The $b \to s$ anomalies and Dark Matter

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Mainly based on [arXiv:1803.04703]

Flavour and DM Workshop
Karlsruhe

What this talk is about

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**

The $b \to s$ anomalies

2013 - Episode IV: A new hope

2014 - Episode V: LHCb strikes back

2015 - Episode VI: Return of the anomalies

2016 - Episode I: The Belle menace

2017 - Episode II: Attack of R_K*

2018 - Episode III: ???

The $b \to s$ anomalies

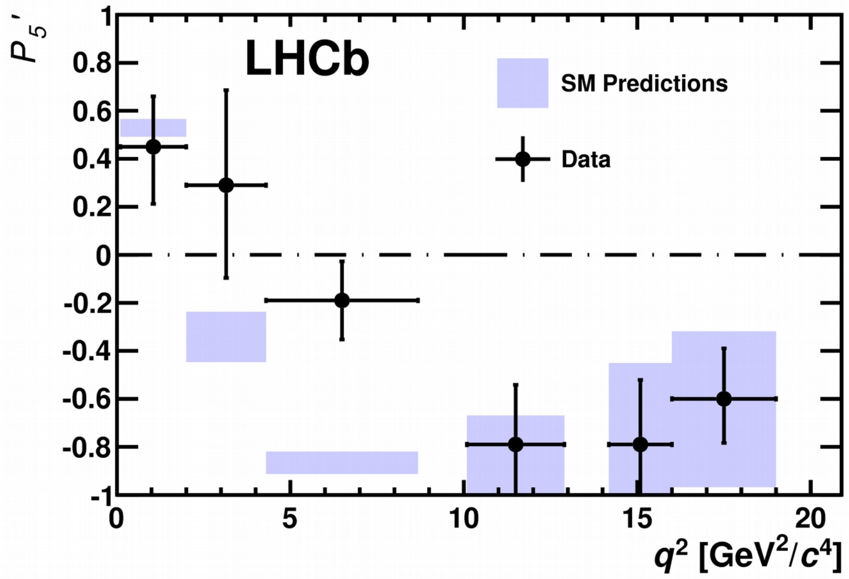
[LHCb, 2013]
1305.2168, 1308.1707, 1403.8044

Episode IV: A new hope

2013 : First anomalies found by LHCb

- Data collected: $1\ \mathrm{fb}^{-1}$ $(3\ \mathrm{fb}^{-1}$ in some observables$)$
- Decrease (w.r.t. the SM) in several branching ratios
- Several anomalies in angular observables

arXiv:1308.1707

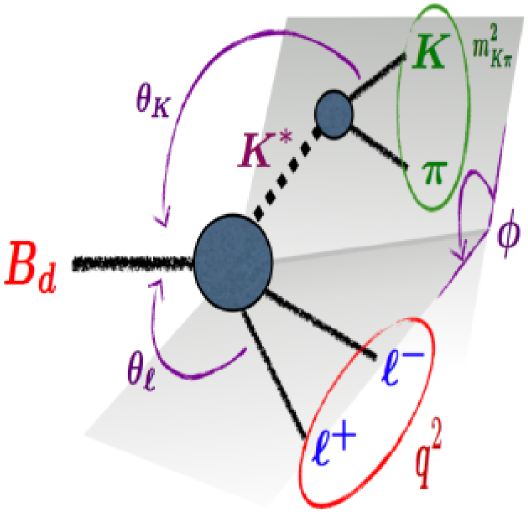


Popular example: P_5' in $B \to K^* \mu^+ \mu^-$

The $b \to s$ anomalies

$B \to K^* (\to K\pi)\, \mu^+\mu^-$ differential angular distribution

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\Big[J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l$$
$$+J_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + J_4\sin 2\theta_K\sin 2\theta_l\cos\phi + J_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+(J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l + J_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+J_8\sin 2\theta_K\sin 2\theta_l\sin\phi + J_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$



[Figure borrowed from Javier Virto]

J_i : functions of q^2, C_i, FF

Optimized observables
[Descotes-Genon et al, 2012, 2013]

$$P_5' = \frac{J_5}{2\sqrt{-J_{2s}J_{2c}}}$$

The $b \to s$ anomalies

[LHCb, 2014]
arXiv:1406.6482

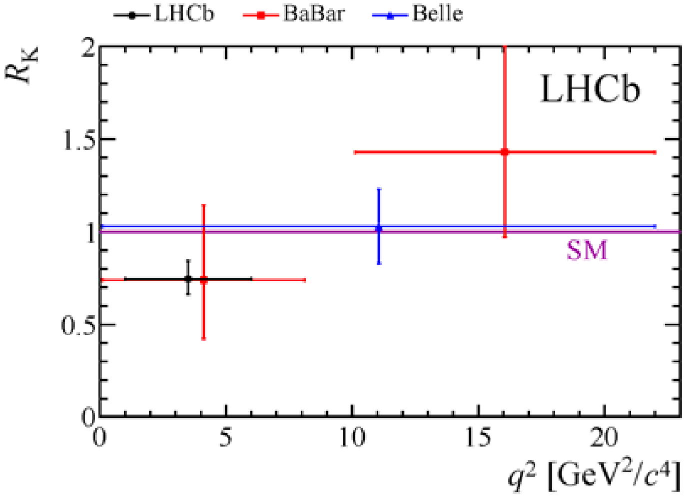
Episode V: LHCb strikes back

2014 : Lepton universality violation

Obtained with 3 fb^{-1}

$$R_K = [R_K]_{[1,6]} = \left.\frac{\text{BR}(B \to K\mu^+\mu^-)}{\text{BR}(B \to K e^+ e^-)}\right|_{q^2\in[1,6]\text{GeV}^2} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

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



2.6σ away from the SM

The $b \to s$ anomalies

[LHCb, 2015]
1512.04442

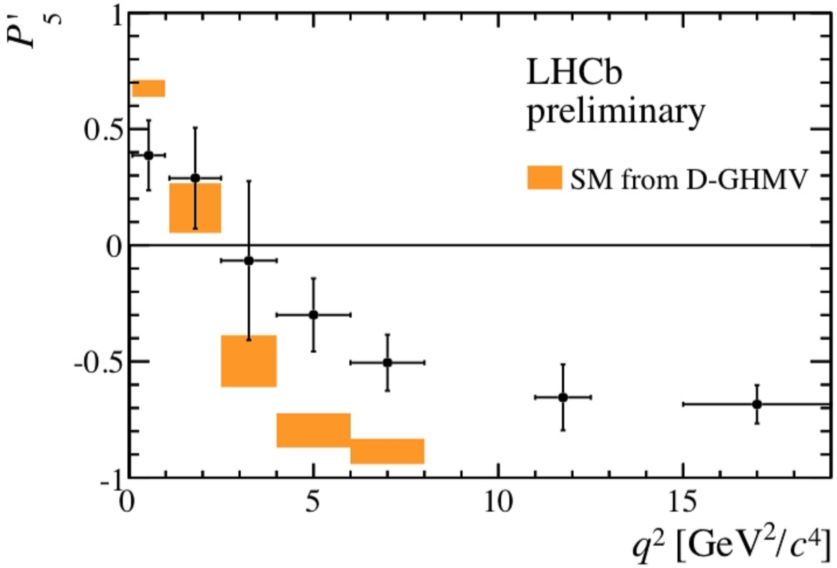
Episode VI: Return of the anomalies

2015 : LHCb confirms first anomalies

$$\text{All observables updated to } 3\ \text{fb}^{-1}$$

[Complete LHC Run I dataset]

Errors shrunk...
... anomalies persist

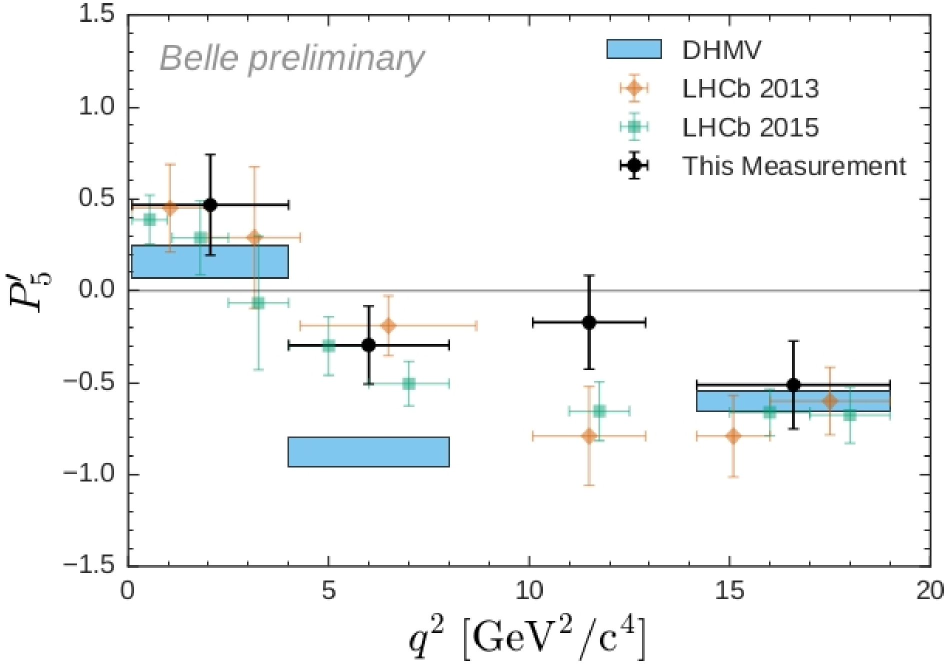


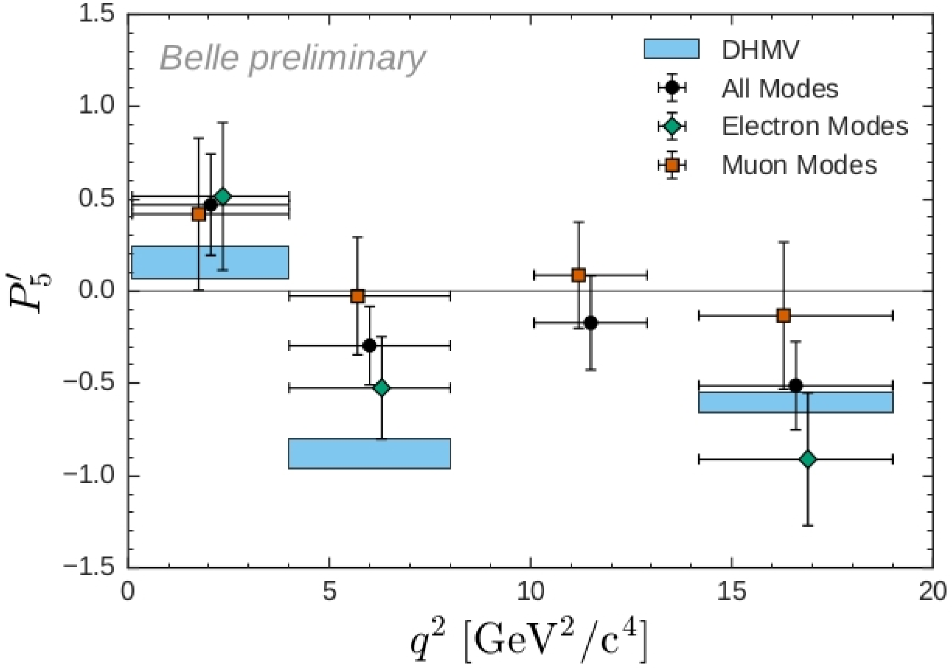
The $b \to s$ anomalies

[Belle, 2016]
1612.05014

Episode I: The Belle menace

2016 : Belle finds additional hints





P_5' anomaly confirmed

Little LFVU indication

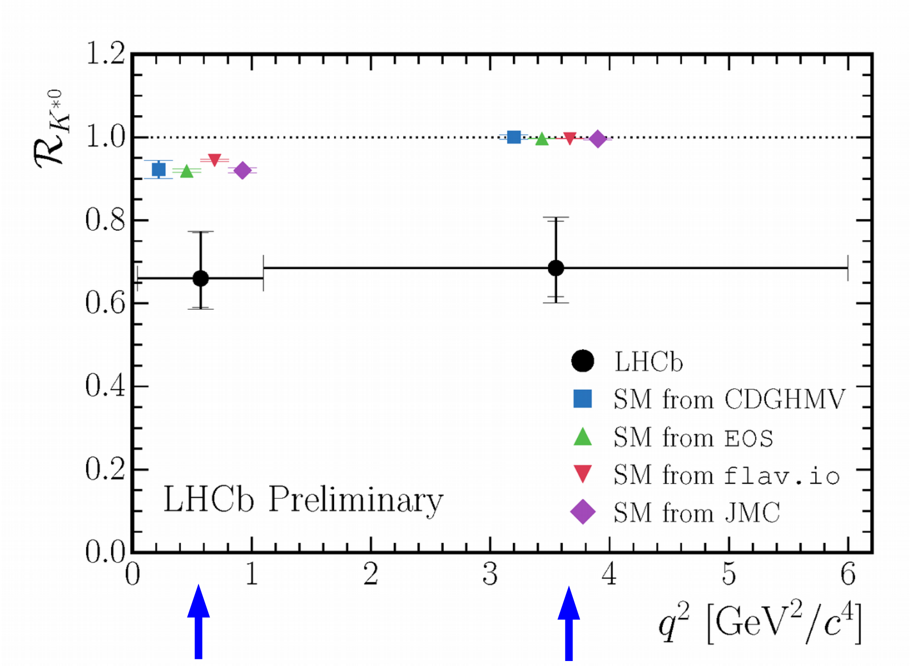
The $b \to s$ anomalies

[LHCb, 2017]
1705.05802

Episode II: Attack of R_{K^*}

2017 : More universality violation in LHCb

Obtained with 3 fb^{-1}



low bin

central bin

The $b \to s$ anomalies

Episode III: Revenge of the Standard Model?

?

Hopefully not!

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

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

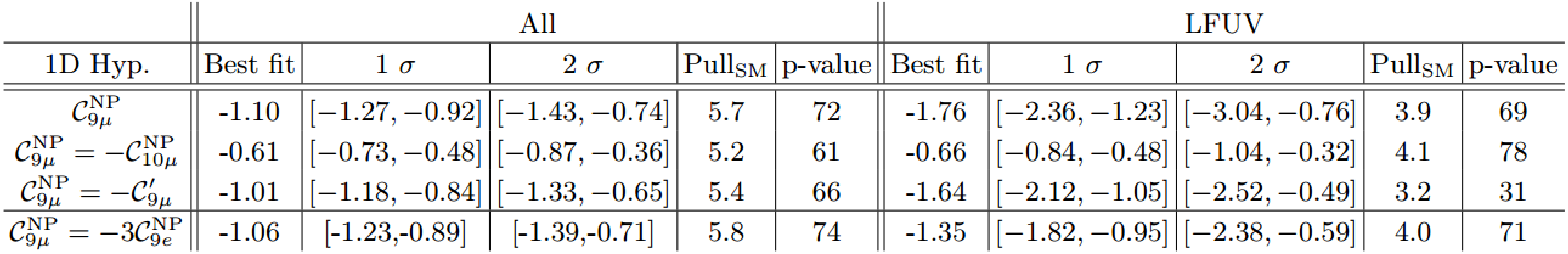
$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)\,\left(\bar{\ell}\gamma^\mu \gamma_5 \ell\right) \qquad \mathcal{O}_{10}' = (\bar{s}\gamma_\mu P_R b)\,\left(\bar{\ell}\gamma^\mu \gamma_5 \ell\right)$$

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

[analogous for primed operators]

Global fits

Table from Capdevila et al, 1704.05340



	All					LFUV				
1D Hyp.	Best fit	1 σ	2 σ	Pull$_{\rm SM}$	p-value	Best fit	1 σ	2 σ	Pull$_{\rm SM}$	p-value
$\mathcal{C}_{9\mu}^{\rm NP}$	-1.10	$[-1.27,-0.92]$	$[-1.43,-0.74]$	5.7	72	-1.76	$[-2.36,-1.23]$	$[-3.04,-0.76]$	3.9	69
$\mathcal{C}_{9\mu}^{\rm NP}=-\mathcal{C}_{10\mu}^{\rm NP}$	-0.61	$[-0.73,-0.48]$	$[-0.87,-0.36]$	5.2	61	-0.66	$[-0.84,-0.48]$	$[-1.04,-0.32]$	4.1	78
$\mathcal{C}_{9\mu}^{\rm NP}=-\mathcal{C}_{9\mu}'$	-1.01	$[-1.18,-0.84]$	$[-1.33,-0.65]$	5.4	66	-1.64	$[-2.12,-1.05]$	$[-2.52,-0.49]$	3.2	31
$\mathcal{C}_{9\mu}^{\rm NP}=-3\mathcal{C}_{9e}^{\rm NP}$	-1.06	[-1.23,-0.89]	[-1.39,-0.71]	5.8	74	-1.35	$[-1.82,-0.95]$	$[-2.38,-0.59]$	4.0	71

All observables

"clean" + "dirty"

Only LFUV observables

"clean"

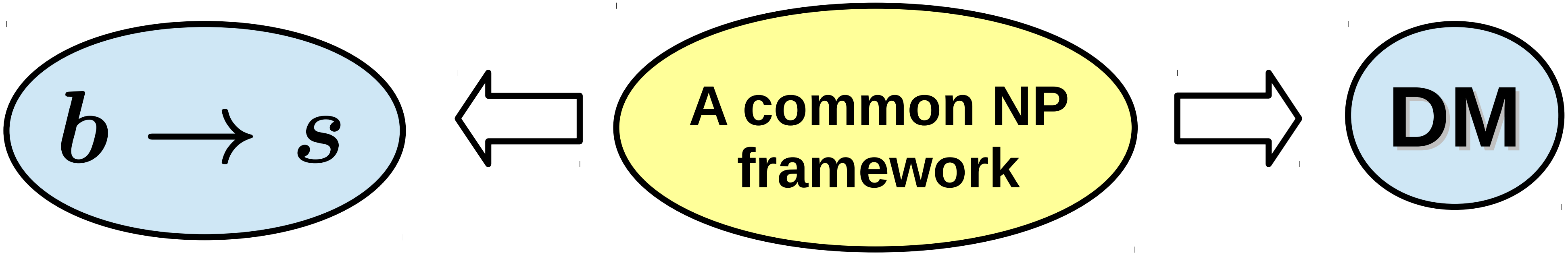
<u>New Physics hypothesis preferred over SM</u> by more than 5 σ (4 σ if only LFUV)

The $\mathcal{C}_{9\mu}$ coefficient seems to be crucial

Qualitatively similar results in 1704.05435 and 1704.05438

Killing two birds with one stone

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



$b \to s$ ⇐ **A common NP framework** ⇒ **DM**

Chuck Norris fact of the day

Chuck Norris can kill two stones with one bird

Outline

Model classification

A portal model

Aristizabal-Sierra, Staub, AV
[1503.06077]

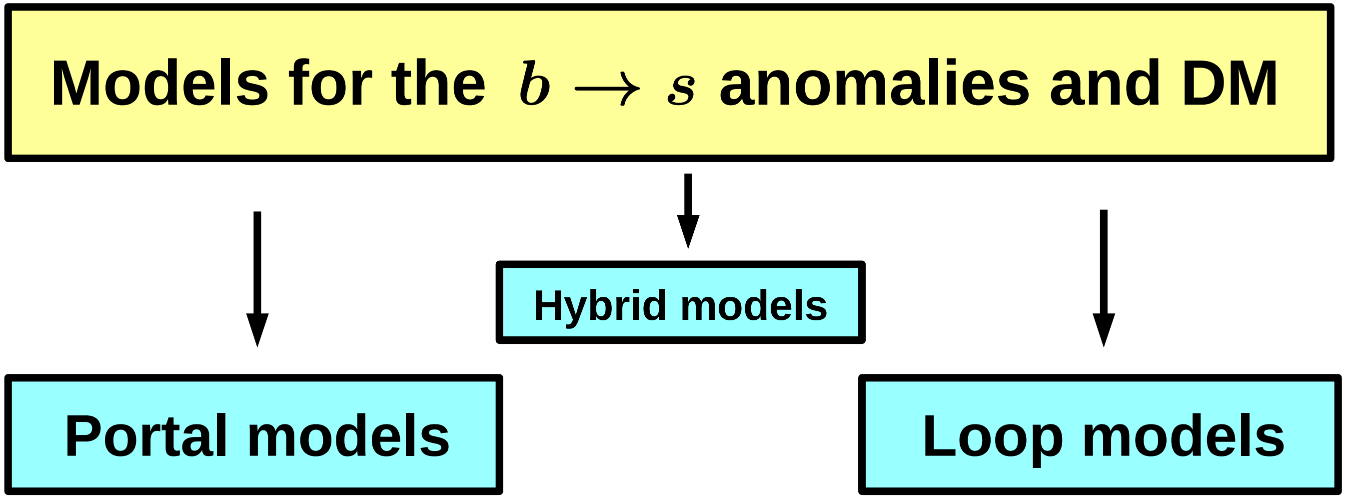
A loop model

Kawamura, Okawa, Omura
[1706.04344]

Model classification

Linking $b \to s$ and DM

[AV, 2018]



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

Hybrid models

Portal models

Loop models

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]

LFV phenomenology in
P. Rocha-Moran, AV
[1809.XXXXX]

Z’ : what do we need?

Z' model building

Easiest (but not unique) solution to the b-s anomalies

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 ⟶ **Dark Matter**

A model with a Z’ portal

[Aristizabal Sierra, Staub, AV, 2015]

Vector-like = “joker”
for model builders

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

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]

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

Vector-like = “joker”
for model builders

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

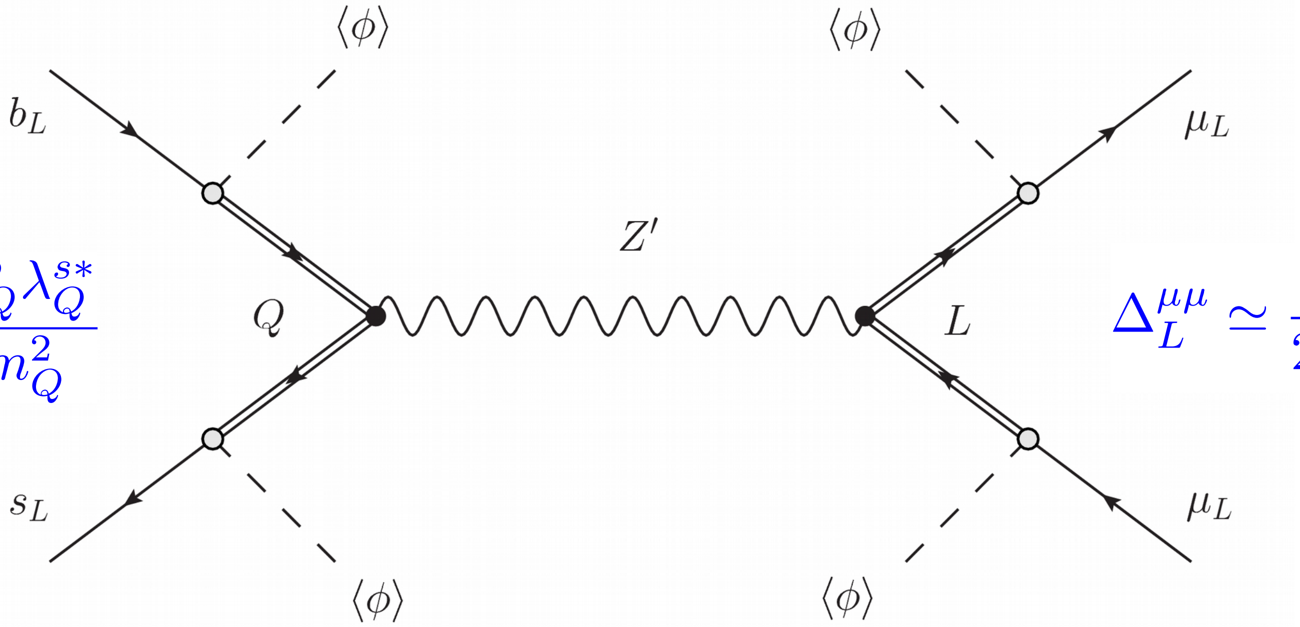
Vector-like (Dirac)
masses

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

VL – SM mixing

Solving the $b \to s$ anomalies

[Aristizabal Sierra, Staub, AV, 2015]



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

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

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

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

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

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

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

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

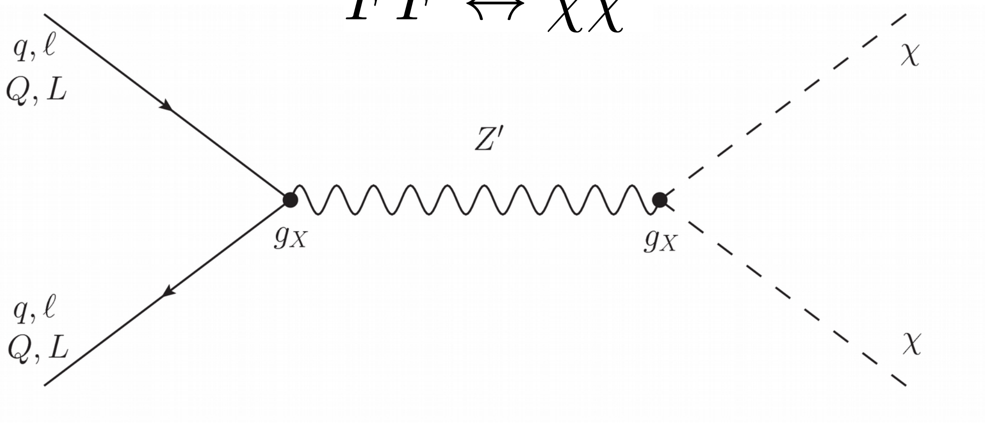
Odd under $\mathbb{Z}_2$

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

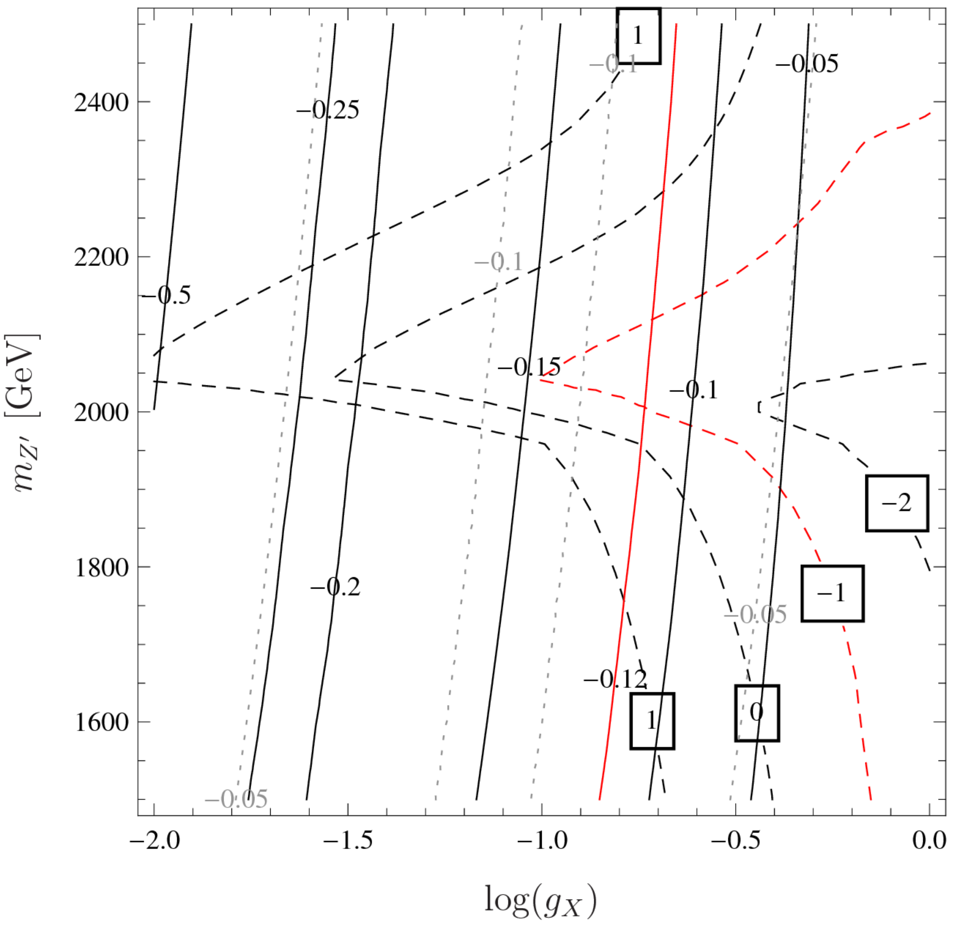
However:
Higgs portal also possible

Assumption:

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

DM and $b \to s$ anomalies

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



[DM RD Computed with **micrOMEGAs**]

Parameters:

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

$$\lambda_L^\mu = 0.5$$

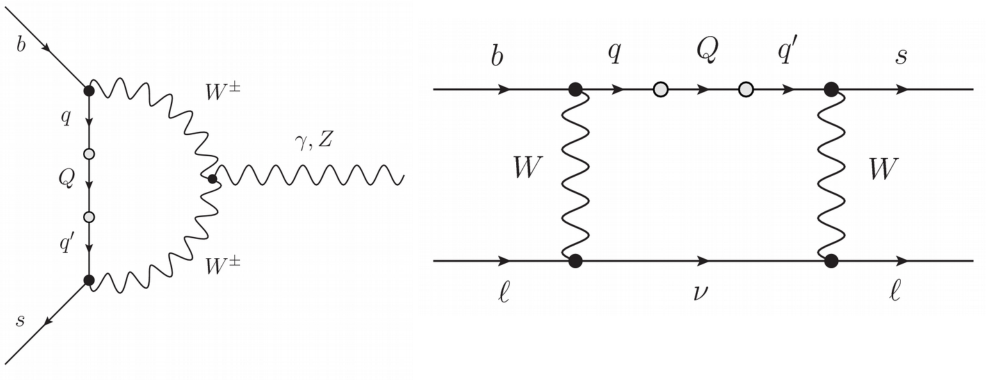
$$m_Q = m_L = 1 \text{ TeV}$$

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

- 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



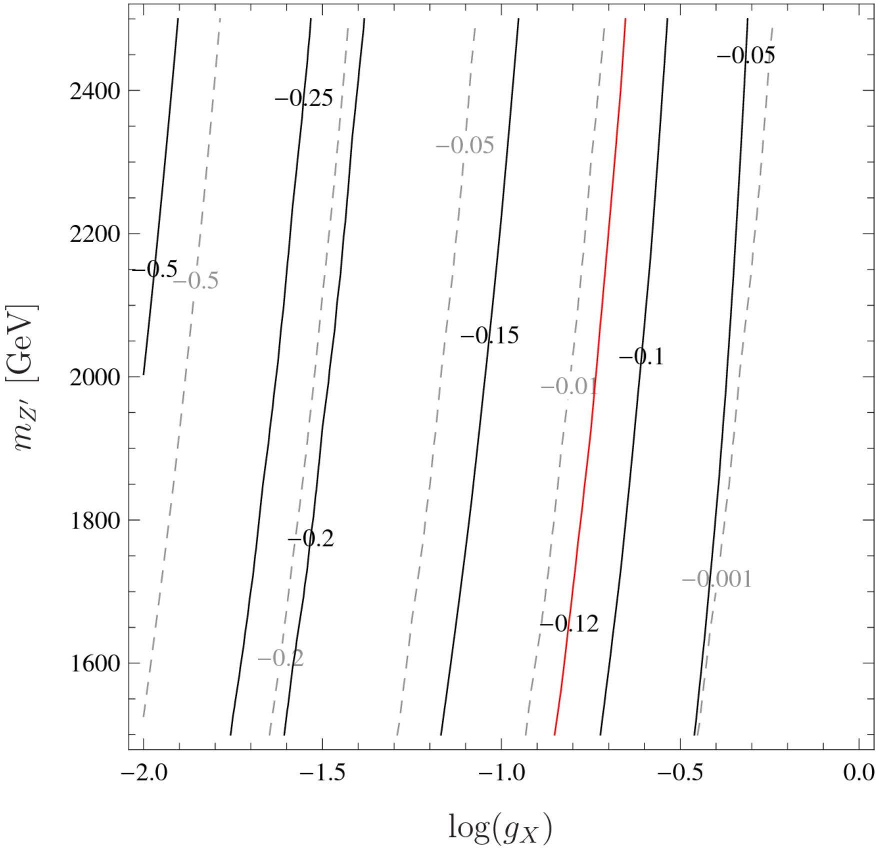
- Non-negligible corrections to C_9
- Unwanted contributions to other Wilson coefficients

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)



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!

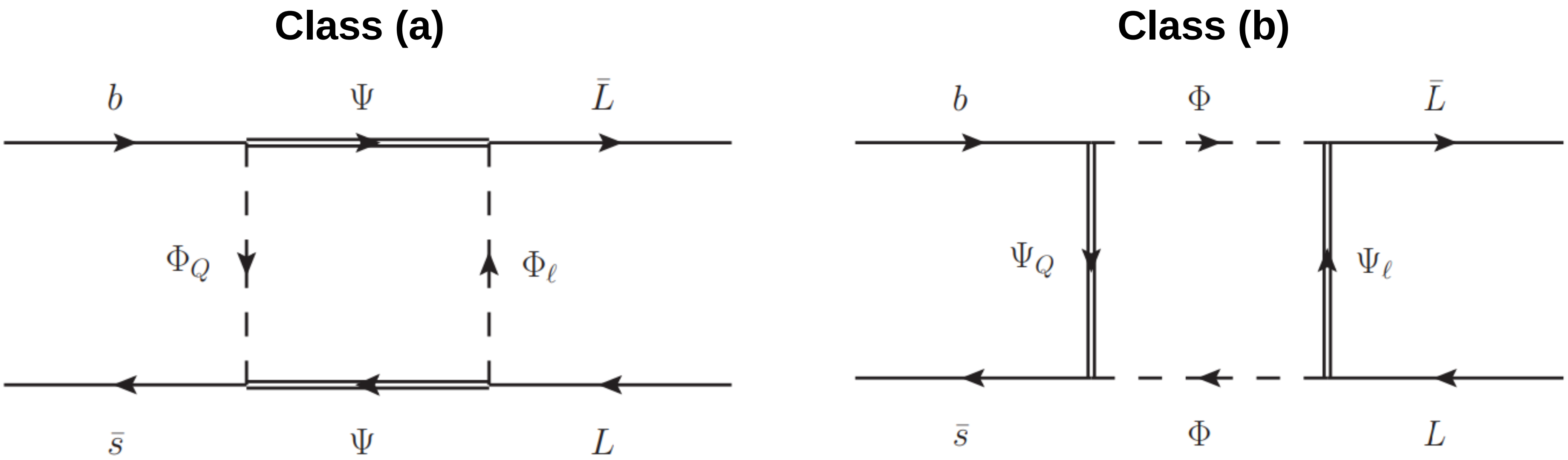
A loop model


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 <u>colorless neutral states</u> **(DM candidates)**

Different contributions to B_s-mixing

An example loop model

[Kawamura, Okawa, Omura, 2017]

Global ← **DM stability**

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

DM → X

VL fermions → $\{Q_{L,R}, L_{L,R}$

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

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

No VL – SM mixing
But new Yukawa interactions

Unbroken
U(1)$_X$ symmetry

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

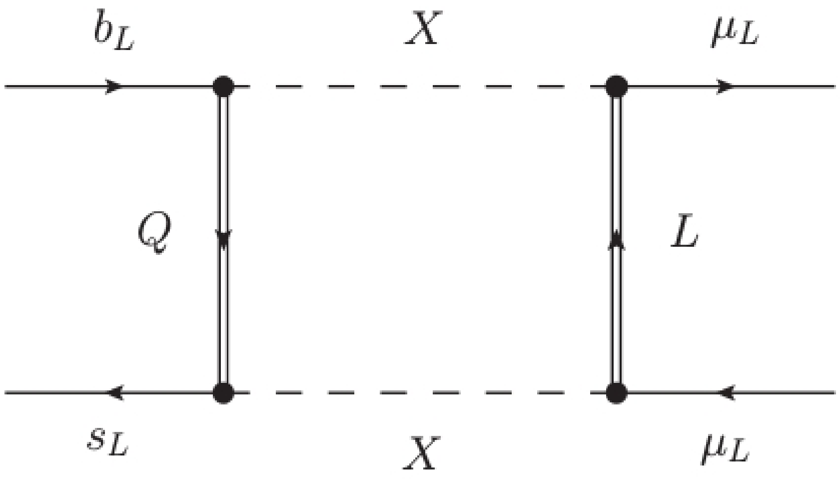
Solving the $b \to s$ anomalies

Scenario A-I, model class b)

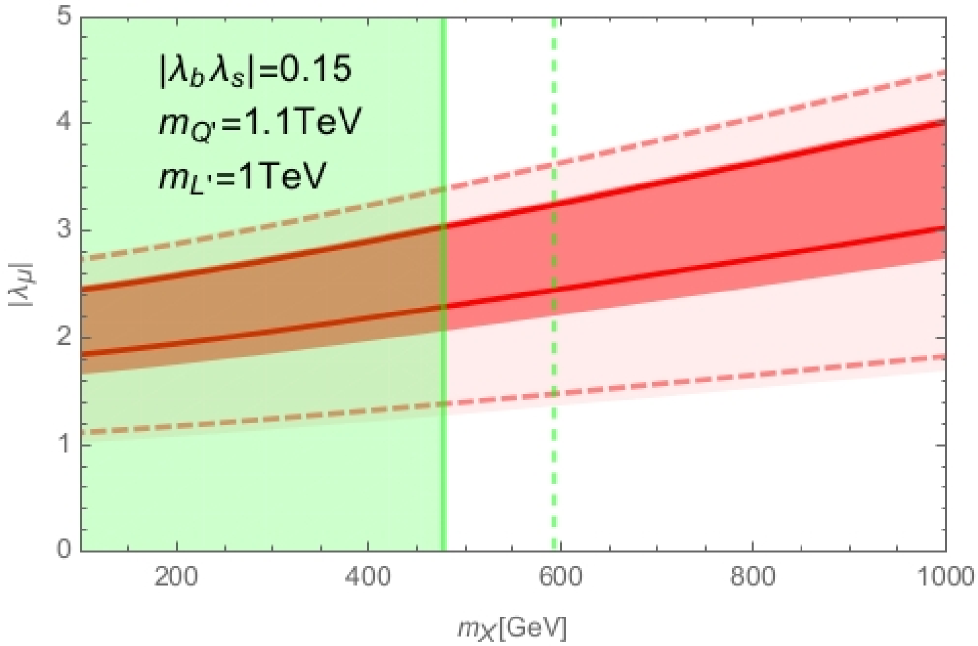
[1608.07832]

[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

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

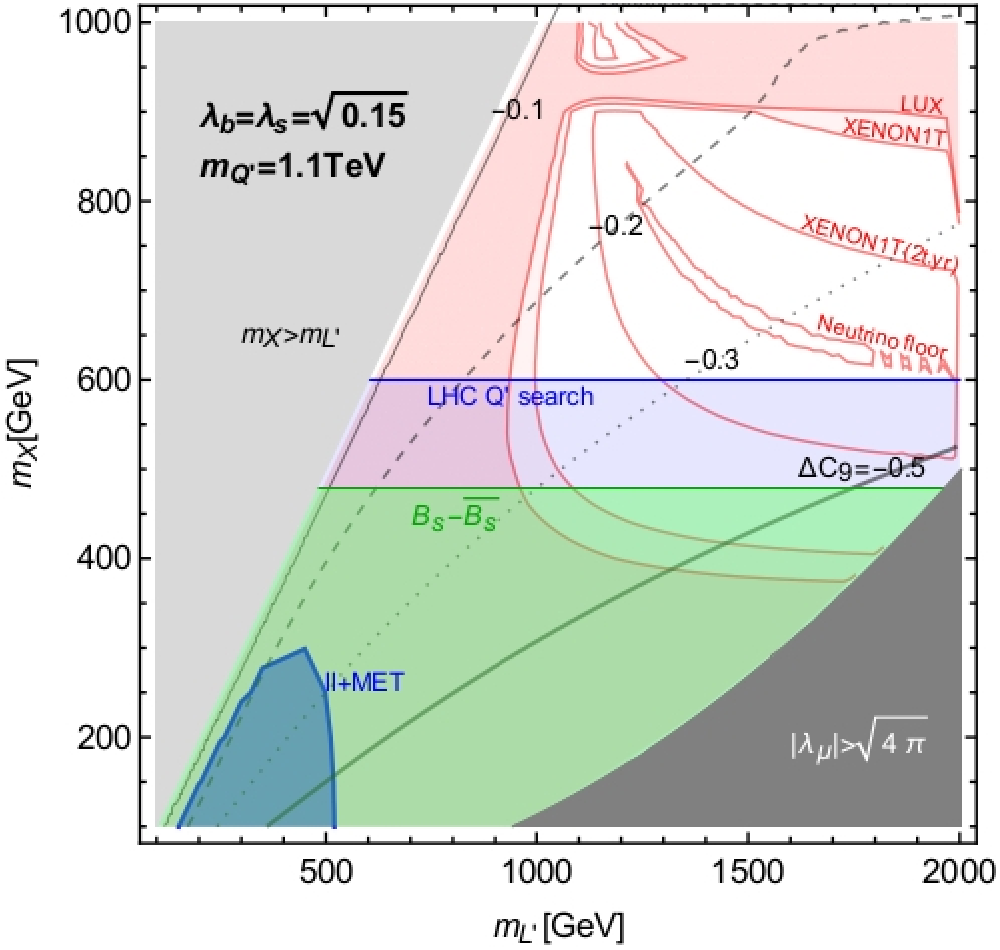
Most relevant annihilation channels
for the relic density

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

(due to large λ_L^μ)

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.

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 neutrino masses, baryogenesis... and Dark Matter

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 neutrino masses, baryogenesis... and Dark Matter

Many new model building directions are yet to be explored!

Thank you for your attention!

Backup slides

Interpretation in terms of the SMEFT

Gauge-invariant operators for the anomalies

[Celis, Fuentes-Martin, AV, Virto, 2017]

SMEFT operator	Definition	Matching	Order
$[Q_{\ell q}^{(1)}]_{aa23}$	$\left(\bar{\ell}_a \gamma_\mu \ell_a\right) \left(\bar{q}_2 \gamma^\mu q_3\right)$	$\mathcal{O}_{9,10}$	Tree
$[Q_{\ell q}^{(3)}]_{aa23}$	$\left(\bar{\ell}_a \gamma_\mu \tau^I \ell_a\right) \left(\bar{q}_2 \gamma^\mu \tau^I q_3\right)$	$\mathcal{O}_{9,10}$	Tree
$[Q_{qe}]_{23aa}$	$\left(\bar{q}_2 \gamma_\mu q_3\right) \left(\bar{e}_a \gamma^\mu e_a\right)$	$\mathcal{O}_{9,10}$	Tree
$[Q_{\ell d}]_{aa23}$	$\left(\bar{\ell}_a \gamma_\mu \ell_a\right) \left(\bar{d}_2 \gamma^\mu d_3\right)$	$\mathcal{O}'_{9,10}$	Tree
$[Q_{ed}]_{aa23}$	$\left(\bar{e}_a \gamma_\mu e_a\right) \left(\bar{d}_2 \gamma^\mu d_3\right)$	$\mathcal{O}'_{9,10}$	Tree
$[Q_{\varphi \ell}^{(1)}]_{aa}$	$\left(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi\right) \left(\bar{\ell}_a \gamma^\mu \ell_a\right)$	$\mathcal{O}_{9,10}$	1-loop
$[Q_{\varphi \ell}^{(3)}]_{aa}$	$\left(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi\right) \left(\bar{\ell}_a \gamma^\mu \tau^I \ell_a\right)$	$\mathcal{O}_{9,10}$	1-loop
$[Q_{\ell u}]_{aa33}$	$\left(\bar{\ell}_a \gamma_\mu \ell_a\right) \left(\bar{u}_3 \gamma^\mu u_3\right)$	$\mathcal{O}_{9,10}$	1-loop
$[Q_{\varphi e}]_{aa}$	$\left(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi\right) \left(\bar{e}_a \gamma^\mu e_a\right)$	$\mathcal{O}_{9,10}$	1-loop
$[Q_{eu}]_{aa33}$	$\left(\bar{e}_a \gamma_\mu e_a\right) \left(\bar{u}_3 \gamma^\mu u_3\right)$	$\mathcal{O}_{9,10}$	1-loop

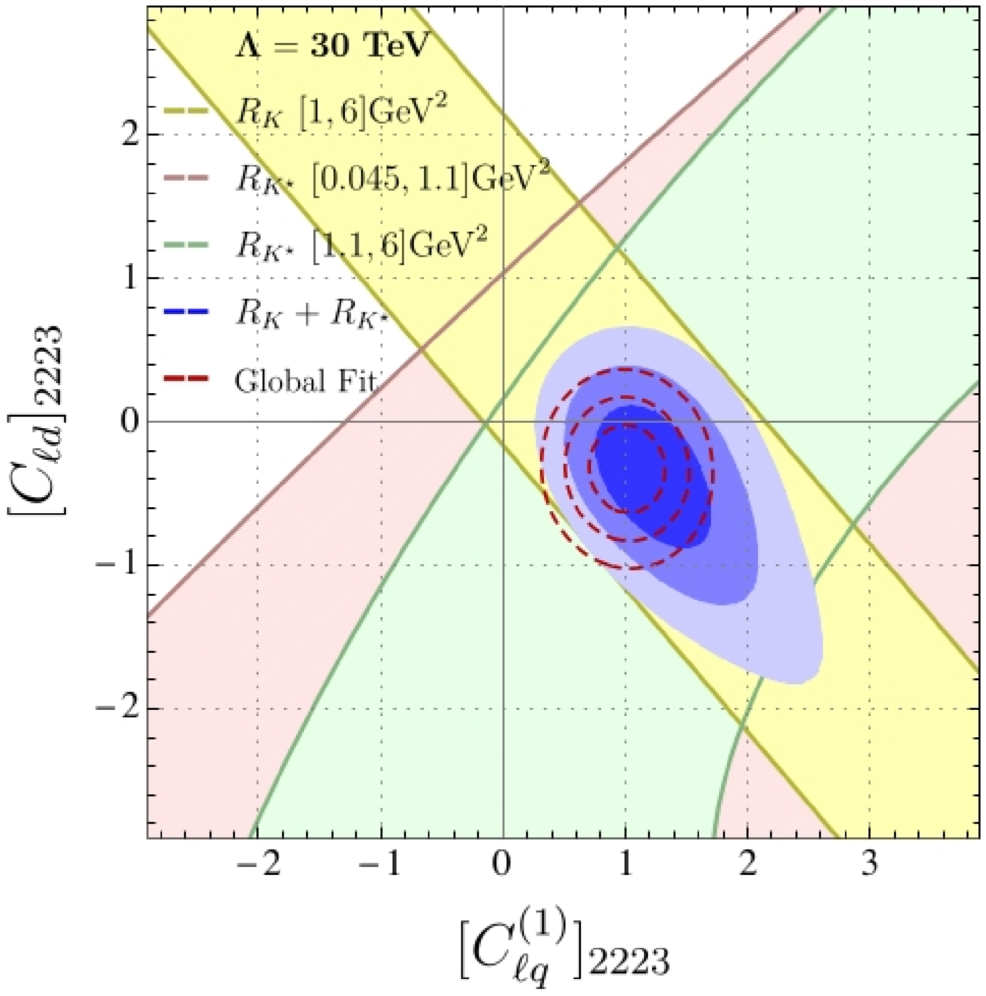
RGE effects (example):

$$[\mathcal{C}_{\ell q}^{(1)}(\mu_{\mathrm{EW}})]_{aa23} = [\mathcal{C}_{\ell q}^{(1)}(\Lambda)]_{aa23} - \frac{y_t^2 \lambda_t^{sb}}{16\pi^2} \log\left(\frac{\Lambda}{\mu_{\mathrm{EW}}}\right) \left([\mathcal{C}_{\varphi \ell}^{(1)}(\Lambda)]_{aa} - [\mathcal{C}_{\ell u}(\Lambda)]_{aa33}\right)$$

Interpretation in terms of the SMEFT

[Celis, Fuentes-Martin, AV, Virto, 2017]

Global fit in terms of the SMEFT



$\boxed{\text{At } \mu = \mu_{\text{EW}}}$

Anomalies explained by $\left[Q_{\ell q}^{(1,3)}\right]_{2223}$

Other operators fail since they predict opposed deviations in R_K and R_{K^*}

$\boxed{\text{At } \mu = \Lambda}$

Tree-level: $\left[Q_{\ell q}^{(1,3)}\right]_{2223}$

$$\Rightarrow \quad \Lambda \sim 1 - 50 \, \text{TeV}$$

New viable operator: $[Q_{\ell u}]_{2233}$

$$\Rightarrow \quad \Lambda \sim 1 \, \text{TeV}$$

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

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

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