Flavourful vector FIPs
for $B \to K$ and $(g - 2)_\mu$ anomalies

Luc Darmé

INFN – LNF

25/05/2021

Based on 2002.11150 and 2106.xxxxx with M. Fedele, K. Kowalska and E. Sessolo
Why always the muons ...

- Experimental anomalies in muon-related observables have been gaining traction in recent months

Flavour-violation in $B \rightarrow K^*(\ast)$ (mostly LHCb)

→ Form a consistent picture in WET
→ Focus in this talk on the $b \rightarrow s$ signatures

$$R_K = \frac{\text{BR}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\text{BR}(B^+ \rightarrow K^+ e^+ e^-)} = 0.846^{+0.042}_{-0.039} \text{ (stat)}^{+0.013}_{-0.012} \text{ (syst)}$$

LHCb 9 fb$^{-1}$

$1.1 < q^2 < 6.0 \text{ GeV}^2/c^4$

[ LHCb-PAPER-2021-004 ]

And many other observables: $R_{K^*}$, Angular obs., etc...

- Both are “low energy precision observables”

→ A great many models with heavy new particles, in this this talk we try to find a common ”low scale” NP explanation
Feebly-Interacting Particles

- **FIPs** = “new neutral particle which interact with the SM via suppressed new interactions”
  - Appear in many NP solution to the SM challenges

- In many cases, flavourful interactions are possible and even expected
  - pNGB from flavour symms.
  - HNL and dark Higgs, etc...

**Diagram:**
- **pNGB / ALPs**
- Light Dark Matter
  - Heavy Neutral Leptons
  - QCD axion
  - + dark photons, dark Higgs...

- **Questions:**
  - The hierarchy problem
  - What is the origin of flavour?
  - The nature of dark matter?
  - Origin of the $\nu$ masses?
  - Why does QCD respect CP?

In this talk we focus also on MeV to tens of GeV scale
Dark EFT approach $\rightarrow$ DEFT

- Goal: fitting the anomalies with the “tree-level” exchange of a light mediator
- Provide additionally solution to $(g - 2)_{\mu}$

- Inputs from WET global fits: we want a negative interference with SM in $\bar{s}\gamma^{\mu}P_{L}b$

- We construct an EFT description of SM (cf. SM$+X$, Portal EFT, etc ...), for this talk we pick:

<table>
<thead>
<tr>
<th>“4 4” model</th>
<th>$Q_{4}^{bsV} = (\bar{s}\gamma_{\rho}P_{L}b)V^{\rho}$,</th>
<th>$Q_{4}^{\mu\mu V} = (\bar{\mu}\gamma_{\rho}\mu)V^{\rho}$,</th>
<th>$\tilde{Q}<em>{4}^{\mu\mu V} = (\bar{\mu}\gamma</em>{\rho}\gamma^{5}\mu)V^{\rho}$,</th>
</tr>
</thead>
<tbody>
<tr>
<td>“6 4” model</td>
<td>$Q_{6}^{bsV} = (\bar{s}\gamma_{\rho}P_{L}b)\partial_{\sigma}V^{\rho\sigma}$</td>
<td>$Q_{4}^{\mu\mu V} = (\bar{\mu}\gamma_{\rho}\mu)V^{\rho}$,</td>
<td>$\tilde{Q}<em>{4}^{\mu\mu V} = (\bar{\mu}\gamma</em>{\rho}\gamma^{5}\mu)V^{\rho}$,</td>
</tr>
</tbody>
</table>

There are of course many other operators...

The anomalies as a true “low scale” effect

Couplings to muons

Use spin-1 FIP, $V$, with $\bar{s}\gamma^{\mu}P_{L}b$
Fitting the anomalies

- As a simple scaling, the anomalies require

\[ \mathcal{C}^{bsV} \mathcal{C}^{\mu\mu V} \left( \frac{q}{\Lambda} \right)^{\delta_1 + \delta_2} \approx 10^{-9} \]

\[ \sqrt{\left( \mathcal{C}_4^{\mu\mu V} \right)^2 - 5 \left( \mathcal{C}_4^{\mu\mu V} \right)^2} \sim 0.05 \left( \frac{1 \text{ GeV}}{m_V} \right)^2 \]

- In details though: explicit momentum dependence of the \( bs\mu\mu \) vertex

\[ C_9 = \frac{4\pi N}{\alpha_{\text{em}}} \left( \mathcal{C}_4^{bsV} - \frac{q^2}{\Lambda^2} \mathcal{C}_6^{bsV} \right) \left( \mathcal{C}_4^{\mu\mu V} - \frac{q^2}{\Lambda^2} \mathcal{C}_6^{\mu\mu V} \right) \]

\[ q^2 - M_V^2 + i\Gamma_V M_V \]

- Since we have \( q^2 \)-dependent observables complete fit needed
  \( \Rightarrow \) Dependence on the width important for \( M_V \) in the GeV range

We assume that \( V \) has an invisible decay width
  \( \Rightarrow \) left as free parameter
Fitting the anomalies

- We implemented the model in HEPfit to account for the $q^2$, tested various combinations
  - Included LFUV ratios $R_K, R_{K^*}$ and the angular observables in $B \to K^*\mu\mu$
  - Significant differences between $C_4$ and $C_6$ case ($q^2$ dependence)

- From fit point of view, both “low” and “high” masses are achievable
  - Resonance + width effects are important!
The troubles with non-conserved currents...

- The interaction between vector FIP and SM can be represented via a “current”
  \[ \mathcal{L}_{\text{int}} \supset V_\mu \mathcal{J}_V^\mu \]
  It does not correspond a priori to a SM global symmetry

- Non-conserved SM currents leads to strong signatures, particularly at small vector masses
  - Most processes scale as \( \frac{E^2}{M_V^2} \), since any on-shell vector leads to as \( M_\mu \sim \frac{q^\mu}{M_V} \)

- We have
  - Tree-level flavour violation, both critical to the anomalies and very strongly constrained
    - \( B_s \) -mixing, \( B_s \to \mu \mu \)
    - \( B \to K^{(*)}V \) on-shell processes, with subsequent visible/invisible \( V \) decay
  - Weak-isospin violation (no coupling to neutrinos)
    - Strong flavour-dependent modification of \( W \) decay rates
  - Axial-coupling interaction to the SM fermions
The GeV-FIP windows "6-4"

\[ Q_{6}^{bsV} = (\bar{s} \gamma_{\rho} P_L b) \partial_\sigma V^{\rho \sigma} \]

\[ Q_{4}^{\mu \nu V} = (\bar{\mu} \gamma_{\rho} \mu) V^\rho, \]

- Low masses very constrained
  - Green points show fit \( B \rightarrow K^{(*)} \)
    observables at 2\( \sigma \) (including invisible decays)
  - Several other subdominant low mass constraints not shown
  - Combined with W decays rules out the low mass region

- Above the B mass, large open parameter space
  - Similar effect for a "4-4" model
  - LHC searches play a critical role!

\[ m_V \, [\text{GeV}] \]

\[ C_4^{\mu \nu V} \]

\[ Z\rightarrow 4\mu, \text{off-shell, ATLAS} \]

\[ W\rightarrow lvV \, \text{tot. width} \]

\[ (g-2)_\mu \pm 2\sigma \]

\[ \text{LFV in W decay, ATLAS+LHCb} \]

\[ Z\rightarrow \mu\mu V, y_{\text{inv.}} = 1, \text{res. ATLAS} \]

\[ \text{All } B\rightarrow K^{(*)} \text{ obs., } 2\sigma \]

The V is assumed to decay always invisibly remains stable below the dimuon threshold
An (partial) UV realisation

- **Aim:** realise an effective bsV vertex via a loop of heavy scalar/light dark fermion
  - Log-enhancement of the loop from scale mismatched

\[ \tilde{g} = -\frac{g_D Q_\Phi}{16\pi^2 m_\Phi^2} \sum_i y_s^i y_b^i F(x_i) \]

- The mediator is the gauge boson of a dark U(1), after SSB in the dark sector
  - Colored “squark”
  - U(1)-charged Dirac dark fermion

- Generating the tree-level muon-coupling in a non-anomalous fashion requires additional model building
Conclusion

• Flavoured FIPs have been long used to fit various “precision anomalies”
• We have constructed an dark “EFT” approach to test the compatibility between MeV to GeV FIP with
  • Flavoured $B \rightarrow K$ anomalies
  • $(g - 2)_\mu$ experimental results
  • All relevant precision physics constraints, both in flavourful and flavour-blind analyses
• The low mass regime is not-favoured by anomaly fits+constraints
• The GeV FIP windows turns out to be particularly interesting
  ➔ Simultaneous fit possible to both anomalies without tuning
• LHC searches are relevant for this region ➔ exciting experimental targets for Run-3 and HL-LHC
Backup slides
B -> K limits in “4 6” model

• Strongest constraints are from “visible” decays
  → large invisible width for V is typically required

• Invisible limits from $B \rightarrow K \nu\nu$ can be re-casted
  → Care must me taken since different kinematics
  → ”Off-shell” component dominates at low masses
B -> K limits in “4 4” model

• Strongest constraints are from “visible” decays
  $\rightarrow$ large invisible width for $V$ is typically required

• No suppression of the on-shell decay $B \rightarrow K^{(*)} V$ leads to very strong constraints at small $V$ masses
**Current status B-anomalies**

1. Updated Belle measurement of $R_{K^*}$  
   **Talk by M. Prim**
   
   \[
   R_{K^*} = \frac{BR(B \to K^* \mu\mu)}{BR(B \to K^+ e^+ e^-)} = \begin{cases} 
   0.90^{+0.27}_{-0.21} \pm 0.10, & \text{for } 0.1 \text{ GeV}^2 < q^2 < 8 \text{ GeV}^2 \\
   1.18^{+0.52}_{-0.32} \pm 0.10, & \text{for } 15 \text{ GeV}^2 < q^2 < 19 \text{ GeV}^2 
   \end{cases}
   \]

2. Updated LHCb measurement of $R_K$  
   **Talk by T. Humair**
   
   \[
   R_K = \frac{BR(B \to K\mu\mu)}{BR(B \to K e e)} = 0.846^{+0.060}_{-0.054}^{+0.016}_{-0.014},
   \]

   \[
   R_K = 0.846^{+0.042}_{-0.039} \text{ (stat)}^{+0.013}_{-0.012} \text{ (syst)}
   \]

---

**Altmannshofer, Stangl, 2103.13370**
Flavour physics and split dark sectors

• Loop-based models of flavour anomalies can feature light particles

• Box diagram based (e.g. with (colored) scalar doublets and light fermions)


• Penguin diagram based
  • E.g. with a colored doublets, plus new dark photon and sterile neutrino-like fermion

See e.g. Arnan, Crivellin, Fedele, Mescia (2019)

See e.g. LD, Fedele, Kowalska, Sessolo (2020)
Feebly-Interaction Particles and portals

- FIPs = “new (quasi-) neutral particle which interact with the SM via suppressed new interactions” → assumed light (MeV to few GeVs)
- Appear in various NP models aiming at dark matter, neutrino masses, strong CP problem, flavour etc …

<table>
<thead>
<tr>
<th>Portal Type</th>
<th>SM operator</th>
<th>FIPs / dark sector</th>
<th>examples …</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scalar portal</td>
<td>$</td>
<td>H</td>
<td>^2 \ (d = 2)$,</td>
</tr>
<tr>
<td>Vector portal</td>
<td>$F_{\mu \nu} \ (d = 2)$,</td>
<td>$F^{\prime \mu \nu}$</td>
<td>Dark photon</td>
</tr>
<tr>
<td>Neutrino portal</td>
<td>$LH \ (d = 5/2)$</td>
<td>$N$</td>
<td>Sterile neutrino/HNL</td>
</tr>
<tr>
<td>Axion portal / fermion portal</td>
<td>$\bar{f}_i \Gamma^\mu f_j \ (d = 3)$</td>
<td>$\partial_\mu a$ $\Psi \Gamma_\mu \Psi$</td>
<td>Axion/ALP</td>
</tr>
</tbody>
</table>

Dark fermions