Theory confronting LFU data

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Motivation

Tests of LFU in B-meson decays

Premise

B-anomalies hint physics beyond the SM(*)

(*) compelling, yet inconclusive

A call for a bottom-up model building adventure
A bottom-up approach

**IR consistency checks**

- **Q0**: Is there a consistent explanation of anomalies within the SM EFT while respecting all experimental constraints?
  [The SM EFT is a motivated framework that encompasses specific short-distance models at low-energies.]

- If yes, **Q1**: what generates the required higher-dimensional operators? What is an emerging set of new heavy mediators? Can they pass the new consistency checks, e.g. direct searches at the LHC?

- If yes, **Q2**: is there a working prototypical model that is fully-calculable and can be extrapolated to high energies?
A bottom-up approach

IR consistency checks

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UV insights and connections

• **Q3**: If such construction exists, how does it fit in the “UV picture”? Could it be linked to open problems of the SM such are the hierarchy, the flavour puzzle, etc.

• **Q4**: What connections with other sectors follow from this? Where should we look further?
New Fermi interactions

\[ \text{SM EFT + U(2) flavour symmetry} \]

- The analysis of SU(2) gauge invariant dimension-6 operators.
- Large number of flavour parameters in the SM EFT. Flavour symmetries and breaking patterns serve as the organising principle [2005.05366].
- Coherent picture of NP [1706.07808]

1) Semi-leptonic four-fermion operators involving left-handed fermions

\[ \mathcal{L} \supset \frac{c_{QijLkl}^{(3)}}{\Lambda^2} (\bar{Q}_i \gamma_\mu \sigma^a Q_j)(\bar{L}_k \gamma^\mu \sigma_a L_l) + \frac{c_{QijLkl}^{(1)}}{\Lambda^2} (\bar{Q}_i \gamma_\mu Q_j)(\bar{L}_k \gamma^\mu L_l) \]

2) U(2)_q \times U(2)_l flavour symmetry with minimal breaking spurions
New Fermi interactions

### SM EFT + U(2) flavour symmetry

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2) U(2)_{Q} \times U(2)_{L} flavour symmetry with minimal breaking spurions

- Triplet versus singlet operator: new dynamics gives \( b \to c \tau \nu \) but not \( b \to s \nu \nu \)
- The role of U(2):
  - Accommodates for the right ratio of CC and NC anomalies
  - Protects against LFU tests in kaons and light lepton flavours
- Drell-Yan constraints important [1609.07138, 1811.07920]. Suppression of flavour-blind int. [1704.09015].
- Radiatively induced effects important [1606.00524, 1807.02068]
- NP in right-handed currents could be useful [1909.02519]
New heavy mediators

<table>
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<tr>
<th>Colour singlet</th>
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\text{Colour singlet} & \quad \text{Colour triplet} \\
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\begin{array{... | (SU(3), SU(2), U(1)) | (SU(3), SU(2), U(1)) |
| Q \rightarrow L | Q \rightarrow L |
| L \rightarrow L | L \rightarrow L |
| (SU(3), SU(2), U(1)) | (SU(3), SU(2), U(1)) |
Simplified models

New heavy mediators

\[ C_T \left( \bar{Q}_L^i \gamma_\mu \sigma^a Q^j_L \right) \left( \tilde{L}_L^\alpha \gamma_\mu \sigma^a L^\beta_L \right) + C_S \left( \bar{Q}_L^i \gamma_\mu Q^j_L \right) \left( \tilde{L}_L^\alpha \gamma_\mu L^\beta_L \right) \]
**Simplified models**

- **New heavy mediators**

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- **Scalar LQ:**
  - $S_1 \sim (\bar{3}, 1, 1/3)$
  - $S_2 \sim (3, 3, 1/3)$

- **Vector LQ:**
  - $U^1_i \sim (3, 1, 2/3)$
  - $U^2_i \sim (3, 3, 2/3)$

\[ C_T (\bar{Q}^j_L \gamma_\mu \sigma^a Q^j_L)(\bar{L}^\alpha_L \gamma_\mu \sigma^a L^\beta_L) + C_S (\bar{Q}^j_L \gamma_\mu Q^j_L)(\bar{L}^\alpha_L \gamma_\mu L^\beta_L) \]

- **Vector LQ singlet** is the most successful single mediator: $M \sim \text{TeV}, g_{33} \sim 1$.

Successful simplified models with multiple mediators exist, e.g. $S_1 + S_3$. 

1706.07808
The prototype

Vector LQ singlet option

• Massive vector crave an UV completion.

• This is the Pati-Salam leptoquark!

• Quark-lepton unification \( 4 = 3q + 1l \) resolves the charge quantisation puzzle.

• Low-scale Pati-Salam model possible (no proton decay). However, the original Pati-Salam leptoquark mass \( \geq \) PeV by FCNC, e.g. \( K_L \rightarrow \mu e \).

• How to achieve a successful TeV-scale quark-lepton unification?

“4321 models”

1706.05033, 1708.08450, 1712.01368, 1802.04274,
1805.09328, 1808.00942, 1903.11517, 1910.13474,
2004.11376, ...
**The prototype: 432I**

**432I gauge sector**

\[ G \equiv SU(4) \times SU(3)' \times SU(2)_L \times U(1)' \]

SSB: \( \langle \Omega_3 \rangle, \langle \Omega_1 \rangle \)

15 broken generators

\[ G_{SM} \equiv SU(3)_c \times SU(2)_L \times U(1)_Y \]

\[ \rightarrow Z' \ (1, 1, 0) \]

\[ \rightarrow G' \ (8, 1, 0) \]

\[ \rightarrow (3, 1, 2/3) \]

Leptoquark
The prototype: 4321

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4321 fermionic content

- **Class I:** All three generations of SM fermions charged under 321.
- **Class II:** The third SM generation charged under 421.
- Mixing with the vector-like fermion doublets.

\[ \rightarrow Z' \ (1, 1, 0) \]
\[ \rightarrow G' \ (8, 1, 0) \]
\[ \rightarrow (3, 1, 2/3) \text{ Leptoquark} \]
Exhaustive phenomenological studies show there is a prototype model with rich signatures at low- and high-$p_T$. 

\[ 1 \quad 8 \quad 0 \quad 8 \quad . \quad 0 \quad 0 \quad 9 \quad 4 \quad 2 \]
The flavour puzzle & PS$^3$

Flavour deconstruction

**LFU**: at long distances the only difference is the mass

\[ \gamma, g, W, Z \]

\[ \text{SU(3)} \times \text{SU(2)} \times \text{U(1)} \]

\[ e, \mu, \tau \]

but remember

\[ \gamma \]

\[ \text{U(1)}_Q \]

\[ e^+, p^+ \]

Far apart at short distances!

[Taken from Isidori]
Flavour deconstruction

**LFU**: at long distances the only difference is the mass

\[ \gamma, g, W, Z \]

\[ SU(3) \times SU(2) \times U(1) \]

\[ \psi_{1,2,3}^{L,R} \]

but remember

\[ \gamma \]

\[ U(1)_Q \]

\[ e^+, p^+ \]

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---

**The PS\(^3\) model**

\[ [PS]^3 = [SU(4) \times SU(2)_L \times SU(2)_R]^3 \]

\[ PS_1 = PS^{(5)}|_{z=z_1} \]

\[ PS_2 = PS^{(5)}|_{z=z_2} \]

\[ PS_3 = PS^{(5)}|_{z=z_3} \]

- **4D formulation:**
  - One PS gauge group per family.
  - Hierarchical SSBs down to the 4321 at the TeV scale.

- Natural realisation in extra dimensions

[1712.01368]
Connections: Neutrino physics

- The options for the neutrino masses consistent with this picture are drastically narrowed.

\[
\begin{pmatrix} \psi^u_R \end{pmatrix}^T = \begin{pmatrix} u^3_R & \nu^3_R \end{pmatrix}
\]

\[
m'_t = \frac{v_{EW}}{\sqrt{2}} \left( y_H^u \cos \beta + \frac{1}{2\sqrt{6}} y_{\Phi}^u \sin \beta \right)
\]

\[
m'_{\nu_\tau} = \frac{v_{EW}}{\sqrt{2}} \left( y_H^u \cos \beta - \frac{3}{2\sqrt{6}} y_{\Phi}^u \sin \beta \right)
\]

- Disastrous prediction! Needs a fix.

Inverse seesaw mechanism 1802.04274

Introduce a singlet

\[
L_S = -\Omega_1^T \overline{S}_R \lambda_R \psi^u_R - \overline{S}_R M_R \nu'_R - \frac{1}{2} \overline{S}_R \mu_S S_R + \text{h.c.}
\]

- Connection:
  B-anomalies and the PMNS non-unitarity
Hierarchical strongly first order phase transitions in the early Universe

**Footprint:** Stochastic gravitational wave radiation with the characteristic three-peaked signature (the Triglav signature).
B-anomalies showed the power of data to sparkle new ideas.

- New directions in model building
- New connections / Spectacular signatures

(1) Working models exist, however, the final judge is the experiment.