Explaining the $b \to s$ anomalies with a dark sector

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Based on arXiv:1503.06077
In collaboration with **D. Aristizábal Sierra** and **F. Staub**

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Introduction

The $b \longrightarrow s$ anomalies

AKA “the LHCb anomalies”

In this workshop:

[Altmannshofer, Buras (?), Crivellin, Hiller, Jaeger, Nardecchia, Zwicky, maybe someone else (?)]

The $b \to s$ anomalies

Composite Higgs

Buras, Girrbach-Noe, Niehoff, Stangl, Straub

Model building

Z' boson

Altmannshofer, Aristizabal Sierra, Buras, Crivellin, D' Ambrosio, Gauld, Girrbach-Noe, Goertz, Gori, Haisch, Heeck, Niehoff, Pospelov, Staub, Straub, Vicente, Yavin

Leptoquarks

Biswas, Chowdhuri, de Medeiros Varzielas, Gripaios, Han, Hiller, Lee, Mohanta, Nardecchia, Renner, Sahoo, Schmaltz

$b \to s$ anomalies

Global fits

Alonso, Altmannshofer, Beaujean, Bobeth, Descotes-Genon, Ghosh, Grinstein, Hiller, Hurth, Mahmoudi, Martin Camalich, Matias, Nardecchia, Neshatpour, Renner, Schmaltz, Straub, van Dyk, Virto

Implications - LFV -

Bhattacharya, Boucenna, Datta, de Medeiros Varzielas, Glashow, Gripaios, Guadagnoli, Hiller, Kane, London, Mohanta, Nardecchia, Renner, Sahoo, Shivashankara, Valle, Vicente

SM uncertainties

Altmannshofer, Bharucha, Descotes-Genon, Ghosh, Hiller, Hofer, Horgan, Hurth, Jaeger, Liu, Lyon, Martin Camalich, Matias, Meinel, Straub, Virto, Wingate, Zwicky

The $b \to s$ anomalies

B to S anomalies

The $b \to s$ anomalies

Beyond the Standard Model

The $b \to s$ anomalies

Boring

Sizable corrections

The $b \to s$ anomalies

B-physics in Slovenia

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 dark sector

[arXiv:1503.06077]

The model

[Aristizabal Sierra, Staub, AV, 2015]

Vector-like = “joker” for model builders

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

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

The model

[Aristizabal Sierra, Staub, AV, 2015]

Vector-like = “joker”
for model builders

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

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

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

Symmetry breaking and dark matter

[Aristizabal Sierra, Staub, AV, 2015]

$$\langle H^0 \rangle = \frac{v}{\sqrt{2}} \qquad \langle \phi \rangle = \frac{v_\phi}{\sqrt{2}}$$

Massive Z' boson: $m_{Z'} = 2 g_X v_\phi$

DM candidate: χ

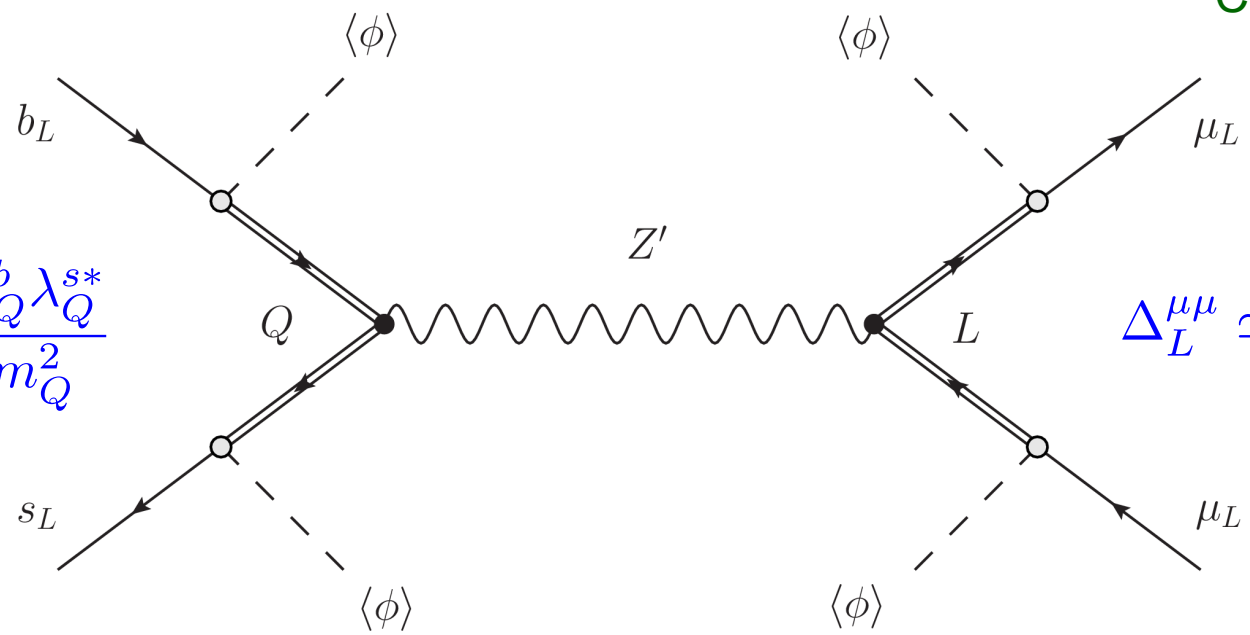
$$\begin{aligned} \mathcal{V}(\chi) \;=\; & m_\chi^2 |\chi|^2 + \frac{\lambda_\chi}{2} |\chi|^4 + \lambda_{H\chi} |H|^2 |\chi|^2 \\ & + \lambda_{\phi\chi} |\phi|^2 |\chi|^2 + \left(\mu \, \phi \chi^2 + \text{h.c.} \right) \end{aligned}$$

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

Automatic DM stability

Solving the LHCb anomalies

Similar to Altmannshofer et al, Crivellin et al, 2014



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

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

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

Contributions to $\mathcal{O}_{9,10}$

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

Some constraints

$B_s \to \mu^+\mu^-$

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

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

$B_s - \bar{B}_s$ mixing

[Altmannshofer et al, 2014]

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

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

What about LFV?

[Glashow et al, 2014]

Lepton universality violation generically implies lepton flavor violation

Gauge basis

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

Mass basis

$$\mathcal{O} = (\bar{q}\gamma_\alpha P_L q)\ \left(\bar{\ell}\gamma^\alpha P_L \ell\right)$$

Related to neutrino oscillations?
[Boucenna, Valle, AV, 2015]

However, in this model LFV can be suppressed with the parameter choice:

$$\lambda_L^{e,\tau} \ll 1$$

[although $\lambda_L^{\mu} \sim \mathcal{O}(1)$]

Numerical results

Numerical results

Is the model viable?

And if so...

What is the favored region of **parameter space**?

Are **other Wilson coefficients** affected?
[= are **loop corrections** sizable?]

Some comments on DM

However:

Higgs portal also possible [see talks by Grzadkowski and Lebedev]

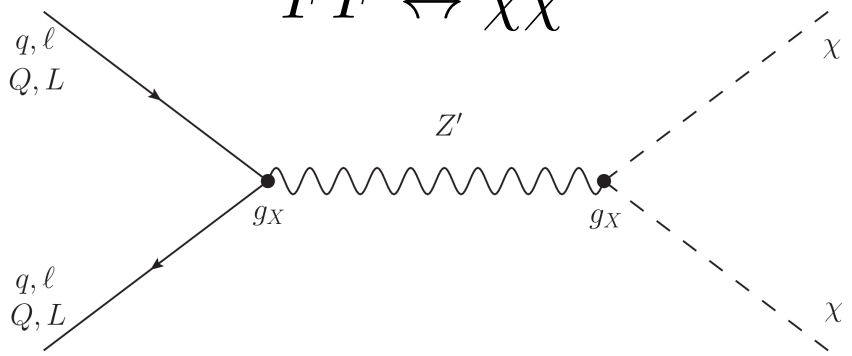
Assumption:

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

→ **Z' portal**

Interplay between flavor and DM

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



$$\sigma(s) \sim \left|\Delta^{f_i f_j}\right|^2 g_X^2 \frac{1}{s} \frac{m_{Z'}^4}{\left(m_{Z'}^2 - s\right)^2 - m_{Z'}^2 \Gamma_{Z'}^2} F_{\text{kin}}$$

Favorable conditions

$$m_\chi > m_{Q,L}$$

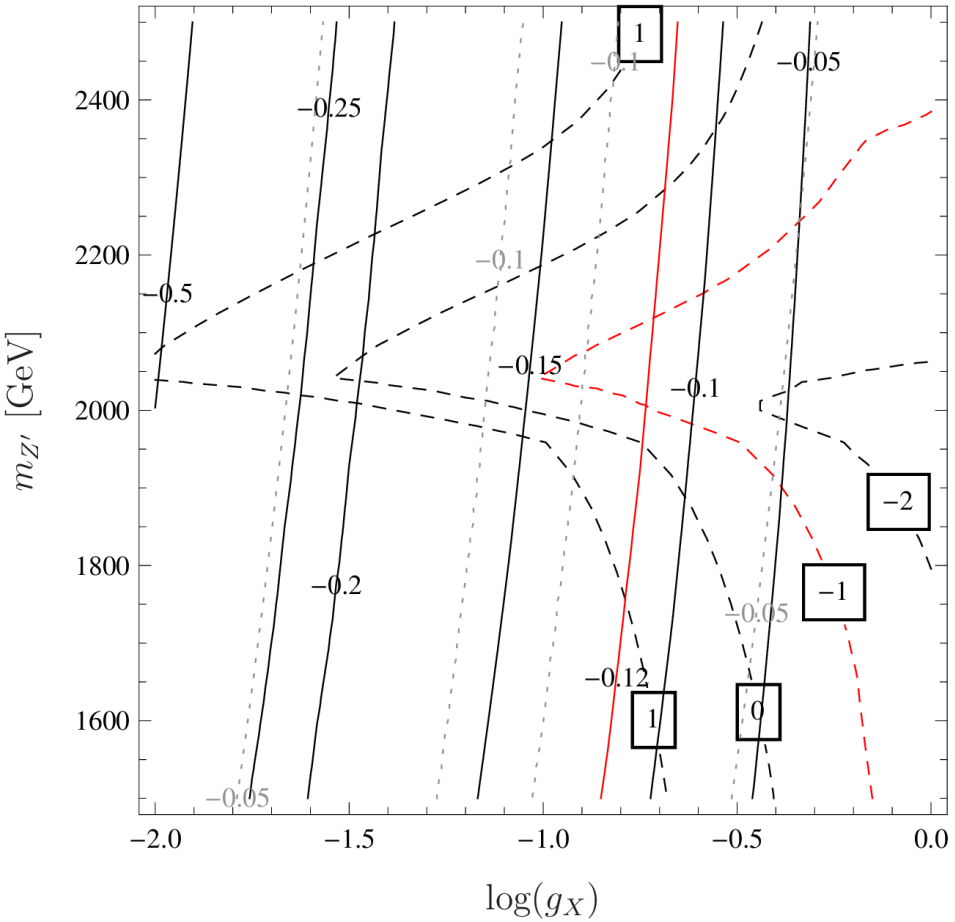
$$m_{Z'} > m_\chi$$

$$m_\chi \simeq \frac{m_{Z'}}{2}$$

(resonance)

Dark matter and LHCb 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:

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

$$\lambda_L^\mu = 0.5$$

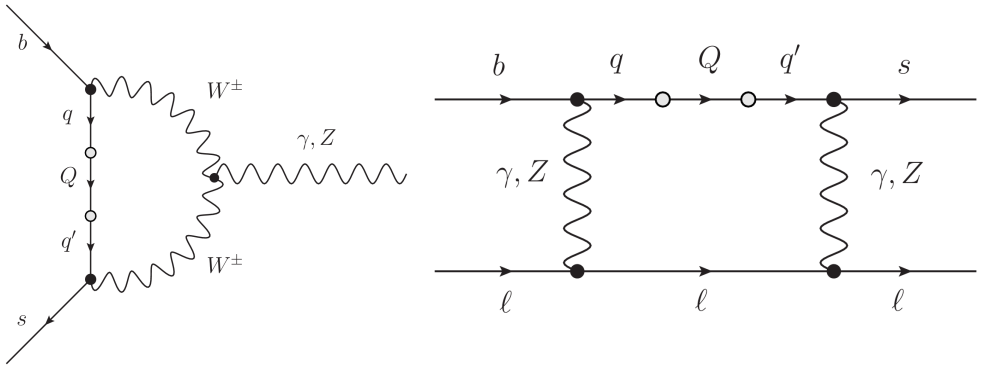
$$m_Q = m_L = 1\ \text{TeV}$$

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

- 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



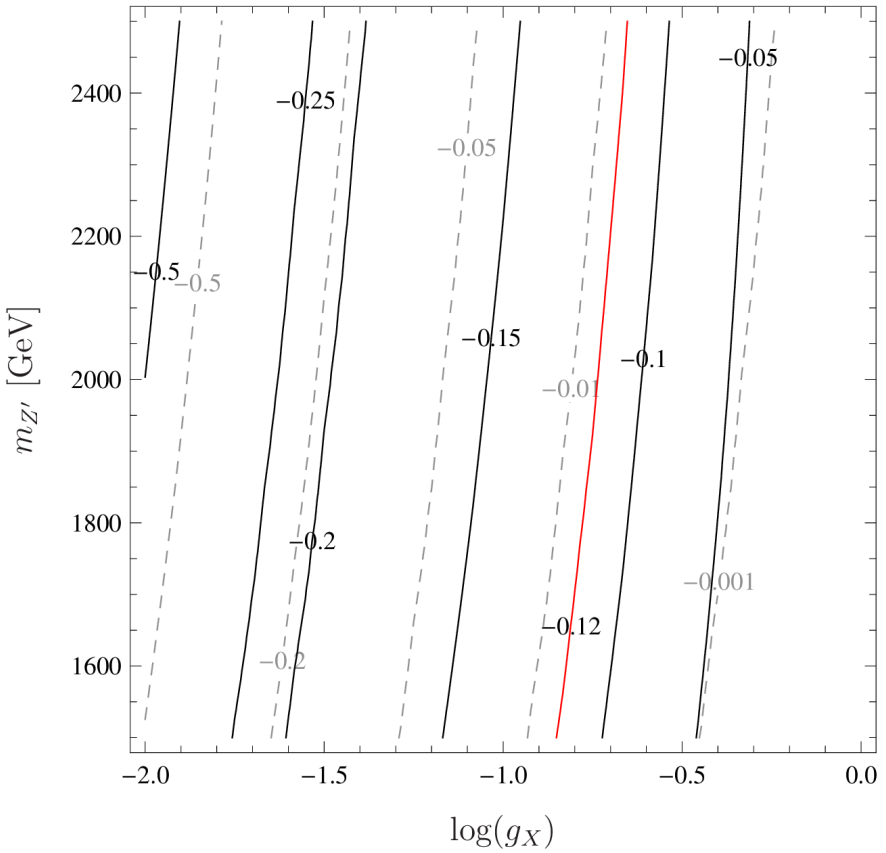
- Non-negligible corrections to C_9
- Unwanted contributions to other Wilson coefficients

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



Final remarks

Before going for coffee...

Final remarks

Something unexpected has been found at LHCb

Whether is new physics or not, only time can tell

In the meantime: let's do some physics and try to learn as much as possible!

Thank you!

Backup slides

Z-Z' mixing

Nothing prevents U(1) factors from mixing

$$\mathcal{L} \supset \varepsilon F^{Y}_{\mu\nu} F^{\mu\nu}_{X}$$

Problem: The Z' would have flavor violating couplings to all SM fermions

However, this is under control in this model:

- Not induced via renormalization group running if it is zero at some high-energy scale
- Suppressed for $m_Q \sim m_L$

$$\varepsilon_{\text{1-loop}} \propto \frac{g_1 g_X}{16\pi^2} \log\left(\frac{m_Q}{m_L}\right)$$

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

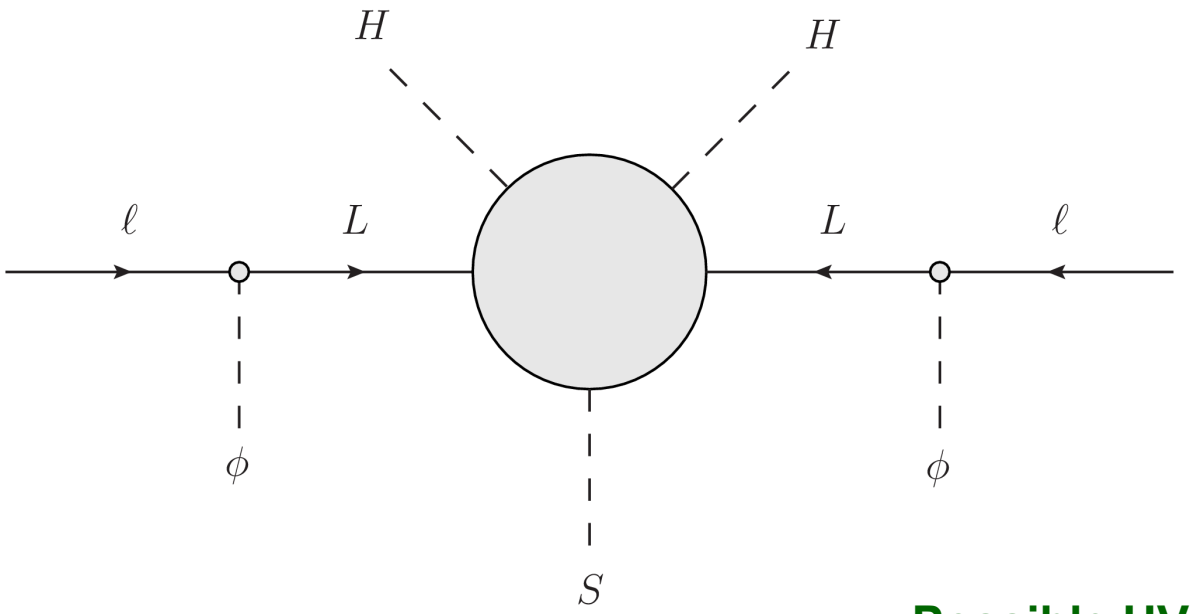
Easily extendable

Many observables ready to be computed in your favourite model!

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

Neutrino masses

Non-trivial neutrino mass generation



$$S = (1, 1, 0, -4)$$

[preserves $\mathbb{Z}_2$]

$$\mathcal{O}_\nu = \frac{1}{\Lambda_\nu^5} \ell\ell H H \phi\phi S$$

Possible UV completion

Vector-like fermion $F = (1, 1, 0, 2)$

$$\mathcal{L} \supset \lambda_S S \overline{F^c} F + y \overline{L} H F$$

Are the LHCb anomalies related to neutrino oscillations?

[Boucenna, Valle, AV, 2015]

Gauge basis

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

Mass basis

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

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

What if $U_\ell = K^\dagger$?

Neutrino oscillations

Neutrinos ⟷ B-physics