{5}_3$	-2	L	-2	d^c+2L	-1	L
$\bar{5}_4$	1/2	L	1/2	L	3/2	L
$\bar{5}_5$	1/2	d^c	-3/4	-	-9/4	d^c+L
$\bar{5}_6$	3	d^c	7/4	d^c	1/4	d^c
$\bar{5}_7$	1/2	-	-2	d^c	-1	d^c

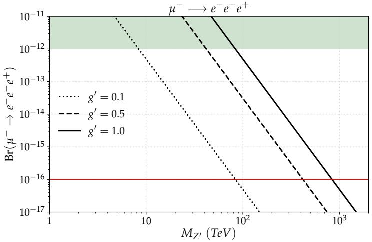
⋆ The SM fields appear with non-universal $U(1)'$ charges.... however $\mathbf{K}-\overline{\mathbf{K}}$ oscillations and other LFV processes leave no room for an explanation of the R_K-anomalies.

⋆ For all the MSSM-spectrum models **dominant bounds** comes from the $\mathbf{K_0}-\overline{\mathbf{K_0}}$ system and muon decay $\mu \to e^- e^- e^+$.

Z' bounds

Example: Model D predictions





⇓

⇓

$$\Delta M_K^{Z'} \simeq 3.967 \times 10^{-14} \left(\frac{g'\, TeV}{M_{Z'}} \right)^2$$

bound: $\Delta M_K^{NP} < 0.2 \Delta M_K^{exp.}$ [1808.04097]

for $g' \simeq 0.5 \longrightarrow M_{Z'} \gtrsim 120$ TeV

$$\mathrm{Br}(\mu \to 3e) \simeq 4.92 \times 10^{-5} \left(\frac{g' \;\mathrm{TeV}}{M_{Z'}} \right)^4$$

- current bound: $Br(\mu \to 3e) < 10^{-12}$ [PDG]
for $g' \simeq 0.5 \longrightarrow M_{Z'}^{cur} \gtrsim 42$ TeV

- future experiments: $Br(\mu \to 3e) < 10^{-16}$
for $g' \simeq 0.5 \longrightarrow M_{Z'}^{fut} \gtrsim 420$ TeV.

⇒ The currently dominant bounds from the Kaon system will be exceeded in the near future by the $\mu \to 3e$ experiments [for a short review see: 1902.0629]

Models with VL exotics

⋆ For the explanation of the R_K anomalies in the present F-theory framework...some other type of mechanism is required...

⋆ ..common approach $\longrightarrow$ explanation through the mixing with extra VL femions

[S. King,1706.06100], [S. Raby et al., 1712.09360, 1911.11075]

⋆ Flux conditions for MSSM+VL states forming complete $(10+\bar{10})$, $(5+\bar{5})$ under $SU(5)$

$$\sum_{i=1}^{4} m_i = -\sum_{j=1}^{7} M_j = 3\,,\ \ \sum_{i=1}^{4} |m_i| = \sum_{j=1}^{7} |M_j| = 5$$

$$|m_1+1|+|m_2-N_7|+|m_3-N_8|+|m_4-N_9| = 5$$

$$|m_1-1|+|m_2+N_7|+|m_3+N_8|+|m_4+N_9| = 5$$

$$1+|M_2-1|+|M_3-1|+|M_4-1|+|M_5+N_7+N_8|+|M_6+N_7+N_9|+|M_7+N_9+N_8| = 7$$

⋆ Scan of the flux parameter space returns ...$\Longrightarrow$ 1728 set of fluxes

Models with VL exotics

⋆ Further restrictions... search for models where the three MSSM families have universal $U(1)'$ charges and only the charges of the vector-like fields will differ

$\Downarrow$

⋆ From the resulting 1728 models $\longrightarrow$ **192** of them appear with the desired property

$\Downarrow$

⋆ These 192 models fall into five classes with respect to their $SU(5) \times U(1)'$ properties

$\downdownarrows$

(Representative solutions for the five class of models A', B', C', D' and E')

$\downdownarrows$

Model	m_1	m_2	m_3	m_4	M_1	M_2	M_3	M_4	M_5	M_6	M_7	N_7	N_8	N_9	c_1	c_2	c_3
A'	1	2	1	-1	0	-1	0	0	-1	-2	1	1	0	0	0	$\frac{\sqrt{15}}{4}$	$-\frac{1}{4}$
B'	1	2	-1	1	0	0	0	0	-1	-3	1	1	0	0	0	$-\frac{1}{2}\sqrt{\frac{15}{34}}$	$-\frac{11}{2\sqrt{34}}$
C'	2	1	1	-1	0	0	0	1	-3	-1	0	0	1	0	$\frac{\sqrt{3}}{2}$	$-\frac{1}{4}\sqrt{\frac{3}{2}}$	$\frac{1}{4}\sqrt{\frac{5}{2}}$
D'	2	-1	1	1	0	-1	0	1	-1	-2	0	0	0	1	$-\frac{1}{2}\sqrt{\frac{5}{6}}$	$-\frac{5}{8}\sqrt{\frac{5}{3}}$	$\frac{3}{8}$
E'	1	-1	2	1	0	0	1	-1	0	-1	-2	0	1	0	$2\sqrt{\frac{10}{93}}$	$-\sqrt{\frac{5}{93}}$	$\frac{4}{\sqrt{31}}$

(and their corresponding models) $\longrightarrow$

Models with VL exotics

Model **A'**		Model **B'**		Model **C'**		Model **D'**		Model **E'**	
$\sqrt{10}Q'$	SM	$\sqrt{85}Q'$	SM	Q'	SM	$\sqrt{10}Q'$	SM	$\sqrt{310}Q'$	SM
1/2	$Q+2u^c$	-2	$Q+2u^c$	1/4	$2Q+3u^c+e^c$	-3/4	$2Q+3u^c+e^c$	9/2	$Q+2u^c$
1/2	$2Q+u^c+3e^c$	-2	$2Q+u^c+3e^c$	-1/2	$Q+u^c+e^c$	-1/2	$\overline{Q}+\overline{u^c}+\overline{e^c}$	11/2	$\overline{Q}+\overline{u^c}+\overline{e^c}$
-2	$Q+u^c+e^c$	-1/2	$\overline{Q}+\overline{u^c}+\overline{e^c}$	1/4	$Q+2e^c$	7/4	$Q+u^c+e^c$	9/2	$2Q+u^c+3e^c$
-1/2	$\overline{Q}+\overline{u^c}+\overline{e^c}$	11/2	$Q+u^c+e^c$	1/4	$\overline{Q}+\overline{u^c}+\overline{e^c}$	-3/4	$Q+2e^c$	-8	$Q+u^c+e^c$
-1	H_u	4	H_u	-1/2	H_u	3/2	H_u	-9	H_u
1	d^c+2L	-4	L	-1/4	L	-1/4	d^c+2L	-1	L
-3/2	L	-3/2	L	1/2	L	1	L	-9	$\overline{d^c}$
1	L	7/2	L	0	$\overline{d^c}$	3/2	$\overline{d^c}$	-7/2	d^c+2L
-3/2	d^c	-3/2	d^c	-1/4	$3d^c+2L$	9/4	d^c+L	1	$\overline{L}$
1	$2d^c+L$	7/2	$3d^c+2L$	-3/4	d^c+L	-1/4	$2d^c+L$	-27/2	d^c+L
3/2	$\overline{d^c}+\overline{L}$	-6	$\overline{d^c}+\overline{L}$	0	$\overline{L}$	-1	$\overline{L}$	-7/2	$2d^c+L$

⋆ Models with this feature can explain the observed R_K-anomalies provided there is substantial mixing of the SM fermions with the vector-like exotics.

⋆ At the same time, lepton universality is preserved among the three chiral families and severe bounds from the Kaon system and other flavour violating processes are not violated.

...Work in progress

Summary

- LHCb results $\rightarrow$ violation of lepton universality $\rightarrow$ NP is required!

- NP candidates: Z' neutral gauge bosons (coupled differently to fermion families), Vector-like exotics, Leptoquarks,...

- We performed a systematic analysis of a class of semi-local F-theory models with $SU(5) \times U(1)'$ gauge symmetry obtained from a covering E_8 symmetry.

- Imposing anomaly cancellation we have constructed all possible $U(1)'$ combinations and found as a generic property the appearance of non-universal Z'-couplings to the three families of quarks and leptons.

- We have classified two types of spectrum: **1)** Models with MSSM (+singlets) spectrum, and **2)** Models with MSSM+ a complete family of VL exotics (+singlets).

- We found 54 'MSSM' solutions distributed in four classes.

- Models with Z' coupled non-universally but only with MSSM spectrum, are not capable to interpret the observed LHCb anomalies. Using Kaon mixing and future $\mu \rightarrow 3e$ bounds we obtain $M_{Z'}$ at few hundred TeV.

- We have found 1728 'VL'-models $\rightarrow$ in 192 of them the $U(1)'$ charges of the vector-like states differ from the universal $U(1)'$ charges of the MSSM families.

- 'VL' Models with this feature can explain the observed R_K-anomalies provided there is substantial mixing of the SM fermions with the VL exotics....

(*...search underway for a successful model*)

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Thank you very much !