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

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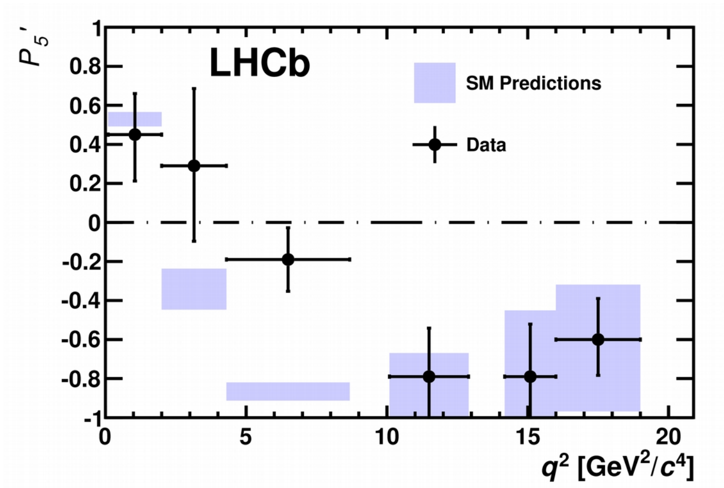
From flavor anomalies to direct discoveries of New Physics

The $b \to s$ anomalies

Episode IV: A new hope

2013 : First anomalies found by LHCb



Episode V: LHCb strikes back

2014 : Lepton universality violation

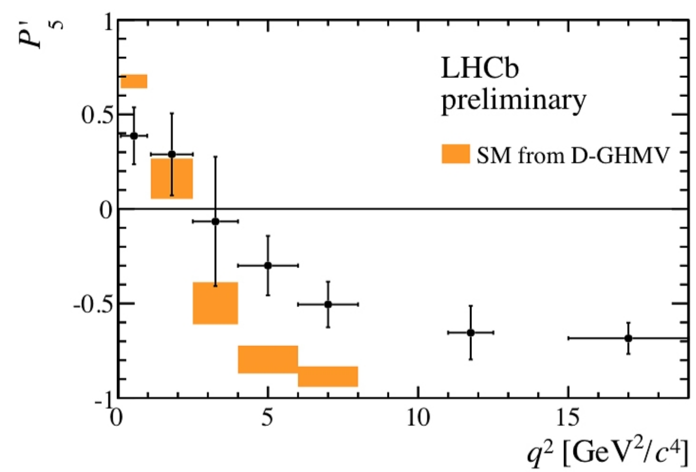
$$R_K = \frac{\mathrm{BR}(B \to K \mu^+ \mu^-)}{\mathrm{BR}(B \to K e^+ e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

$$R_K^{\mathrm{SM}} \sim 1.00 \pm 0.01$$

2.6σ away from the SM

Episode VI: Return of the anomalies

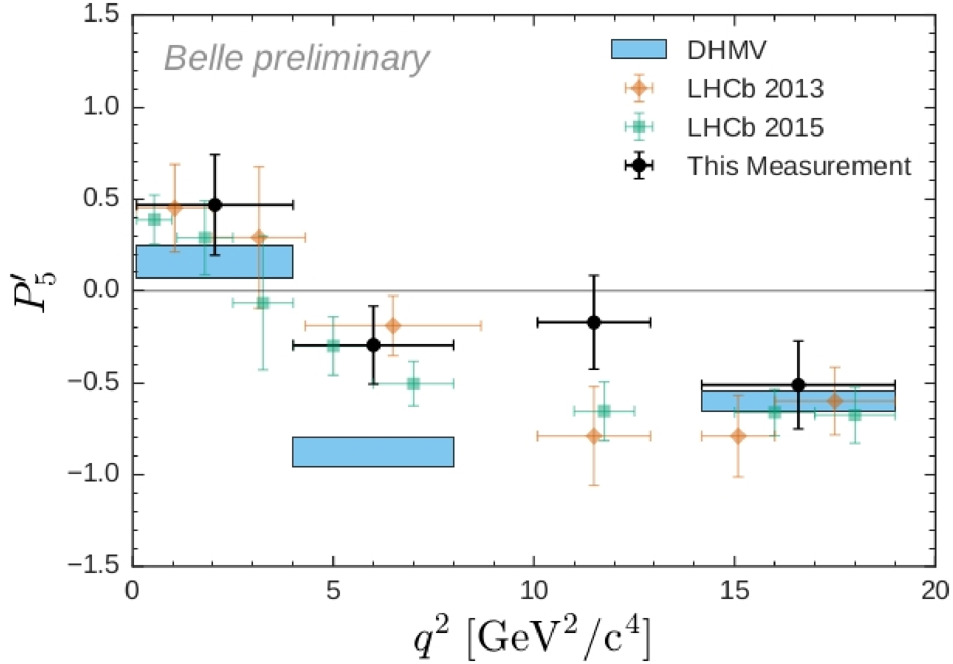
2015 : LHCb confirms first anomalies



The $b \to s$ anomalies

Episode I: The Belle menace

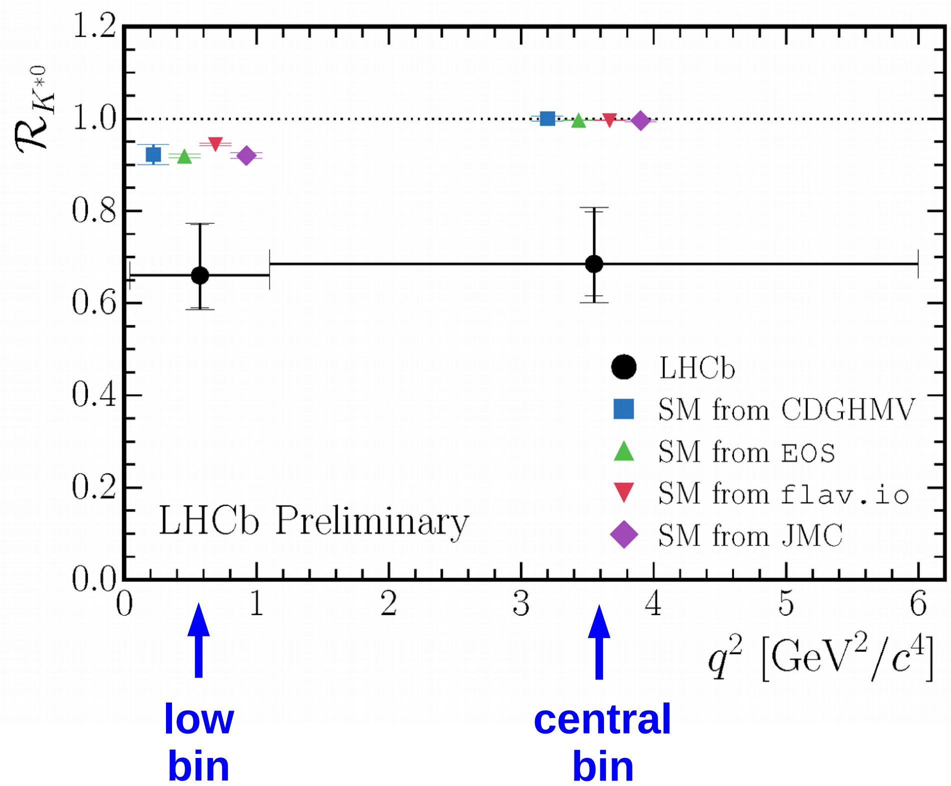
2016 : Belle finds additional hints



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

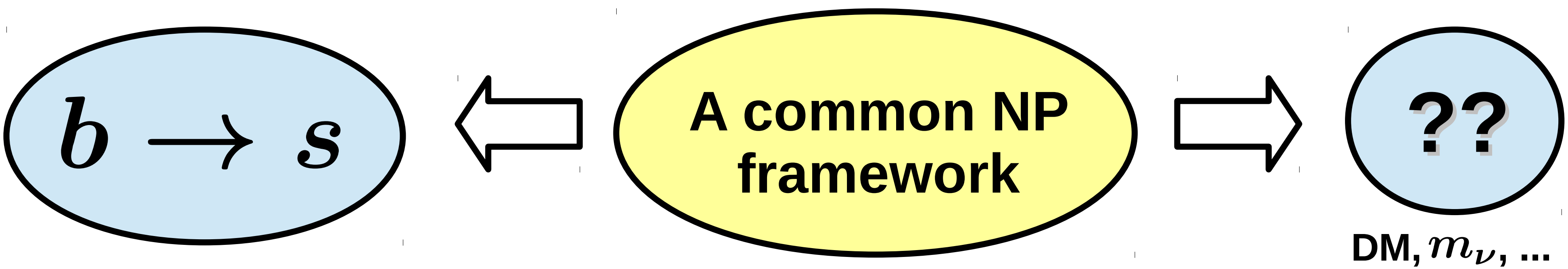

leptoquarks
U_1
S_3
W'
(Pati-Salam)^3
4321
Z'
Adventurous model builder

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 $b \to s$ anomalies

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

Outline

$b \to s$ **and dark matter**

$b \to s$ **and neutrinos**

Summary

Note:
I will omit many interesting models
Apologies!

$b \to s$ anomalies and Dark Matter

Flavor 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

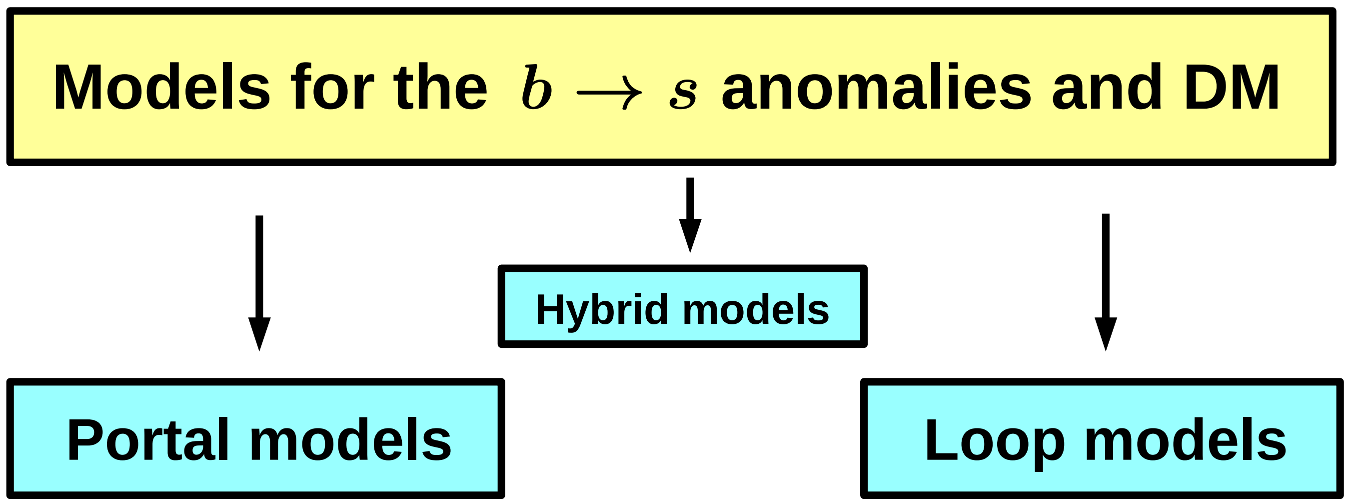
NP models for flavor anomalies ($b \to s$) with a DM candidate ⟵ **This talk**

Model classification

Linking $b \to s$ and DM

See talks by James Cline and Cédric Delaunay

[AV, 1803.04703]



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

Example:

Aristizabal-Sierra, Staub, AV
[1503.06077]

The required NP contributions to $b \to s$ 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 $\mathcal{O}_9$ (and optionally to $\mathcal{O}_{10}$)
- 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

[Aristizabal Sierra, Staub, AV, 2015]

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

Vector-like = “joker”
for model builders

Vector-like fermions

Link to SM fermions

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

Scalars

$$\phi = (\mathbf{1}, \mathbf{1}, 0, 2) \qquad \chi = (\mathbf{1}, \mathbf{1}, 0, -1)$$

$U(1)_X$ breaking

Dark matter candidate

A model with a Z’ portal

[Aristizabal Sierra, Staub, AV, 2015]

Vector-like = “joker”
for model builders

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

$$\mathcal{L}_m = m_Q \overline{Q} Q + m_L \overline{L} L$$

Vector-like (Dirac) masses

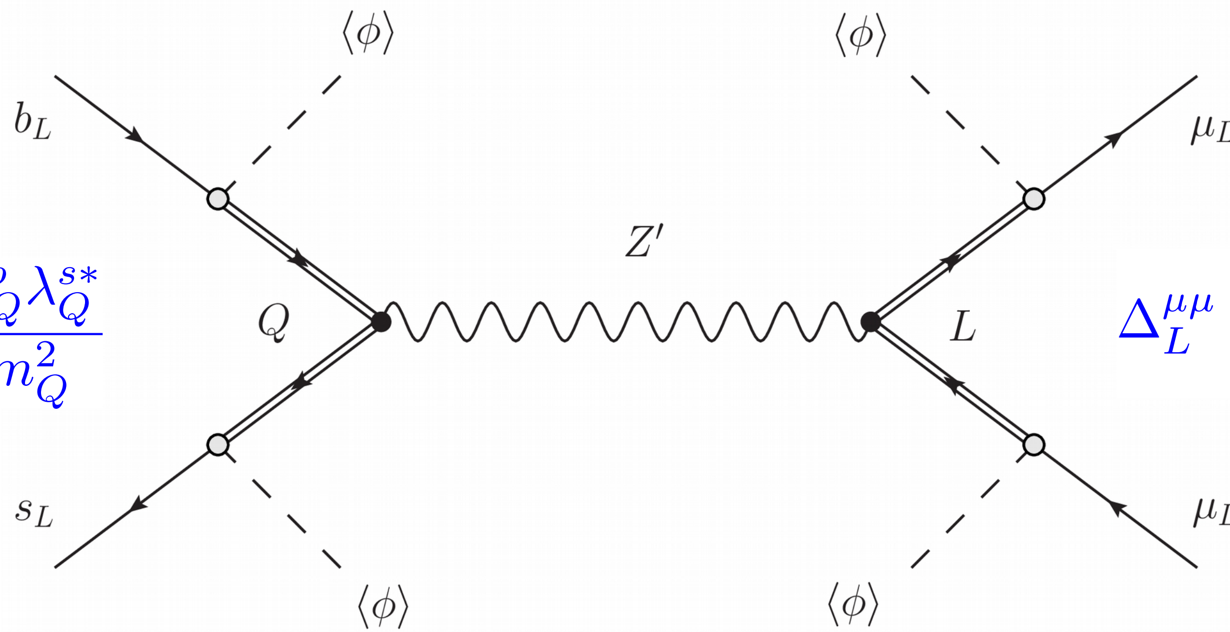
$$\mathcal{L}_Y = \lambda_Q \overline{Q_R} \phi q_L + \lambda_L \overline{L_R} \phi \ell_L + \text{h.c.}$$

VL – SM mixing

Solving the $b \to s$ anomalies

[Aristizabal Sierra, Staub, AV, 2015]

$$\Delta_L^{bs} \simeq g_X v_\phi^2 \, \frac{\lambda_Q^b \lambda_Q^{s*}}{m_Q^2}$$



$$\Delta_L^{\mu\mu} \simeq \frac{2\, g_X |\lambda_L^\mu|^2 v_\phi^2}{2 m_L^2 + |\lambda_L^\mu|^2 v_\phi^2}$$

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

$$C_9^{\rm NP} = -C_{10}^{\rm NP}$$

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

$$U(1)_X \quad \rightarrow \quad \mathbb{Z}_2$$

[Krauss, Wilczek, 1989]
[Petersen et al, 2009]
[Aristizabal Sierra, Dhen, Fong, AV, 2014]

$$\chi = (\mathbf{1}, \mathbf{1}, 0, -1)$$

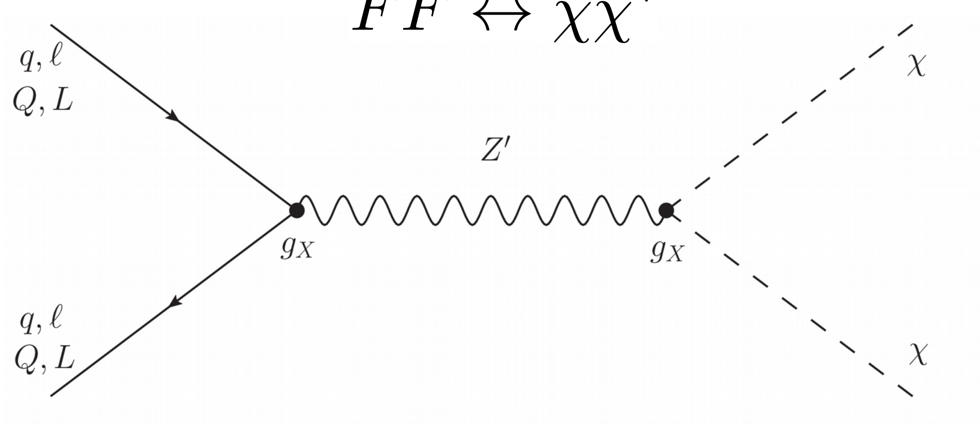
Odd under $\mathbb{Z}_2$

Automatically stable

The dynamics behind the $b \to s$ anomalies stabilizes the DM and provides a production mechanism

DM production

$$\bar{F} F \leftrightarrow \chi \chi^*$$



Z' portal

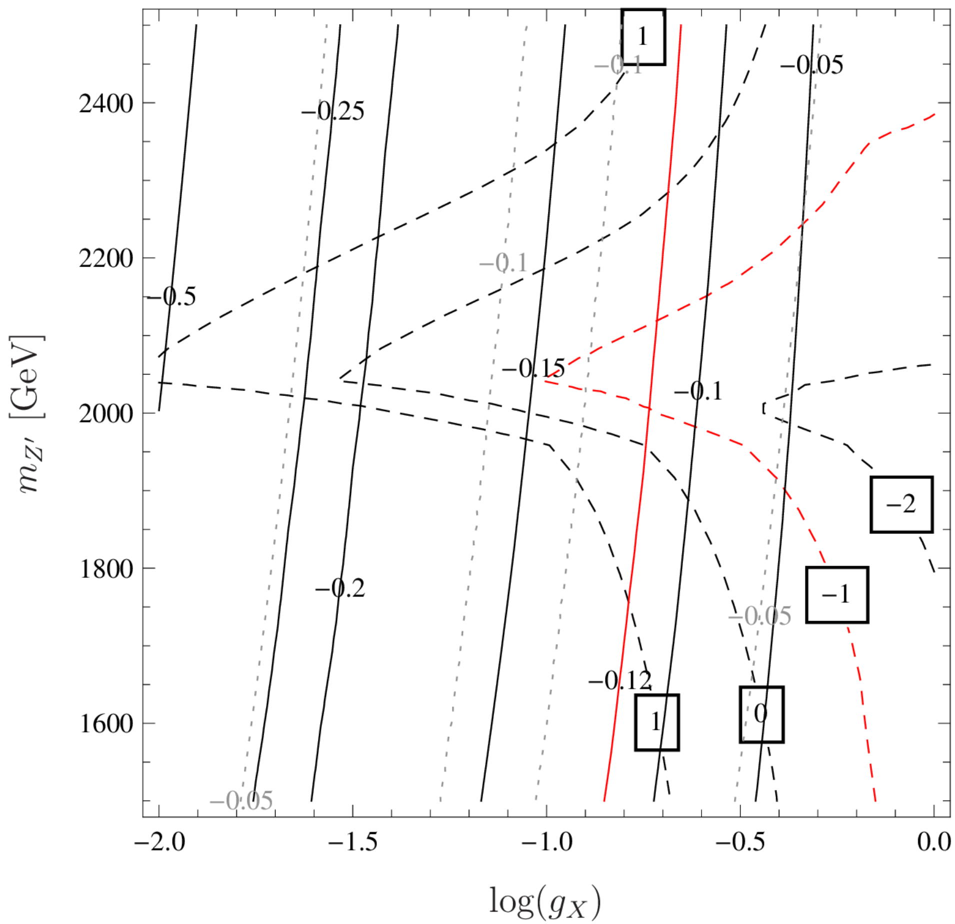
Interplay between Flavor and DM

However:
Higgs portal also possible

Assumption:
$\lambda_{H\chi} \ll 1$

DM and $b \to s$ anomalies

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



[DM RD Computed with **micrOMEGAs**]

Parameters:

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

$$\lambda_L^\mu = 0.5$$

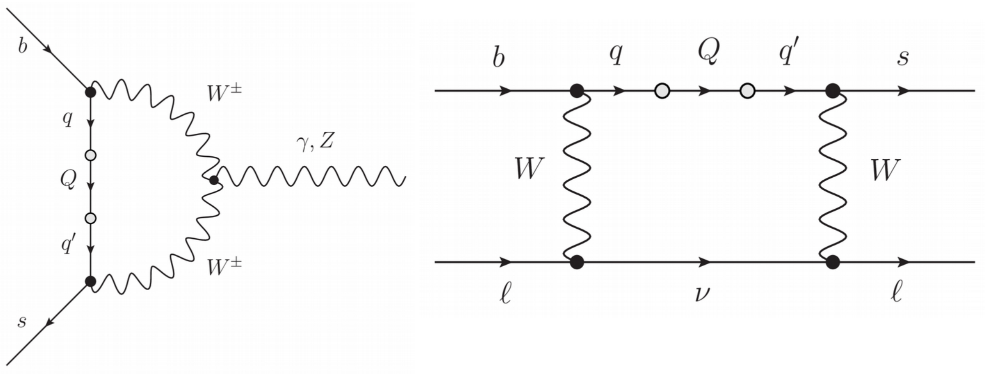
$$m_Q = m_L = 1 \text{ TeV}$$

$$m_\chi^2 = 1 \text{ TeV}^2$$

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

Loop corrections

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



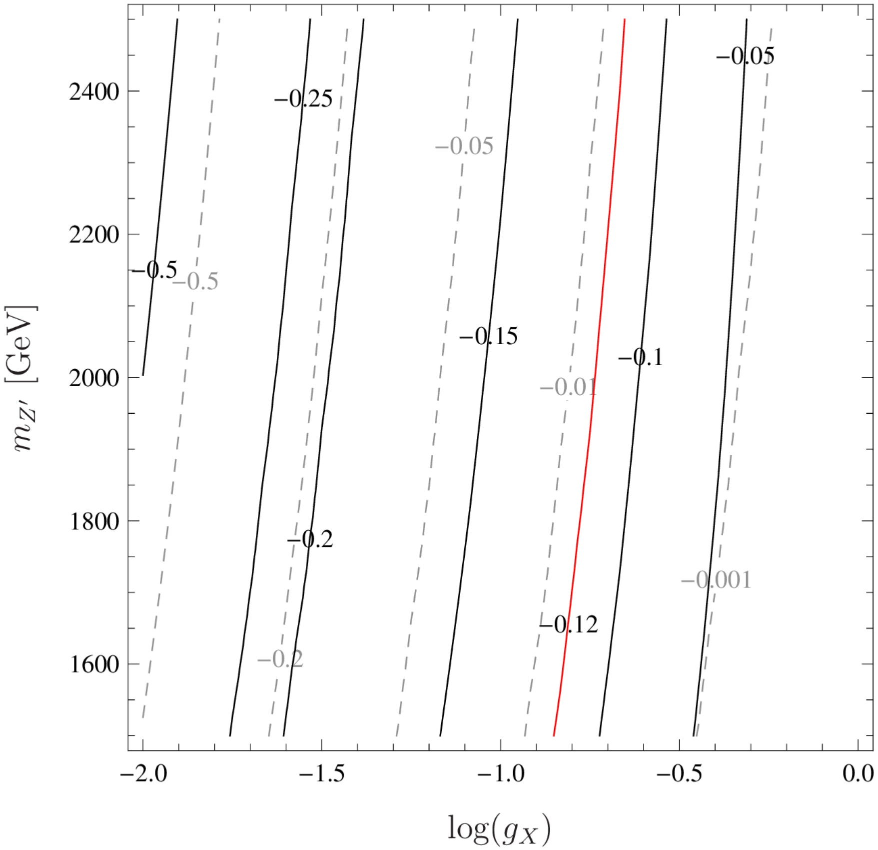
- Non-negligible corrections to C_9
- Unwanted contributions to other Wilson coefficients

However: "Valid" region is safe

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

[Computed with **FlavorKit**]

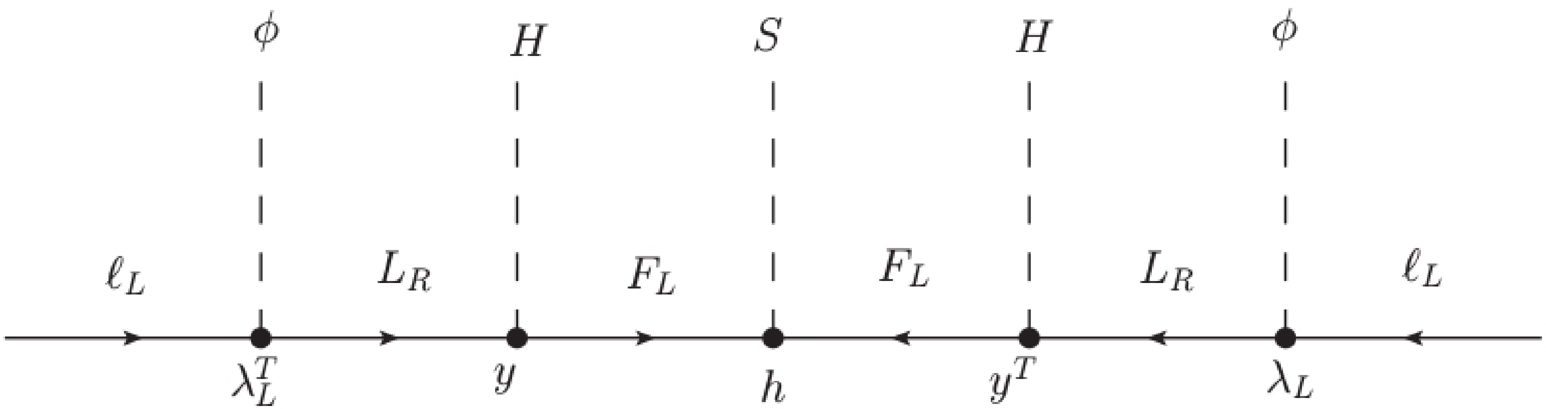
$C_9^{\rm NP}/C_9^{\rm SM}$ (full) $C_7^{\rm NP}/C_7^{\rm SM}$ (dotted gray)



Neutrino masses

Non-trivial embedding of neutrino masses

Rocha-Moran, AV
[1810.02135]



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

$h \ll 1$

allows for light neutrinos and large Yukawa couplings

Inverse seesaw (-like) mechanism

LFV phenomenology in 1810.02135

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!

A loop model

DM here

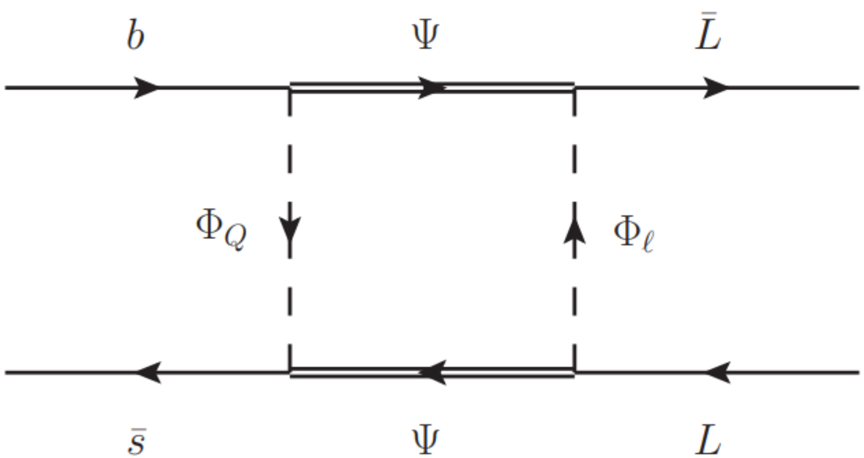
Kawamura, Okawa, Omura

[1706.04344]

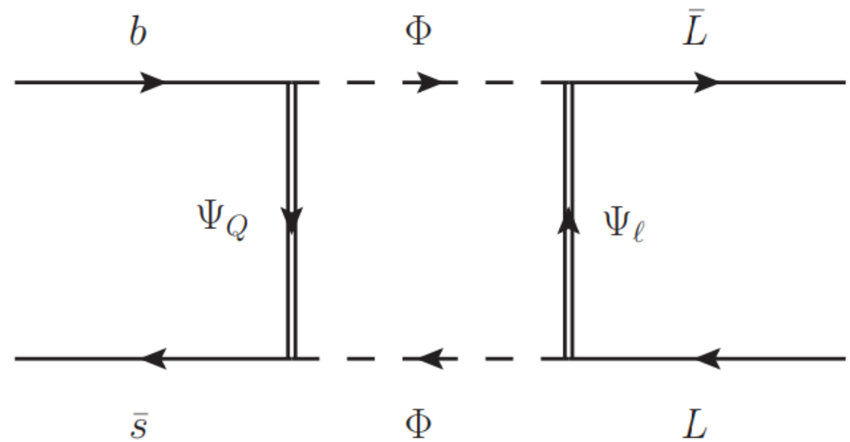
Loops and $b \to s$ anomalies

[Gripaios et al, 2015]
[Arnan et al, 2016]

Class (a)



Class (b)



Figures from Arnan et al [1608.07832]

Model classification

All possible quantum numbers → Some multiplets include colorless neutral states **(DM candidates)**

Different contributions to B_s-mixing

An example loop model

[Kawamura, Okawa, Omura, 2017]

Global ← DM stability

Field	Spin	$SU(3)_c \times SU(2)_L \times U(1)_Y$	$U(1)_X$
DM → X	0	$(\mathbf{1}, \mathbf{1}, 0)$	-1
VL fermions → $Q_{L,R}$	$\frac{1}{2}$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$	1
VL fermions → $L_{L,R}$	$\frac{1}{2}$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$	1

$$\mathcal{L}_Y = \lambda_Q \overline{Q_R}\, X\, q_L + \lambda_L \overline{L_R}\, X\, \ell_L + \text{h.c.}$$

$$\langle X \rangle = 0 \quad \Rightarrow$$

No VL – SM mixing
But new Yukawa interactions

Unbroken
$U(1)_X$ symmetry

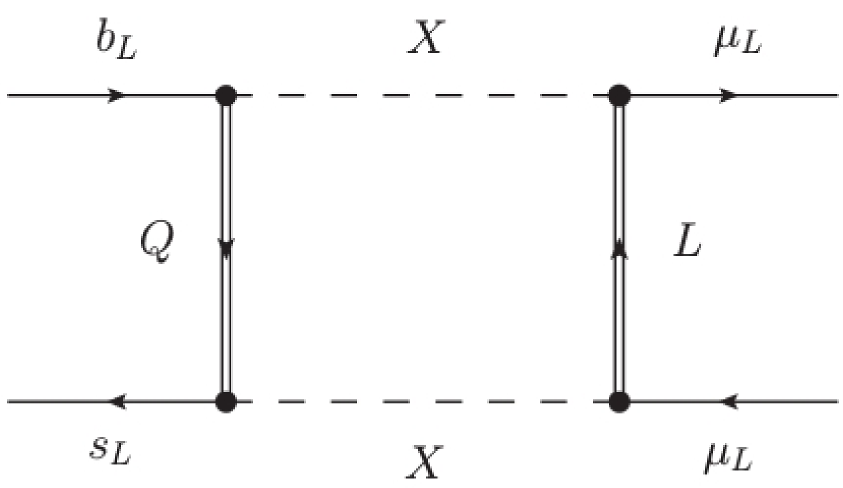
→ Loop explanation to the $b \to s$ anomalies

Solving the $b \to s$ anomalies

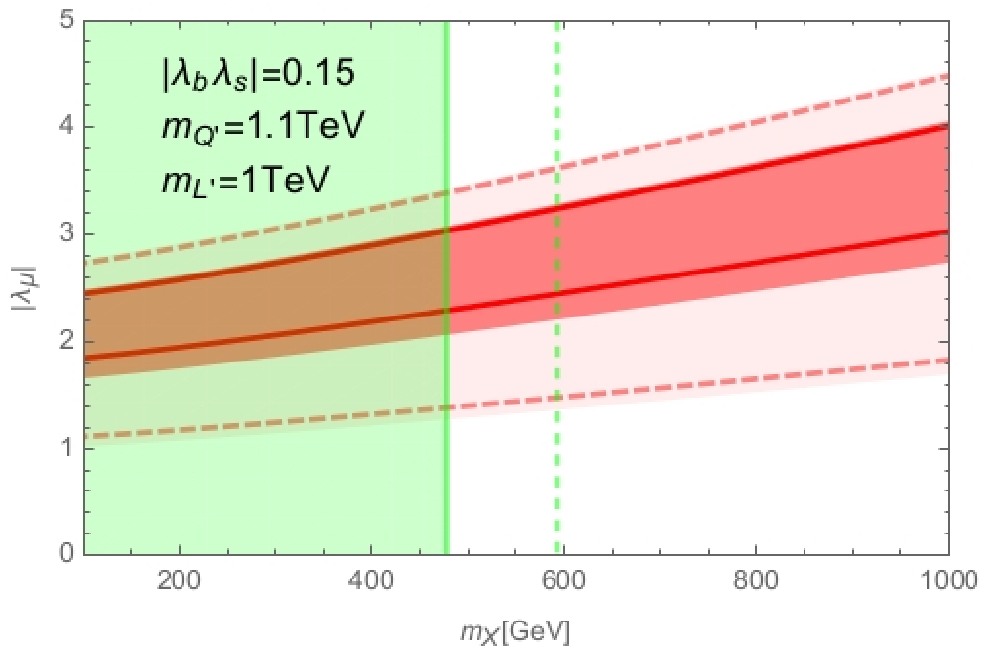
Scenario A-I, model class b)
[1608.07832]

[Kawamura, Okawa, Omura, 2017]

$$C_9^{\mu,\mathrm{NP}} = -C_{10}^{\mu,\mathrm{NP}} = \frac{\lambda_Q^b \lambda_Q^{s*} |\lambda_L^\mu|^2}{64\,\pi^2\, V_{tb} V_{ts}^*} \frac{\Lambda_v^2}{m_Q^2 - m_L^2} \left[f\left(\frac{m_X^2}{m_Q^2}\right) - f\left(\frac{m_X^2}{m_L^2}\right) \right]$$



Loop realization of O_9 and O_{10}



Dark Matter

[Kawamura, Okawa, Omura, 2017]

Lightest particle charged under U(1)$_X$

Stable and promising DM candidate

$$X = (\mathbf{1}, \mathbf{1}, \mathbf{0})$$

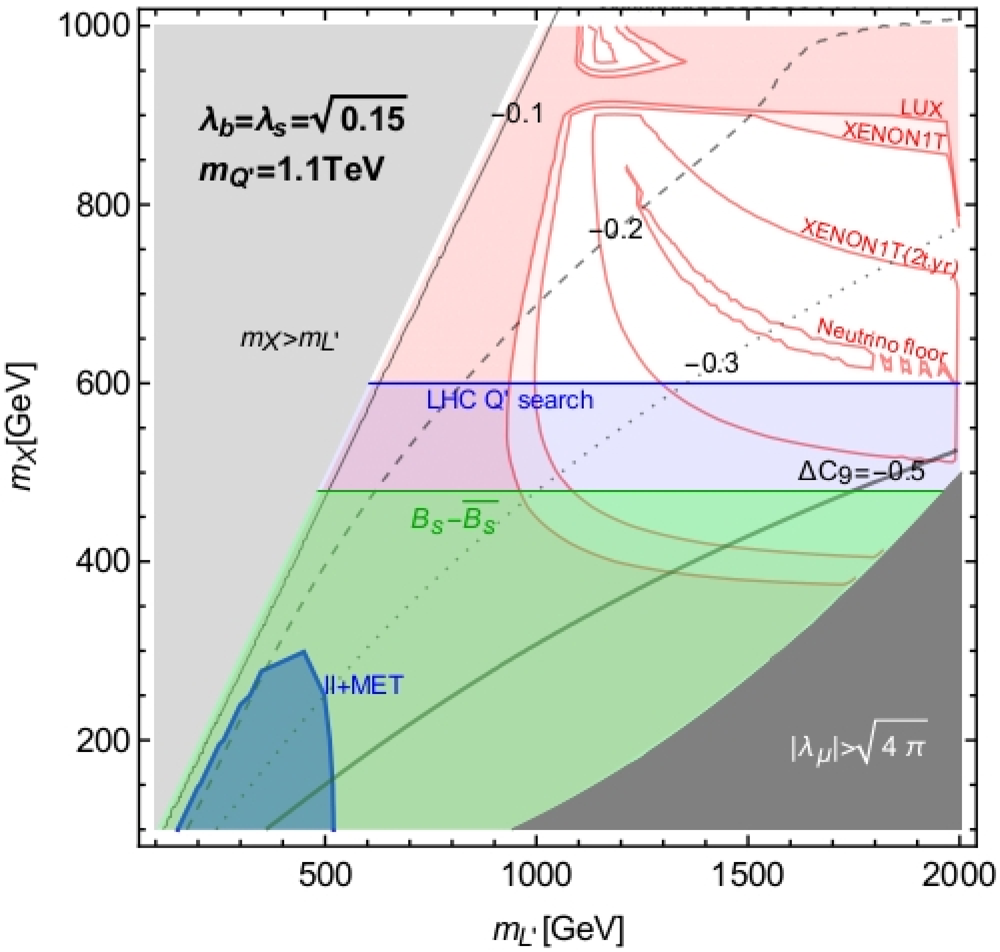
Most relevant annihilation channels for the relic density

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

$$(\text{due to large } \lambda_L^\mu)$$

The model explains the anomalies at 2σ

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



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 scalar DM candidate. Neutrino masses are also accommodated via a type-I seesaw mechanism.

Cline, Cornell [1711.10770]

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

Dhargyal [1711.09772]

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

$b \to s$ anomalies and Neutrinos

LFUV and neutrino masses

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: the link to neutrinos?

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

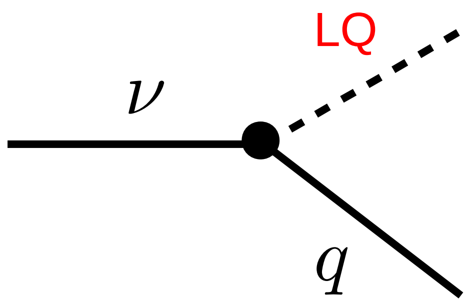
Why two?

$$\ell \; q \; \phi$$

L: +1 0 -1

One can always arrange
for a conserved L

Why radiative?



Must go to loop

Aristizabal Sierra, Hirsch, Kovalenko [0710.5699]

Cai, Herrero-Garcia, Schmidt, AV, Volkas [1706.08524]

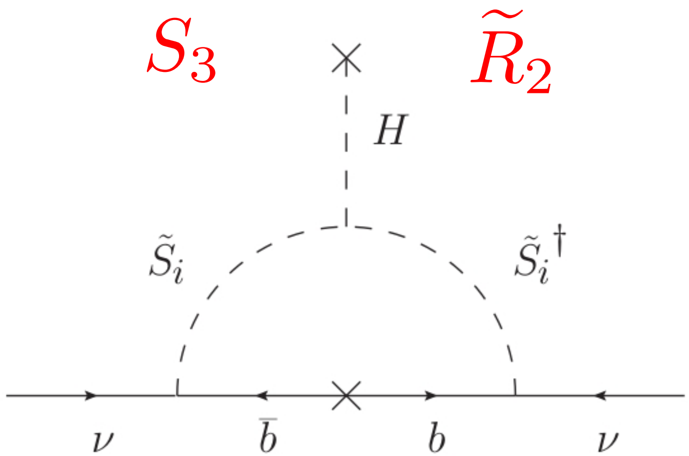
Also in RPV

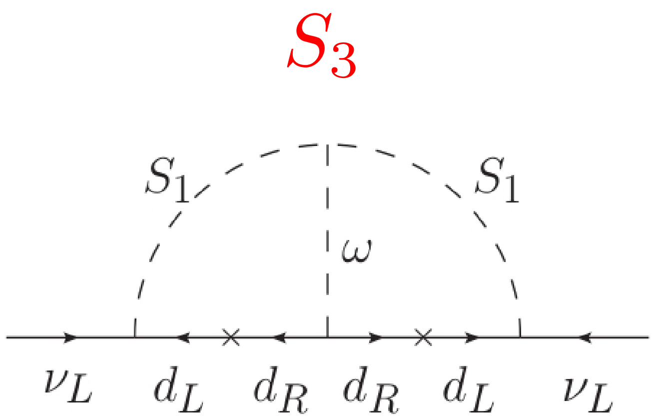
$$\tilde{d}_R^* \sim S_1$$

Leptoquarks: the link to neutrinos?

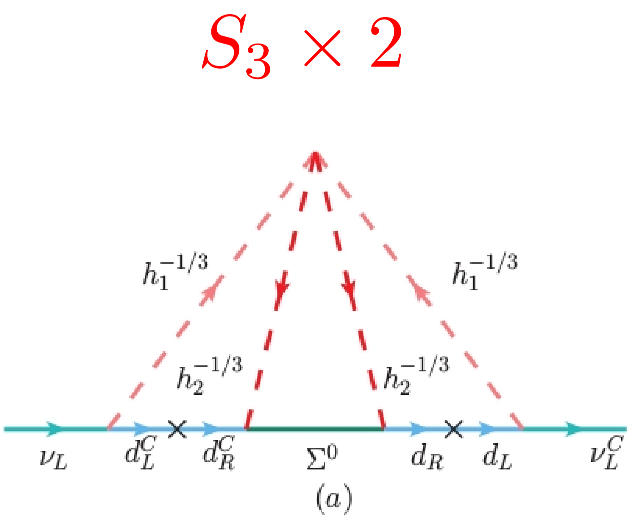
(Some) leptoquark models for the B-anomalies and neutrino masses

Päs, Schumacher [1510.08757]	Guo et al [1707.00522]	Hati et al [1806.10146]





ω : diquark



1-loop **2-loop** **3-loop**

Version with vector LQs in 1603.07672

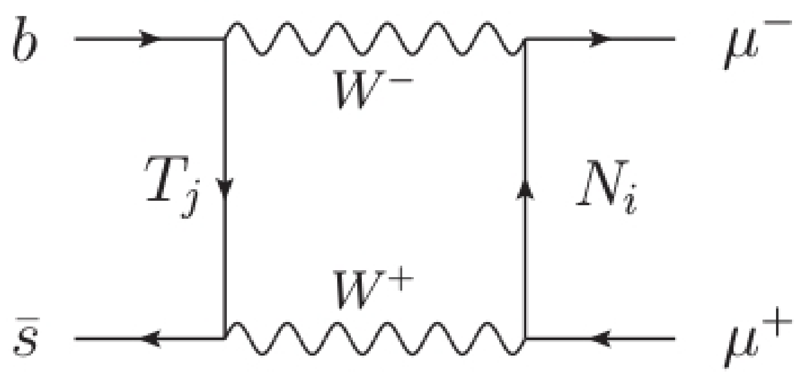
Heavy neutrinos in loops

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

$$b \to s\mu\mu \ \Leftrightarrow \ b \to d\mu\mu$$

Question:
neutrino mass
generation

$$|U_{eN}| \sim 0$$

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

Non-universality
from lepton mixing

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

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 $b \to s$ 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!

Thank you for your attention!

Backup slides

Interpreting the anomalies

$$\boxed{\boldsymbol{b \to s}}$$

Effective hamiltonian

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

C_i : Wilson coefficients

$\mathcal{O}_i$: Operators

$$\mathcal{O}_9 = (\bar{s}\gamma_\mu P_L b) \left(\bar{\ell}\gamma^\mu \ell\right)$$

$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b) \left(\bar{\ell}\gamma^\mu \gamma_5 \ell\right)$$

$$\mathcal{O}_9' = (\bar{s}\gamma_\mu P_R b) \left(\bar{\ell}\gamma^\mu \ell\right)$$

$$\mathcal{O}_{10}' = (\bar{s}\gamma_\mu P_R b) \left(\bar{\ell}\gamma^\mu \gamma_5 \ell\right)$$

$$C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$$

[analogous for primed operators]

$\boldsymbol{B_s \to \mu^+\mu^-}$

$$\mathcal{O} = (\bar{s}\gamma_\alpha P_L b)\;(\bar{\mu}\gamma^\alpha P_L \mu) \quad \Rightarrow \quad \overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)$$

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

[CMS and LHCb, 2013]

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

[Bobeth et al, 2013]

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

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

The model is compatible at 2σ

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

[Altmannshofer et al, 2014]

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

$$\frac{m_{Z'}}{|\Delta_L^{bs}|} \gtrsim 244\,\mathrm{TeV}$$

FlavorKit

[Porod, Staub, AV, 2014]

A computer tool that provides automatized analytical and numerical computation of flavor observables. It is based on SARAH, SPheno and FeynArts/FormCalc.

Lepton flavor	Quark flavor
$\ell_\alpha \to \ell_\beta \gamma$	$B^0_{s,d} \to \ell^+ \ell^-$
$\ell_\alpha \to 3\,\ell_\beta$	$\bar{B} \to X_s \gamma$
$\mu - e$ conversion in nuclei	$\bar{B} \to X_s \ell^+ \ell^-$
$\tau \to P\,\ell$	$\bar{B} \to X_{d,s} \nu \bar{\nu}$
$h \to \ell_\alpha \ell_\beta$	$B \to K \ell^+ \ell^-$
$Z \to \ell_\alpha \ell_\beta$	$K \to \pi \nu \bar{\nu}$
	$\Delta M_{B_{s,d}}$
	ΔM_K and ε_K
	$P \to \ell \nu$

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!

Manual: arXiv:1405.1434
Website: http://sarah.hepforge.org/FlavorKit.html

LFV in B meson decays

What about LFV?

[Glashow et al, 2014]

Lepton universality violation generically implies lepton flavor violation

Gauge basis

Mass basis

$$\mathcal{O} = \widetilde{C}^Q \left(\bar{q}' \gamma_\alpha P_L q'\right) \widetilde{C}^L \left(\bar{\ell}' \gamma^\alpha P_L \ell'\right) \longrightarrow \mathcal{O} = C^Q \left(\bar{q} \gamma_\alpha P_L q\right) C^L \left(\bar{\ell} \gamma^\alpha P_L \ell\right)$$

$$C^L = U_\ell^\dagger \, \widetilde{C}^L \, U_\ell$$

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

Are the anomalies related to neutrino oscillations?

Working hypothesis: What if $U_\ell = K^\dagger$?

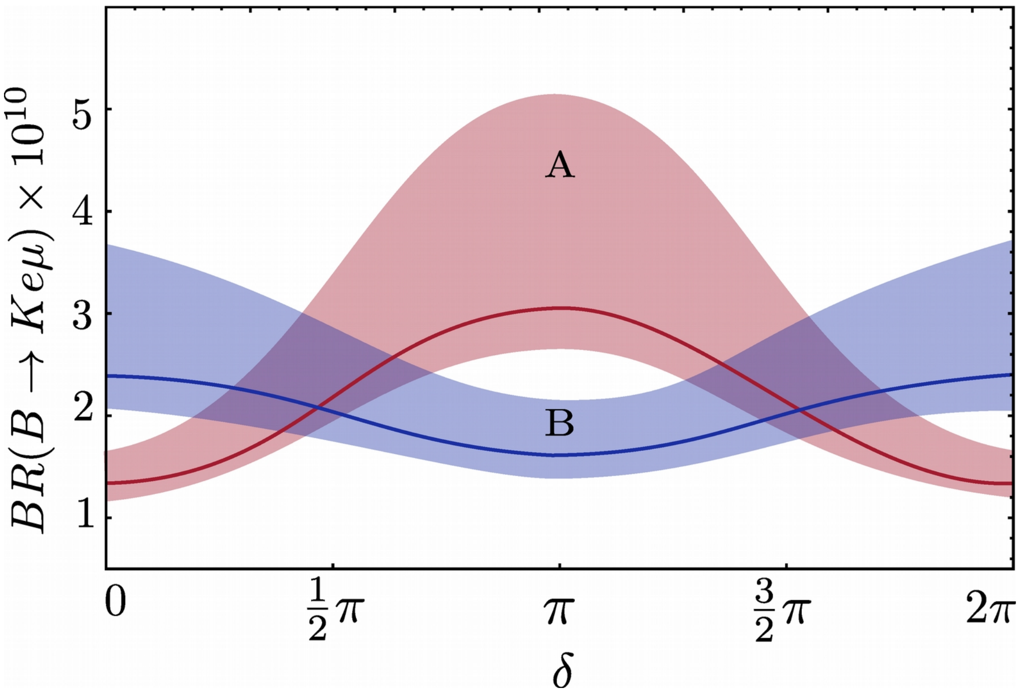
[Boucenna, Valle, AV, 2015]

↑

Neutrino oscillations

Neutrinos ⟷ B-physics

LHCb sensitivity $\sim 10^{-10}$



Lines: BF
Bands: 1σ