The $b \rightarrow s$ anomalies as a guide beyond the Standard Model

Avelino Vicente
IFIC – CSIC / U. Valencia

5th Workshop on Flavour Physics in the LHC Era

New physics with heavy mesons and baryons
The $b \rightarrow s$ anomalies

**Episode IV: A new hope**

2013 : First anomalies found by LHCb

**Episode V: LHCb strikes back**

2014 : Lepton universality violation

\[ R_K = \frac{\text{BR}(B \rightarrow K\mu^+\mu^-)}{\text{BR}(B \rightarrow Ke^+e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036 \]

\[ R_K^{\text{SM}} \sim 1.00 \pm 0.01 \]

2.6$\sigma$ away from the SM

**Episode VI: Return of the anomalies**

2015 : LHCb confirms first anomalies
The $b \to s$ anomalies

**Episode I: The Belle menace**

2016: Belle finds additional hints

$P_5'$ anomaly confirmed
+ little LFVU indication

**Episode II: Attack of $R_{K^*}$**

2017: More universality violation in LHCb

[ No new episode in 2018 though.... ]
Who ordered that?  (again)
Who ordered that? (again)

What can we do with it?
What can we do with it?

Great opportunity for model builders

New data-driven models:
not even imagined without anomalies
leptoquarks

$U_1 \quad S_3$

(Pati-Salam)$^3$

4321

W'

Adventurous model builder
We might discover something new...

... perhaps an unexpected connection
Killing two birds with one stone

What if the explanation to these anomalies also solves other physics problems?

Chuck Norris fact of the day

*Chuck Norris can kill two stones with one bird*
I will concentrate on the $b \rightarrow s$ anomalies

... if you have a model for $R(D)$ and $R(D^*)$ that’s good enough, I will not ask for more!
Outline

$b \rightarrow s$ and dark matter

$b \rightarrow s$ and neutrinos

Summary

Note:
I will omit many interesting models
Apologies!
$b \rightarrow s$ anomalies and Dark Matter
Flavor and Dark Matter can be connected in many ways...

- Stability of DM from a flavor symmetry
  - Continuous or discrete
  - Part of a multiplet of the flavor symmetry: “flavored DM”
- Flavor origin of a stabilizing symmetry
- Relation to neutrino masses and mixings
- Minimal Flavor Violation

Enhancement of flavor effects due to new dark sectors

DM relic density determined by flavor processes
  - Flavored coannihilation
  - Scotogenic model with RH neutrino DM

NP models for flavor anomalies (\(b \rightarrow s\)) with a DM candidate

This talk
Model classification
Linking $b \rightarrow s$ and DM

Models for the $b \rightarrow s$ anomalies and DM

- **Portal models**
- **Loop models**
- **Hybrid models**

The mediator responsible for the NP contributions to $b \rightarrow s$ transitions also mediates the DM production in the early Universe.

Example:
Aristizabal-Sierra, Staub, AV
[1503.06077]

The required NP contributions to $b \rightarrow s$ transitions are induced with loops containing the DM particle.

Example:
Kawamura, Okawa, Omura
[1706.04344]
A portal model

Aristizabal-Sierra, Staub, AV
[ 1503.06077 ]
Z’ : what do we need?

Z' model building
Easiest (but not unique) solution

List of “ingredients”:

• A Z' boson that contributes to $O_9$ (and optionally to $O_{10}$)

• The Z' must have flavor violating couplings to quarks

• The Z' must have non-universal couplings to leptons

• Optional (but highly desirable!): interplay with some other physics
A model with a $Z'$ portal

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_X$$

Vector-like = “joker” for model builders

**Vector-like fermions**

$$Q = \left(3, 2, \frac{1}{6}, 2\right)$$

$$L = \left(1, 2, -\frac{1}{2}, 2\right)$$

**Scalars**

$$\phi = (1, 1, 0, 2)$$

$$\chi = (1, 1, 0, -1)$$

$U(1)_X$ breaking

Dark matter candidate
A model with a Z' portal

\[ \text{SU}(3)_c \otimes \text{SU}(2)_L \otimes \text{U}(1)_Y \otimes \text{U}(1)_X \]

Vector-like = "joker" for model builders

\[ \mathcal{L}_m = m_Q \bar{Q}Q + m_L \bar{L}L \]

\[ \mathcal{L}_Y = \lambda_Q \bar{Q}_R \phi q_L + \lambda_L \bar{L}_R \phi \ell_L + \text{h.c.} \]

VL – SM mixing

[Arístizabal Sierra, Staub, AV, 2015]
Solving the $b \rightarrow s$ anomalies

\[ \Delta_{L}^{bs} \simeq g_{X}v_{\phi}^{2}\frac{\lambda_{Q}^{b}\lambda_{Q}^{s*}}{m_{Q}^{2}} \]

\[ \Delta_{L}^{\mu\mu} \simeq \frac{2g_{X}|\lambda_{L}^{\mu}|^{2}v_{\phi}^{2}}{2m_{L}^{2} + |\lambda_{L}^{\mu}|^{2}v_{\phi}^{2}} \]

\[ \mathcal{O} = (\bar{s}\gamma_{\alpha}P_{L}b) (\bar{\mu}\gamma^{\alpha}P_{L}\mu) \]

\[ C_{9}^{\text{NP}} = -C_{10}^{\text{NP}} \]

Alternatives with direct $Z'$ couplings

Altmannshofer et al, 2014, Crivellin et al, 2014, 2015 [$L_{\mu} - L_{\tau}$], Celis et al, 2015 [BGL], ...
Dark Matter

DM stability

\[ U(1)_X \rightarrow \mathbb{Z}_2 \]
\[ \chi = (1, 1, 0, -1) \]
Odd under \( \mathbb{Z}_2 \)
Automatically stable

DM production

The dynamics behind the \( b \rightarrow s \) anomalies stabilizes the DM and provides a production mechanism.

Z' portal

Interplay between Flavor and DM

However:
Higgs portal also possible
Assumption:
\[ \lambda_{H\chi} \ll 1 \]
DM and $b \rightarrow s$ anomalies

$C_9^{\text{NP}} / C_9^{\text{SM}}$ (full) $\log(\Omega_{\text{DM}}h^2)$ (dashed) $C_9^{\text{NP}} / C_9^{\text{SM}}$ (tree) (dotted gray)

Parameters:

$\lambda_Q^b = \lambda_Q^s = 0.025$

$\lambda_L^\mu = 0.5$

$m_Q = m_L = 1$ TeV

$m_x^2 = 1$ TeV$^2$

- Compatible with flavor constraints (small quark mixings)
- Resonance required to get the correct DM relic density
- Large loop effects for low $g_X$
Neutrino masses

Non-trivial embedding of neutrino masses

\[ m_\nu \simeq \frac{v^2 v_\phi^2 v_S}{2\sqrt{2}} \lambda_L^{-1} y m_F^{-1} h \left(m_F^{-1}\right)^T y^T \left(m_L^{-1}\right)^T \lambda_L \]

\[ h \ll 1 \]

allows for light neutrinos and large Yukawa couplings

Inverse seesaw (-like) mechanism

LFV phenomenology in 1810.02135
A loop model

Kawamura, Okawa, Omura
[1706.04344]
Loops and $b \rightarrow s$ anomalies

Model classification

All possible quantum numbers

Different contributions to $B_s$-mixing

Some multiplets include colorless neutral states (DM candidates)

Figures from Arnau et al [1608.07832]
An example loop model

<table>
<thead>
<tr>
<th>Field</th>
<th>Spin</th>
<th>$SU(3)_c \times SU(2)_L \times U(1)_Y$</th>
<th>$U(1)_X$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X$</td>
<td>0</td>
<td>$(1, 1, 0)$</td>
<td>-1</td>
</tr>
<tr>
<td>$Q_{L,R}$</td>
<td>$\frac{1}{2}$</td>
<td>$(3, 2, \frac{1}{6})$</td>
<td>1</td>
</tr>
<tr>
<td>$L_{L,R}$</td>
<td>$\frac{1}{2}$</td>
<td>$(1, 2, -\frac{1}{2})$</td>
<td>1</td>
</tr>
</tbody>
</table>

$k_X = \lambda Q_R Q_R X q_L + \lambda L_R L_R X \ell_L + h.c.$

$\langle X \rangle = 0 \implies$ No VL – SM mixing

But new Yukawa interactions

Unbroken $U(1)_X$ symmetry

Loop explanation to the $b \to s$ anomalies

[Kawamura, Okawa, Omura, 2017]
Solving the $b \rightarrow s$ anomalies

Scenario A-I, model class b) [1608.07832]

\[ C_{9,\text{NP}}^\mu = -C_{10,\text{NP}}^\mu = \frac{\lambda_Q^b \lambda_Q^{s*} |\lambda_L^\mu|^2}{64 \pi^2 V_{tb} V_{ts}^*} \frac{\Lambda_v^2}{m_Q^2 - m_L^2} \left[ f \left( \frac{m_X^2}{m_Q^2} \right) - f \left( \frac{m_X^2}{m_L^2} \right) \right] \]

Loop realization of $O_9$ and $O_{10}$

|\lambda_b \lambda_s| = 0.15
\[ m_Q^* = 1.1 \text{TeV} \]
\[ m_L^* = 1 \text{TeV} \]
Dark Matter

Lightest particle charged under $\text{U}(1)_X$

Stable and promising DM candidate

$$X = (1, 1, 0)$$

Most relevant annihilation channels for the relic density

$$XX^* \leftrightarrow \mu^+ \mu^-, \nu\nu$$

(due to large $\lambda^\mu_L$)

The model explains the anomalies at $2\sigma$

Testable by XENON1T and by direct LHC searches (events with $\mu'$s and $E_T^{\text{miss}}$)

[Kawamura, Okawa, Omura, 2017]
$b \rightarrow s$ anomalies and Neutrinos
The main open question in the lepton sector is the origin of neutrino masses

What if the LFUV hints (remember: L stands for ‘lepton’!) can guide us towards solving this central problem?
Leptoquarks are well-known beasts in neutrino mass model building.

With two leptoquarks (or a leptoquark and another exotic) one can induce radiative neutrino masses.

\[ \ell\, q\, \phi \]

L: +1 0 -1

One can always arrange for a conserved L

Why two?

Why radiative?

\[ \nu \rightarrow LQ \]

\[ q \]

Must go to loop

Also in RPV

\[ \tilde{d}_R^* \sim S_1 \]

Aristizabal Sierra, Hirsch, Kovalenko [ 0710.5699 ]

Cai, Herrero-Garcia, Schmidt, AV, Volkas [ 1706.08524 ]
(Some) leptoquark models for the B-anomalies and neutrino masses

Päs, Schumacher
[ 1510.08757 ]

Guo et al
[ 1707.00522 ]

Hati et al
[ 1806.10146 ]

\[ S_3 \]
\[ \tilde{R}_2 \]
\[ \tilde{S}_i \]
\[ \tilde{S}_i^\dagger \]
\[ H \]
\[ \omega \]

\[ \nu_L \]
\[ d_L \]
\[ d_R \]
\[ d_R \]
\[ d_L \]
\[ \nu_L \]

1-loop

\[ \omega \] : diquark

Version with vector LQs in 1603.07672

2-loop

3-loop
Heavy neutrinos in loops

He, Valencia [1706.07570]
Original idea: does NOT work

Botella, Branco, Nebot [1712.04470]
Adding VLQ’s does the job

Predictions:
correlations due to
flavor symmetry

\[ b \rightarrow s\mu\mu \iff b \rightarrow d\mu\mu \]

Question:
nutrino mass
generation

| \[ U_{eN} \] | \sim 0

Non-universality
from lepton mixing

| \[ U_{\mu N} \] | \sim 10^{-3}

See also Li et al [1807.08530] for a
2HDM-III version

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Other ideas related to neutrinos

Boucenna, Valle, AV [ 1503.07099 ]

Possible connection between the anomalies and neutrino oscillations: what if the mixing matrix relevant for B-meson LFV decays is the one measured in neutrino oscillations?

Bhatia, Chakraborty, Dighe [ 1701.05825 ]

Exploration of possible U(1) symmetries compatible with realistic lepton mixing in a type-I seesaw framework. Textures-selected symmetries. $L_\mu - L_\tau$ particular case.

Heeck, Teresi [ 1808.07492 ]

Pati-Salam model. Anomalies explained by two scalar leptoquarks, whose couplings enter neutrino masses as well. Type-II seesaw dominance is favored.

... and probably other that I missed
Summary
Summary

The anomalies in $b \to s$ transitions constitute an interesting set of hints that may be just be the first glimpse of New Physics.

If New Physics is around the corner, it may include new explanations for dark matter, neutrino masses, baryogenesis...

Many new model building directions are yet to be explored!
Summary

The anomalies in $b \rightarrow s$ transitions constitute an interesting set of hints that may be just be the first glimpse of New Physics.

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Thank you for your attention!
Backup slides
Interpreting the anomalies

Effective hamiltonian

\[ \mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left( C_i O_i + C'_i O'_i \right) + \text{h.c.} \]

- \( C_i \) : Wilson coefficients
- \( O_i \) : Operators

\[
\begin{align*}
O_9 &= (\bar{s}\gamma_\mu P_L b) \left( \bar{\ell}\gamma^\mu \ell \right) \\
O_{10} &= (\bar{s}\gamma_\mu P_L b) \left( \bar{\ell}\gamma^\mu \gamma_5 \ell \right)
\end{align*}
\]

\[
\begin{align*}
O'_9 &= (\bar{s}\gamma_\mu P_R b) \left( \bar{\ell}\gamma^\mu \ell \right) \\
O'_{10} &= (\bar{s}\gamma_\mu P_R b) \left( \bar{\ell}\gamma^\mu \gamma_5 \ell \right)
\end{align*}
\]

\[ C_i = C_i^{\text{SM}} + C_i^{\text{NP}} \]

[ analogous for primed operators ]
$$B_s \to \mu^+ \mu^-$$

$$\mathcal{O} = (\bar{s}\gamma_\alpha P_L b) \ (\bar{\mu}\gamma^\alpha P_L \mu)$$

$$\Rightarrow \ BR(B_s \to \mu^+ \mu^-)$$

Contributes to $\mathcal{O}_9$ and $\mathcal{O}_{10}$

[CMS and LHCb, 2013]

$$\overline{BR}(B_s \to \mu^+ \mu^-)_{\text{exp}} = (2.9 \pm 0.7) \times 10^{-9}$$

[Bobeth et al, 2013]

$$\overline{BR}(B_s \to \mu^+ \mu^-)_{\text{SM}} = (3.65 \pm 0.23) \times 10^{-9}$$

$$-0.25 < C_{10}^{\mu,\text{NP}} / C_{10}^{\mu,\text{SM}} < 0.03 \quad \text{(at } 1\sigma)$$

The model is compatible at $2\sigma$

$$B_s - \bar{B}_s \text{ mixing}$$

[Altmannshofer et al, 2014]

Allowing for a 10% deviation from the SM expectation in the mixing amplitude

$$\frac{m_{Z'}}{|\Delta_{L}^{bs}|} \gtrsim 244 \text{ TeV}$$
A computer tool that provides automatized analytical and numerical computation of flavor observables. It is based on SARAH, SPheno and FeynArts/FormCalc.

<table>
<thead>
<tr>
<th>Lepton flavor</th>
<th>Quark flavor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ell_\alpha \rightarrow \ell_\beta \gamma$</td>
<td>$B_{s,d}^0 \rightarrow \ell^+ \ell^-$</td>
</tr>
<tr>
<td>$\ell_\alpha \rightarrow 3 \ell_\beta$</td>
<td>$\bar{B} \rightarrow X_s \gamma$</td>
</tr>
<tr>
<td>$\mu - e$ conversion in nuclei</td>
<td>$\bar{B} \rightarrow X_s \ell^+ \ell^-$</td>
</tr>
<tr>
<td>$\tau \rightarrow P \ell$</td>
<td>$\bar{B} \rightarrow X_{d,s} \nu \bar{\nu}$</td>
</tr>
<tr>
<td>$h \rightarrow \ell_\alpha \ell_\beta$</td>
<td>$B \rightarrow K \ell^+ \ell^-$</td>
</tr>
<tr>
<td>$Z \rightarrow \ell_\alpha \ell_\beta$</td>
<td>$K \rightarrow \pi \nu \bar{\nu}$</td>
</tr>
<tr>
<td>$\Delta M_{B_{s,d}}$</td>
<td>$\Delta M_K$ and $\epsilon_K$</td>
</tr>
<tr>
<td>$P \rightarrow \ell \nu$</td>
<td>$\nonumber$</td>
</tr>
</tbody>
</table>

Not limited to a single model: use it for the model of your choice

Easily extendable

Many observables ready to be computed in your favourite model!

Website: http://sarah.hepforge.org/FlavorKit.html
LFV in B meson decays

What about LFV?

\[ \mathcal{O} = \tilde{C}^Q \left( \bar{q'} \gamma^\alpha P_L q' \right) \tilde{C}^L \left( \bar{\ell'} \gamma^\alpha P_L \ell' \right) \quad \rightarrow \quad \mathcal{O} = C^Q \left( \bar{q} \gamma^\alpha P_L q \right) C^L \left( \bar{\ell} \gamma^\alpha P_L \ell \right) \]

\[ C^L = U^\dagger_{\ell} \tilde{C}^L U_{\ell} \]

\textit{Lepton universality violation generically implies lepton flavor violation}

However: we must have a flavor theory in order to make predictions

[Glashow et al, 2014]
Are the anomalies related to neutrino oscillations?


Non-trivial link!

Neutrino oscillations

Neutrinos $\leftrightarrow$ B-physics

Lines: BF
Bands: $1\sigma$
Loop corrections

At 1-loop, the vector-like quarks contribute to all operators

- Non-negligible corrections to $C_9$
- Unwanted contributions to other Wilson coefficients

However: “Valid” region is safe

$C_7^{NP} / C_7^{SM} < 1\%$

[Computed with **FlavorKit**]

$C_9^{NP} / C_9^{SM}$ (full)

$C_7^{NP} / C_7^{SM}$ (dotted gray)
Other portal models

Celis et al [ 1608.03894 ]
Horizontal $U(1)_{B_1+B_2-2B_3}$ gauge symmetry. The $Z'$ boson couples directly to the SM quarks while the coupling to muons is induced by mixing with a VL lepton. The DM candidate is a Dirac fermion stabilized by a remnant $\mathbb{Z}_2$ symmetry.

Altmannshofer et al [ 1609.04026 ]
Extension of a popular $U(1)_{L_\mu-L_\tau}$ model with a stable Dirac fermion. Its relic density is determined by $Z'$ portal interactions.

Falkowski et al [ 1803.04430 ]
VL neutrino DM in a setup similar to 1503.06077 with additional VL fermions.

Arcadi et al [ 1803.05723 ]
Similar to 1609.04026 but making use of kinetic mixing.

... and many others!
Other loop models

Chiang, Okada [ 1711.07365 ]

Two models, with global symmetries $U(1) \times \mathbb{Z}_2$ and $U(1) \times \mathbb{Z}_3$, in order to stabilize a \textit{scalar DM candidate}. \textit{Neutrino masses} are also accommodated via a type-I seesaw mechanism.

Cline, Cornell [ 1711.10770 ]

\textit{Minimal number of fields}: a VL quark, an inert scalar doublet and a \textit{fermion singlet (the DM candidate)}. \textit{Testable} in direct DM detection experiments as well as at the LHC, where the NP states can be pair-produced.

Dhargyal [ 1711.09772 ]

\textit{Elaborated model} that also has an \textit{additional U(1) symmetry} and addresses \textit{neutrino masses}.