# Theory status and implications of $R_{K^{(*)}}$

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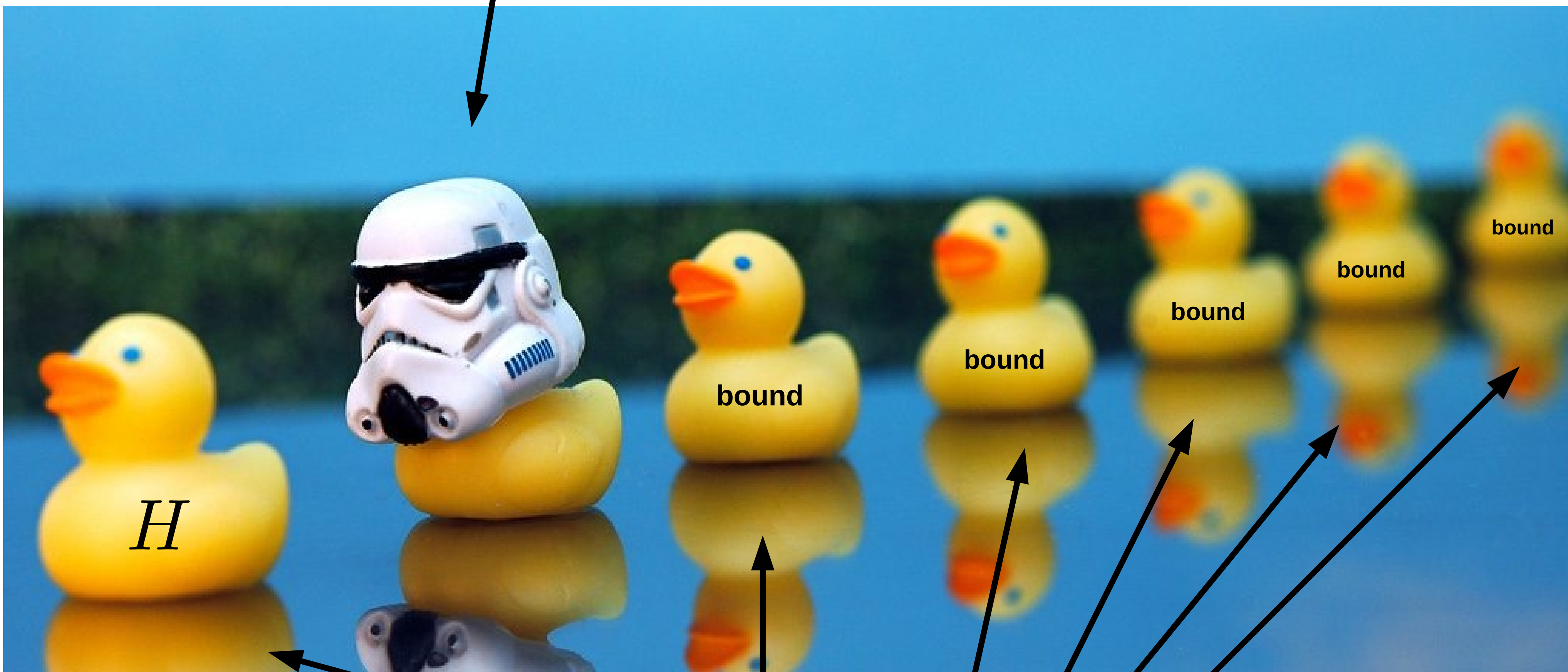
**Beauty 2019**

*18th International Conference on B-Physics at Frontier Machines*

# The LHC so far...

**B-anomalies**



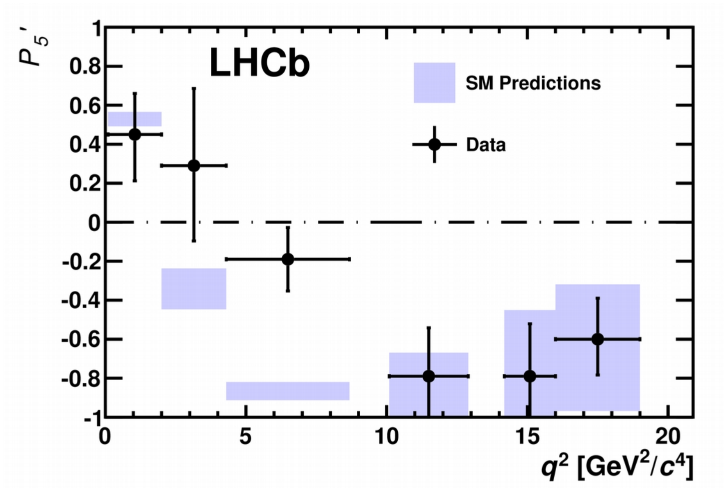

**Other LHC results**

(+ the diphoton that
should not be named)

# 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**

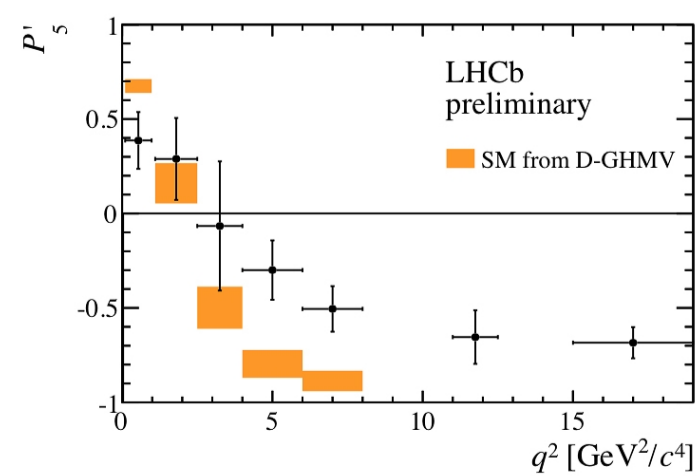
$$R_K = \frac{\mathrm{BR}(B \to K \mu^+ \mu^-)}{\mathrm{BR}(B \to K e^+ e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

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

$2.6\sigma$ away from the SM

## Episode VI: Return of the anomalies

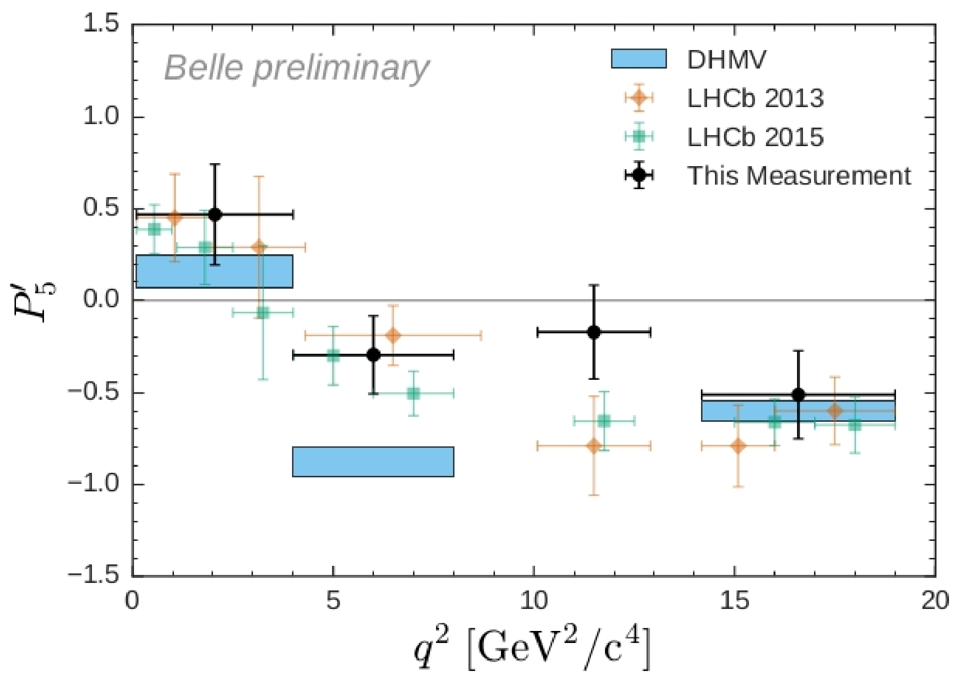
**2015 : LHCb confirms first anomalies**



# The $b \to s$ anomalies

**Episode I: The Belle menace**

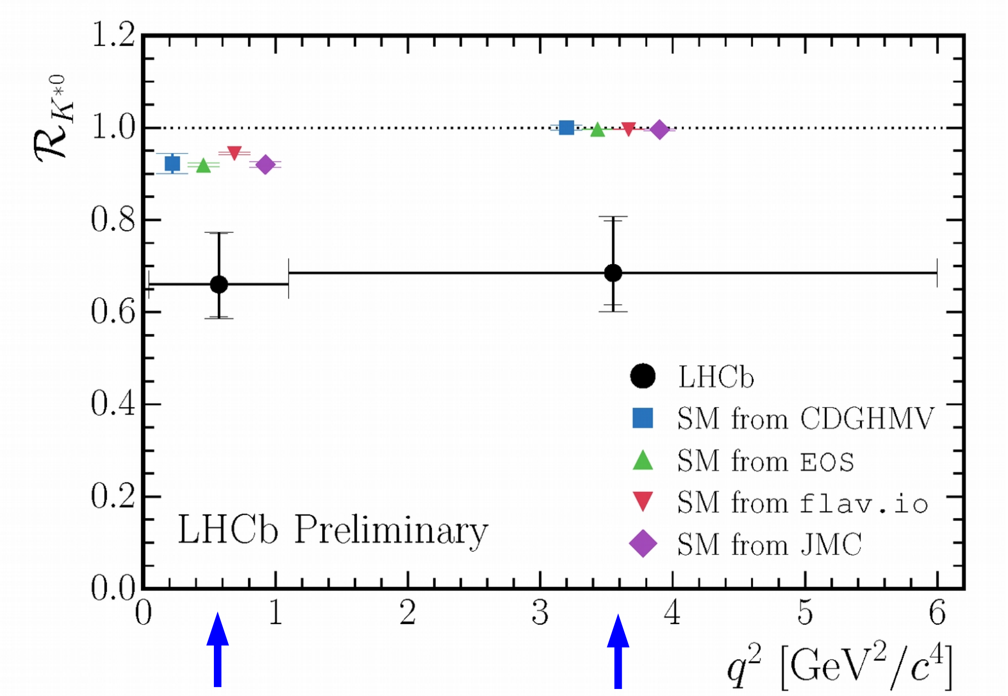
**2016 : Belle finds additional hints**




$P_5$' anomaly confirmed
+ little LFVU indication

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

**2017 : More universality violation in LHCb**




**low bin**

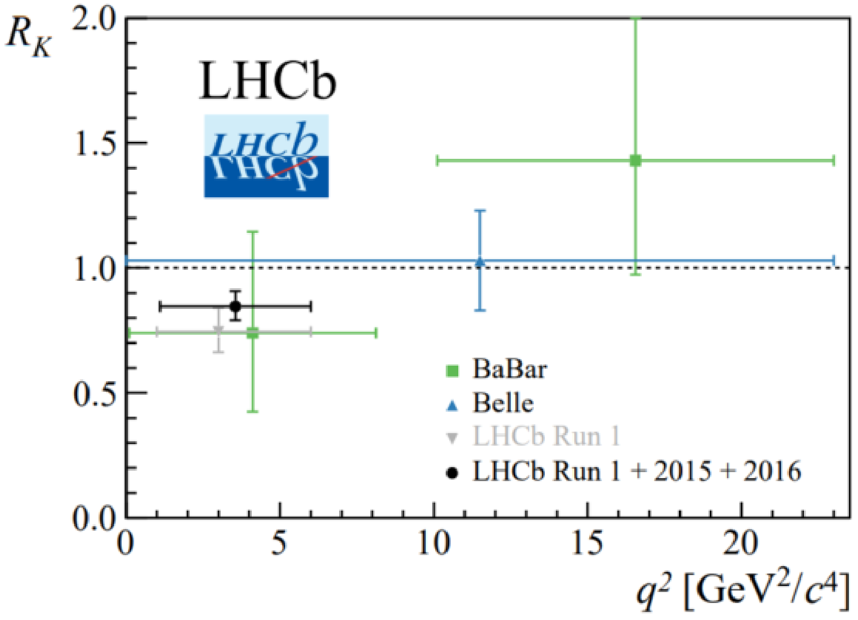
**central bin**

[ No new episode in 2018 though.... ]

# The $b \to s$ anomalies

## Episode III: The revenge of the SM (?)

**2019 : LHCb and Belle news**




$R_{K^*}$

| $q^2$ in GeV$^2$/c$^4$ | All modes |
|---|---|
| [0.045, 1.1] | $0.52^{+0.36}_{-0.26} \pm 0.05$ |
| [1.1, 6] | $0.96^{+0.45}_{-0.29} \pm 0.11$ |
| [0.1, 8] | $0.90^{+0.27}_{-0.21} \pm 0.10$ |
| [15, 19] | $1.18^{+0.52}_{-0.32} \pm 0.10$ |
| [0.045, ] | $0.94^{+0.17}_{-0.14} \pm 0.08$ |

$$R_K = 0.846^{+0.060}_{-0.054}\,(\text{stat})^{+0.016}_{-0.014}\,(\text{syst})$$

# Interpreting the anomalies

From now on...

**Assumption 1:** The anomalies are caused by New Physics

**Assumption 2:** The New Physics states are heavy $(\Lambda \gg m_b)$

This is the perfect ground for...

**Effective Field Theory**

- All the heavy degrees of freedom are integrated out
- Physics described by a collection of non-renormalizable operators
- Model-independent language

# $b \to s$ Effective Field Theory

**$b \to s$ 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

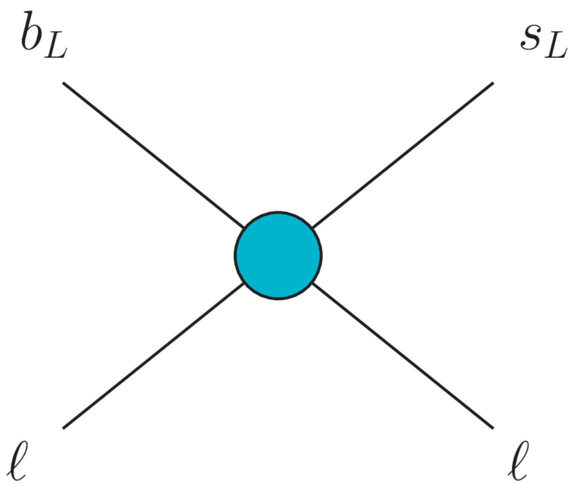
$\mathcal{O}_i$ : Operators

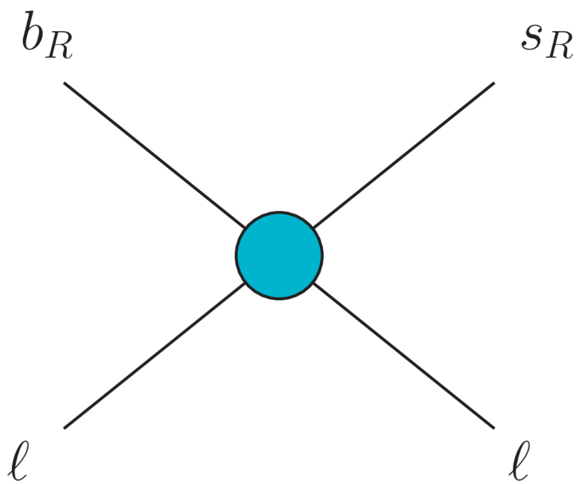
$$\mathcal{O}_7 = (\bar{s} \sigma_{\mu\nu} P_R b) F^{\mu\nu}$$
$$\mathcal{O}_9 = (\bar{s} \gamma_\mu P_L b) \left( \bar{\ell} \gamma^\mu \ell \right)$$
$$\mathcal{O}_{10} = (\bar{s} \gamma_\mu P_L b) \left( \bar{\ell} \gamma^\mu \gamma_5 \ell \right)$$

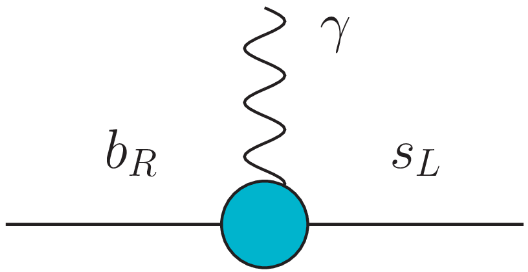
$$\mathcal{O}_7' = (\bar{s} \sigma_{\mu\nu} P_L b) F^{\mu\nu}$$
$$\mathcal{O}_9' = (\bar{s} \gamma_\mu P_R b) \left( \bar{\ell} \gamma^\mu \ell \right)$$
$$\mathcal{O}_{10}' = (\bar{s} \gamma_\mu P_R b) \left( \bar{\ell} \gamma^\mu \gamma_5 \ell \right)$$

# $b \to s$ Effective Field Theory

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




$\mathcal{O}_9 = (\bar{s}\gamma_\mu P_L b)\ \left(\bar{\ell}\gamma^\mu \ell\right)$ $\mathcal{O}_9' = (\bar{s}\gamma_\mu P_R b)\ \left(\bar{\ell}\gamma^\mu \ell\right)$ $\mathcal{O}_7 = (\bar{s}\sigma_{\mu\nu} P_R b)\ F^{\mu\nu}$

# $b \to s$ Effective Field Theory

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

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

[ analogous for primed operators ]

$C_i^{\rm SM}$: calculable

$C_i^{\rm NP}$: what we want to know

Standard Model contributions at $Q = m_b$ :

$$C_7^{\rm SM} = -0.3 \qquad C_9^{\rm SM} = 4.1 \qquad C_{10}^{\rm SM} = -4.3 \qquad C_{\rm rest}^{\rm SM} \lesssim 10^{-2}$$

# Processes and observables

**Inclusive**

$B \to X_s \gamma$ **(BR)** ------------------------ $C_7^{(\prime)}$

$B \to X_s \ell^+ \ell^-$ **(dBR/dq²)** ---------------- $C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$

**Exclusive leptonic**

$B_s \to \ell^+ \ell^-$ **(BR)** ------------------------ $C_{10}^{(\prime)}$

**Exclusive radiative/semileptonic**

$B \to K^* \gamma$ **(BR, S, A$_I$)** ------------------ $C_7^{(\prime)}$

$B \to K \ell^+ \ell^-$ **(dBR/dq²)** ----------------- $C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$

$B \to K^* \ell^+ \ell^-$ **(dBR/dq², angular obs.)** --- $C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$

$B_s \to \phi \, \ell^+ \ell^-$ **(dBR/dq², angular obs.)** --- $C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$

# Processes and observables

**Examples:** [Celis, Fuentes-Martín, AV, Virto, 2017]

$$[R_K]_{[1,6]} \simeq 1.00(1) + 0.230(\mathcal{C}^{\rm NP}_{9\mu-e} + \mathcal{C}'_{9\mu-e}) - 0.233(2)(\mathcal{C}^{\rm NP}_{10\mu-e} + \mathcal{C}'_{10\mu-e})$$

$$[R_{K^*}]_{[0.045,1.1]} \simeq 0.92(2) + 0.07(2)\mathcal{C}^{\rm NP}_{9\mu-e} - 0.10(2)\mathcal{C}'_{9\mu-e} - 0.11(2)\mathcal{C}^{\rm NP}_{10\mu-e} + 0.11(2)\mathcal{C}'_{10\mu-e} + 0.18(1)\mathcal{C}^{\rm NP}_7$$

$$[R_{K^*}]_{[1.1,6]} \simeq 1.00(1) + 0.20(1)\mathcal{C}^{\rm NP}_{9\mu-e} - 0.19(1)\mathcal{C}'_{9\mu-e} - 0.27(1)\mathcal{C}^{\rm NP}_{10\mu-e} + 0.21(1)\mathcal{C}'_{10\mu-e}$$

$$\Rightarrow \quad C_7,\; C_9,\; C'_9,\; C_{10},\; C'_{10}$$

Analogously with other observables...

# Processes and observables

**Examples:** [Celis, Fuentes-Martín, AV, Virto, 2017]

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$$[R_{K^*}]_{[1.1,6]} \simeq 1.00(1) + 0.20(1)\mathcal{C}_{9\mu-e}^{\rm NP} - 0.19(1)\mathcal{C}'_{9\mu-e} - 0.27(1)\mathcal{C}_{10\mu-e}^{\rm NP} + 0.21(1)\mathcal{C}'_{10\mu-e}$$

$$\Rightarrow \quad C_7,\ C_9,\ C_9',\ C_{10},\ C_{10}'$$

Analogously with other observables...

The same Wilson coefficients enter several observables $\Rightarrow$ A pattern of deviations rather than a single anomaly $\Rightarrow$ **Global fit**

**Talk by Sébastien Descotes-Genon**

# Global fits: conclusions

Different fits agree qualitatively, although they differ quantitatively (form factors, treatment of uncertainties...)

New Physics hypothesis preferred over SM by more than 5 $\sigma$
(4 $\sigma$ if only LFUV)

The $C_{9\mu}$ coefficient seems to be crucial. A good fit is obtained with a NP contribution of about 20% of the SM contribution (and opposite sign)

Other muonic coefficients may have NP contributions as well. Preferred 1D scenarios: $C_{9\mu}$, $C_{9\mu} = -C_{10\mu}$ and $C_{9\mu} = -C'_{9\mu}$

No evidence of NP contributions in electronic coefficients

**Exciting results!**

# The scale of New Physics

Notation:

$C_9 \equiv C_{9\mu}$

[Di Luzio, Nardecchia, 2017]

$$\underbrace{\frac{C_9^{\rm NP}}{\Lambda_{\rm NP}^2}}_{\text{NP}} \sim 20\% \times \underbrace{\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} C_9^{\rm SM}}_{\text{SM}}$$

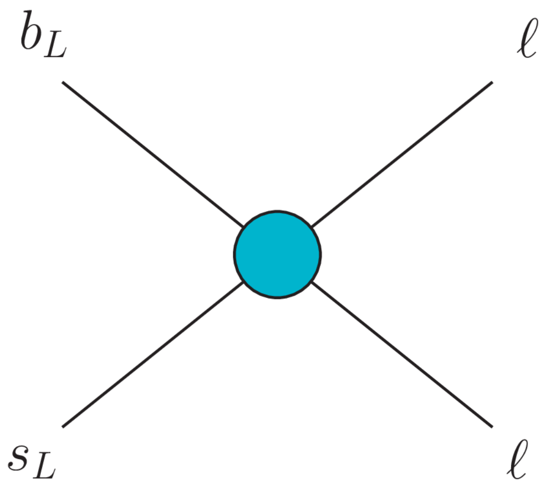
Unsuppressed NP $\quad C_9^{\rm NP} = 1 \quad \Rightarrow \Lambda_{\rm NP} \sim 30\ {\rm TeV}$

CKM-suppressed NP $\quad C_9^{\rm NP} = |V_{tb} V_{ts}^*| \quad \Rightarrow \Lambda_{\rm NP} \sim 6\ {\rm TeV}$

Loop-suppressed NP $\quad C_9^{\rm NP} = \frac{1}{16\pi^2} \quad \Rightarrow \Lambda_{\rm NP} \sim 2.5\ {\rm TeV}$

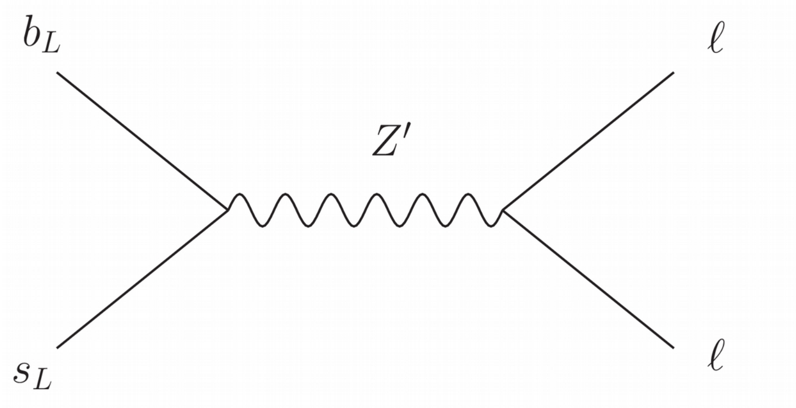
CKM&loop-suppressed NP $\quad C_9^{\rm NP} = \frac{|V_{tb} V_{ts}^*|}{16\pi^2} \quad \Rightarrow \Lambda_{\rm NP} \sim 0.5\ {\rm TeV}$

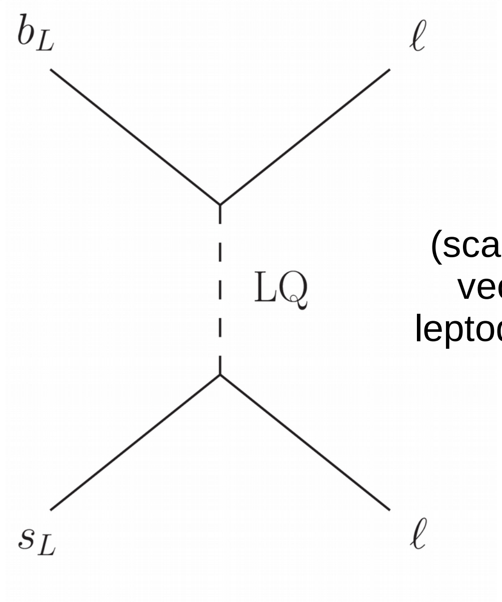
# Opening up the operator




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

**@ tree-level** **+ loops**




(scalar or vector leptoquark)

# Models, models and models


# Models, models and models

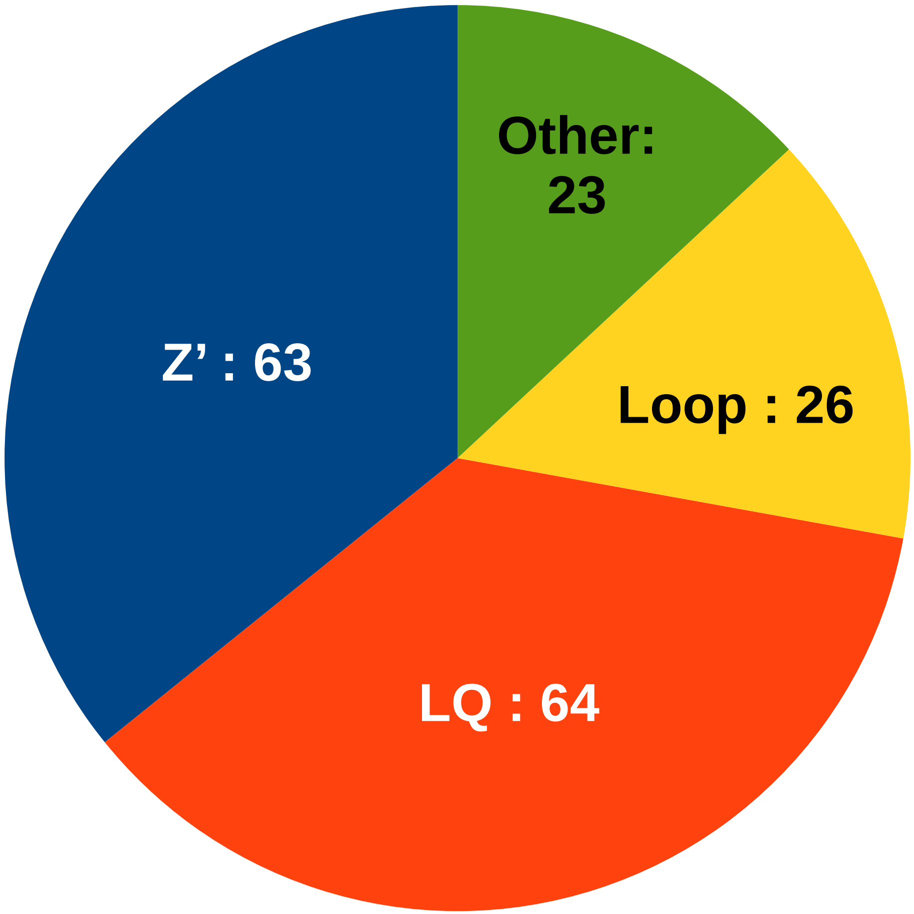
**Great opportunity for model builders**

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


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

# Models, models and models

**Complete models** (*)




(*) My definition of "complete model": fully specified renormalizable model

# Z' : what do we need?

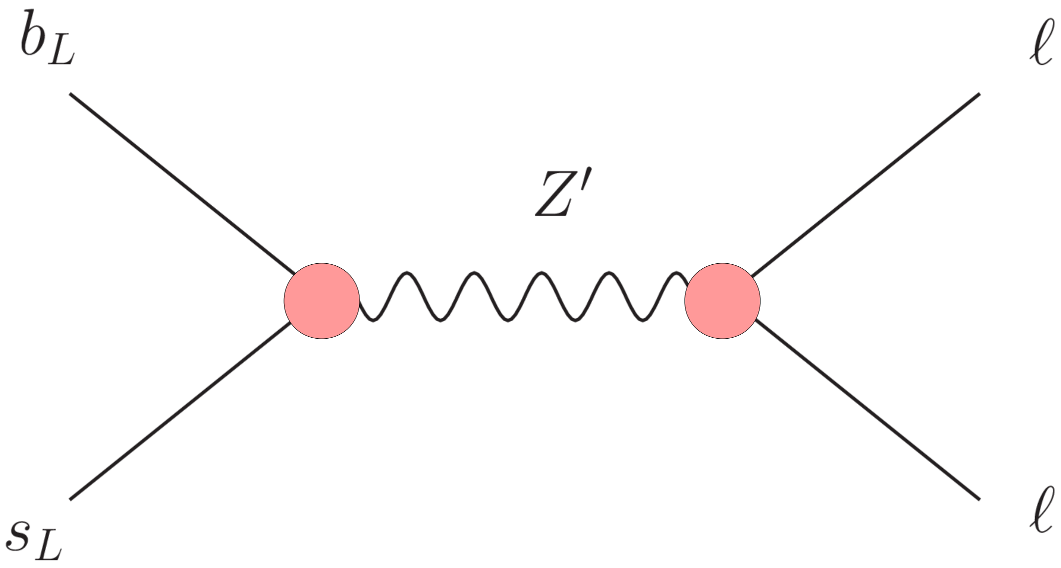
## Z' model building

**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

# Z' : what do we need?




**Z' coupling to fermions**

**Direct:** non-universal gauge symmetry

**Indirect** (*mixing-induced*): non-universality due to mixings

# A Z' model

[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 Z' model

[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

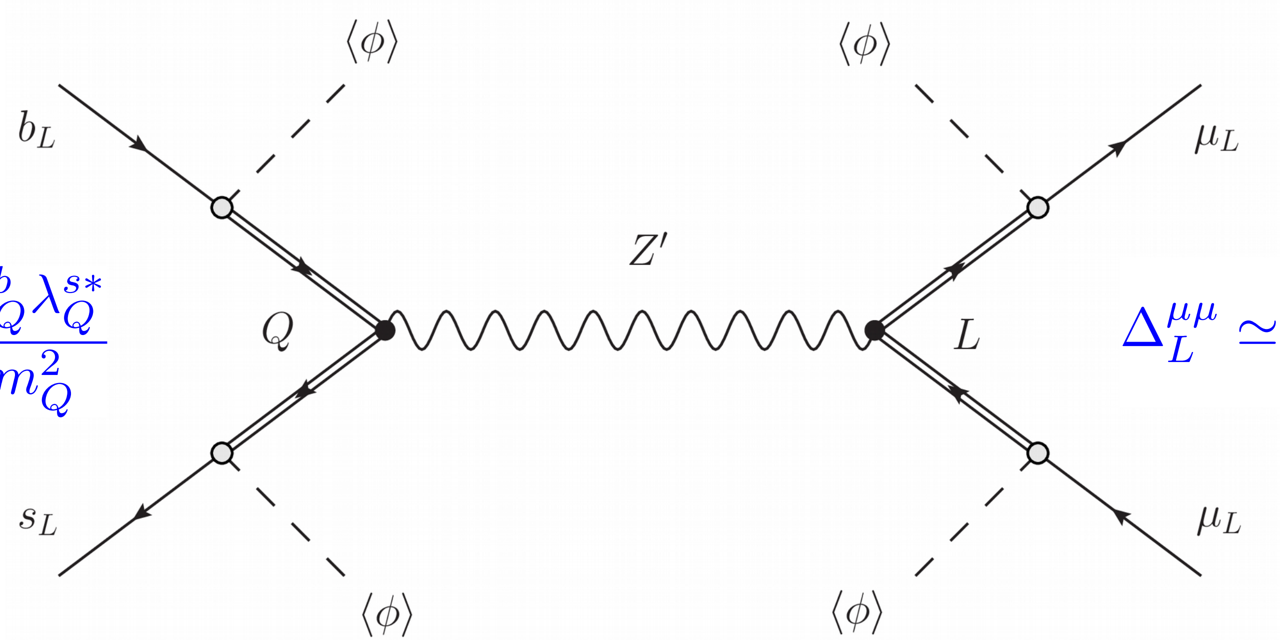
$$\mathcal{L}_Y = \lambda_Q \overline{Q_R} \phi q_L + \lambda_L \overline{L_R} \phi \ell_L + \text{h.c.}$$

VL – SM mixing

# Solving the $b \to s$ anomalies

[Aristizabal Sierra, Staub, AV, 2015]

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

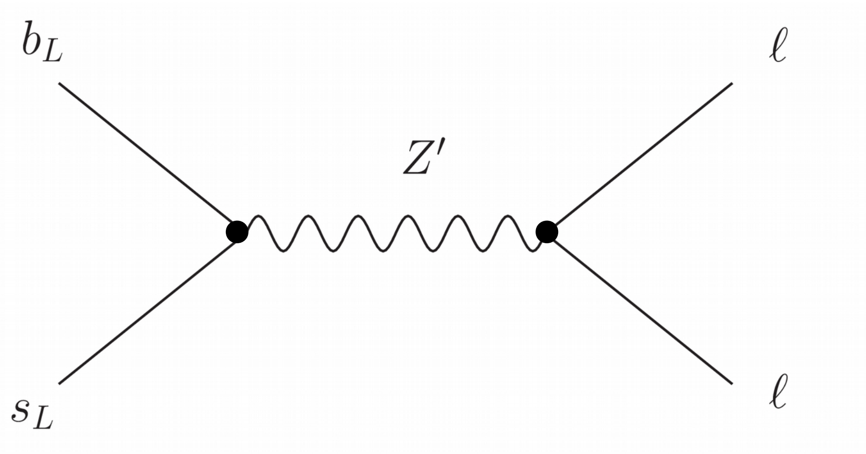



$$\Delta_L^{\mu\mu} \simeq \frac{2\, g_X |\lambda_L^\mu|^2 v_\phi^2}{2m_L^2 + |\lambda_L^\mu|^2 v_\phi^2}$$

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

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

# Direct Z’ couplings

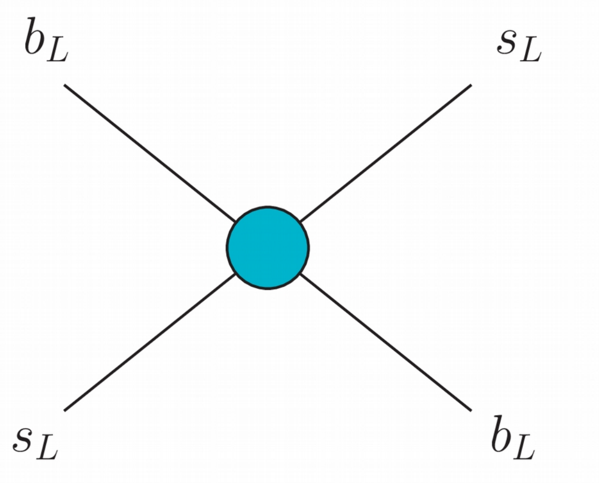


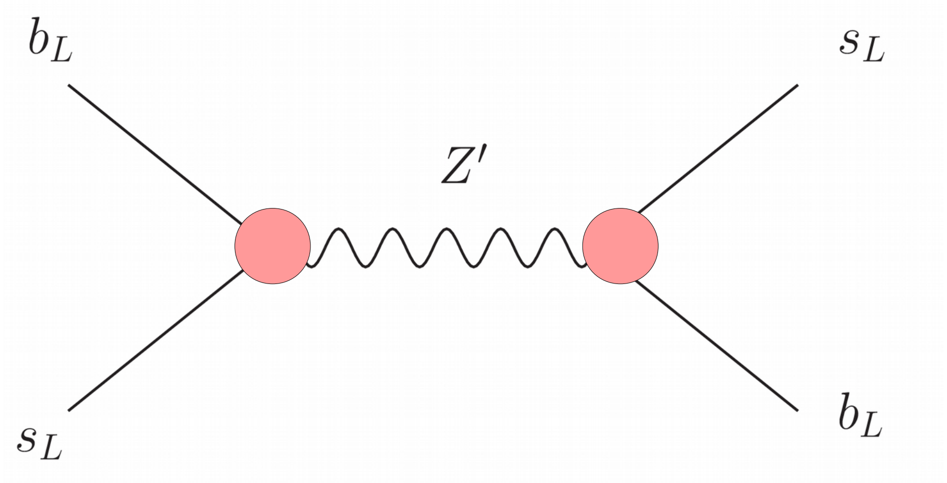

**Direct Z’ couplings to fermions**

- Suitable gauge symmetry
- Anomaly cancellation
- Possible interplay with indirect couplings

| | |
|---|---|
| $L_\mu - L_\tau$ | [Altmannshofer et al, 2014] |
| $L_\mu - L_\tau - a(B_1 + B_2 - 2B_3)$ | [Crivellin et al, 2015] |
| BGL | [Celis et al, 2015] |
| Flavor | [Falkowski et al, 2015] |
| $q \times L_\mu - L_\tau$ | [Crivellin et al, 2016] |
| $x(B_3 - L_e) - (L_\mu - L_\tau)$ | [Ko et al, 2017] |
| $\ldots$ | |

# The $\Delta M_s$ constraint




[Di Luzio et al, 2019]

$$\frac{\Delta M_s^{\mathrm{SM+NP}}}{\Delta M_s^{\mathrm{SM}}} \simeq$$

$$\left| 1 + \frac{1}{360} \left( \frac{C_9^{\mathrm{NP}}}{-0.53} \right)^2 \left( \frac{m_{Z'}/\Delta_L^{\mu\mu}}{1\ \mathrm{TeV}} \right)^2 \right|$$

for a Z’ with real LH couplings

Cancellations when both LH and RH couplings exist

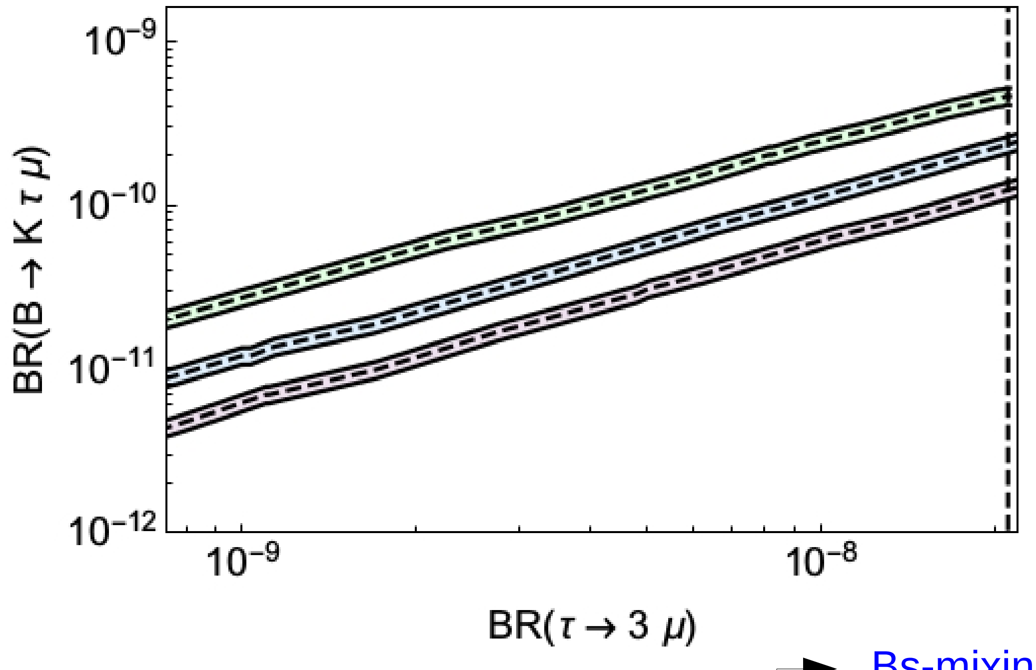
[Crivellin et al, 2015]

However, this is a limitation in models with pure LH couplings

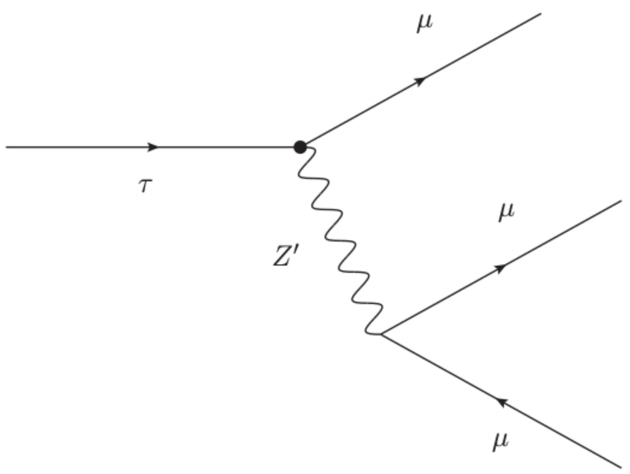
Solution: $\Delta_L^{bs} \ll 1$ & $\Delta_L^{\mu\mu} \sim \mathcal{O}(1)$

[Altmannshofer et al, 2014]

# LFV in a Z’ model




[Rocha-Morán, AV, 2018]




Correlation (almost)* unavoidable

* : could be broken by loops (possible!)

Bs-mixing

$$\frac{\mathrm{BR}(B \to K \tau \mu)}{\mathrm{BR}(\tau \to 3\,\mu)} = 1.7 \cdot 10^7\,\mathrm{TeV}^4 \left( \frac{|\Delta_L^{bs}|}{m_{Z'}} \right)^4 \frac{1}{|C_9^{\mathrm{NP}}|^2}$$

Anomaly

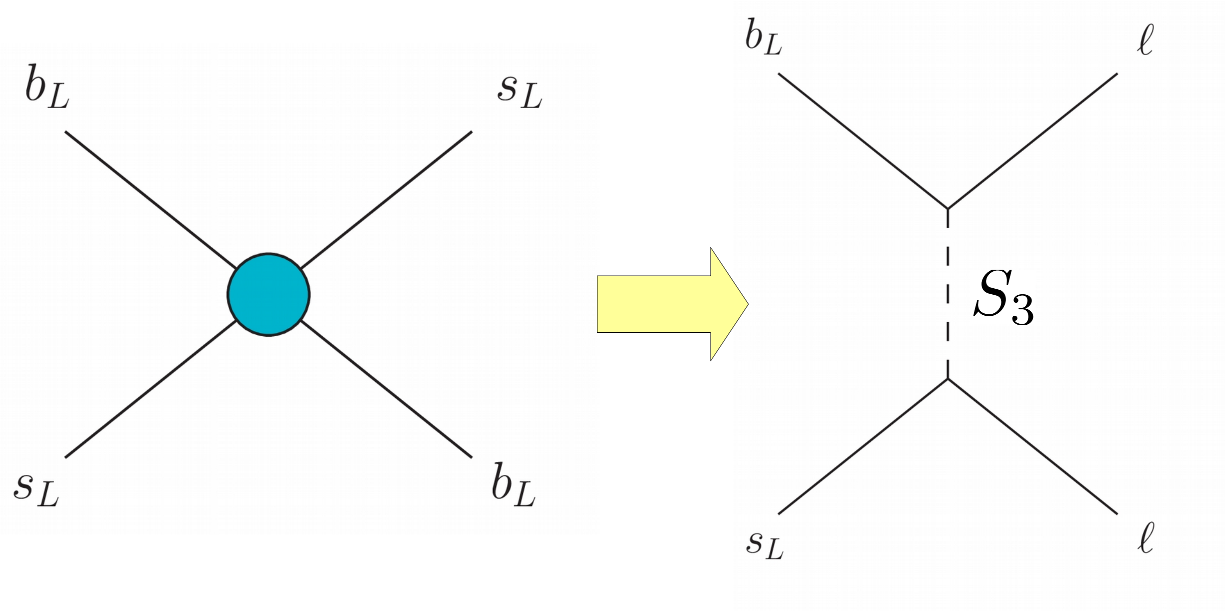
Generic Z’ scenarios
[Crivellin et al, 2015]

$$\boxed{\mathrm{BR}(B \to K \tau \mu)_{\max} \lesssim 8 \cdot 10^{-10}}$$

LHCb @ 50 $\mathrm{fb}^{-1}$

**Talk by Matteo Rama**

# Leptoquarks to the rescue




The "*Leptoquark Bible*"
[Doršner et al, 2016]

$$S_3 = \left( \bar{\mathbf{3}}, \mathbf{3}, \frac{1}{3} \right)$$

$$\mathcal{L}_{S_3} = y_{ij} \, \overline{q_i^c} \, S_3 \, \ell_j + \text{h.c.}$$

$$C_9 = -C_{10} = \frac{4\,\pi^2 \, v^2}{e^2 \, V_{tb} V_{ts}^*} \, \frac{y_{b\mu} \, y_{s\mu}^*}{m_{S_3}^2}$$

[Hiller, Schmaltz, 2014]
[Hiller, Nisandzic, 2017]
[Doršner et al, 2017]
[Hati et al, 2018]
[Angelescu et al, 2018]

**Talk by Nejc Košnik**

# Leptoquark solution to all B-anomalies

| | Model | $R_{K^{(*)}}$ | $R_{D^{(*)}}$ | $R_{K^{(*)}}$ & $R_{D^{(*)}}$ |
|---|---|---|---|---|
| Scalars | $S_1 = (\mathbf{3}, \mathbf{1}, -\frac{1}{3})$ | ✗ | ✓ | ✗ |
| | $R_2 = (\mathbf{3}, \mathbf{2}, \frac{7}{6})$ | ✗ | ✓ | ✗ |
| | $\widetilde{R}_2 = (\mathbf{3}, \mathbf{2}, \frac{1}{6})$ | ✗ | ✗ | ✗ |
| | $S_3 = (\mathbf{3}, \mathbf{3}, -\frac{1}{3})$ | ✓ | ✗ | ✗ |
| Vectors | $U_1 = (\mathbf{3}, \mathbf{1}, \frac{2}{3})$ | ✓ | ✓ | ✓ |
| | $U_3 = (\mathbf{3}, \mathbf{3}, \frac{2}{3})$ | ✓ | ✗ | ✗ |

[Angelescu et al, 2018]

**Options:**

$\boldsymbol{U_1}$ [Di Luzio et al, 2017]
[Bordone et al, 2017]

$\boldsymbol{S_1 + S_3}$

[Crivellin et al, 2017]
[Buttazzo et al, 2017]
[Marzocca, 2018]

$\boldsymbol{S_3 + R_2}$

[Bečirević et al, 2018]

Other (minimal) solutions do not seem to work:

W'/Z' models in tension with high-pT data

$R_{D^{(*)}}$

[Faroughy et al, 2016]

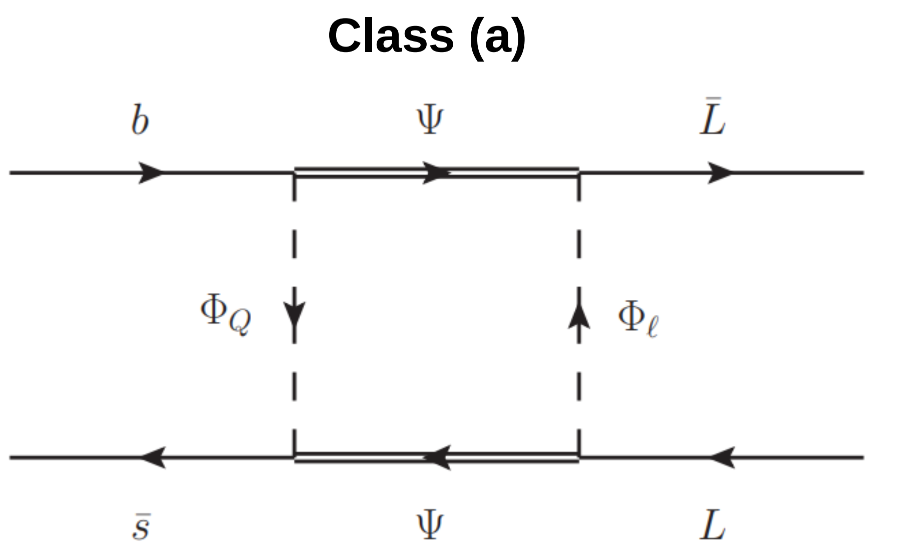
[Greljo et al, 2018]

**Talk by Jernej Kamenik**

**Talk by Teppei Kitahara**

# Loops and $b \to s$ anomalies

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




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

# ***Who ordered that?*** ***(again)***

***Who ordered that?*** ***(again)***

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

# 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, $m_\nu$, ...**

**Chuck Norris fact of the day**

*Chuck Norris can kill two stones with one bird*


# $b \to s$ anomalies and Dark Matter

# Linking $b \to s$ and DM

[ AV, 1803.04703 ]

**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

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

**Example:**

Aristizabal-Sierra, Staub, AV
[ 1503.06077 ]

**Example:**

Kawamura, Okawa, Omura
[ 1706.04344 ]

# Dark Matter

[Aristizabal Sierra, Staub, AV, 2015]

## DM stability

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

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

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

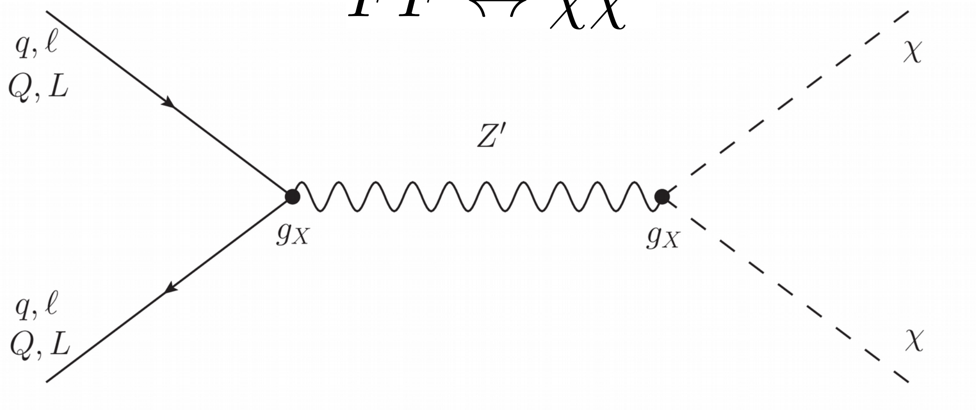
Odd under $\mathbb{Z}_2$

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

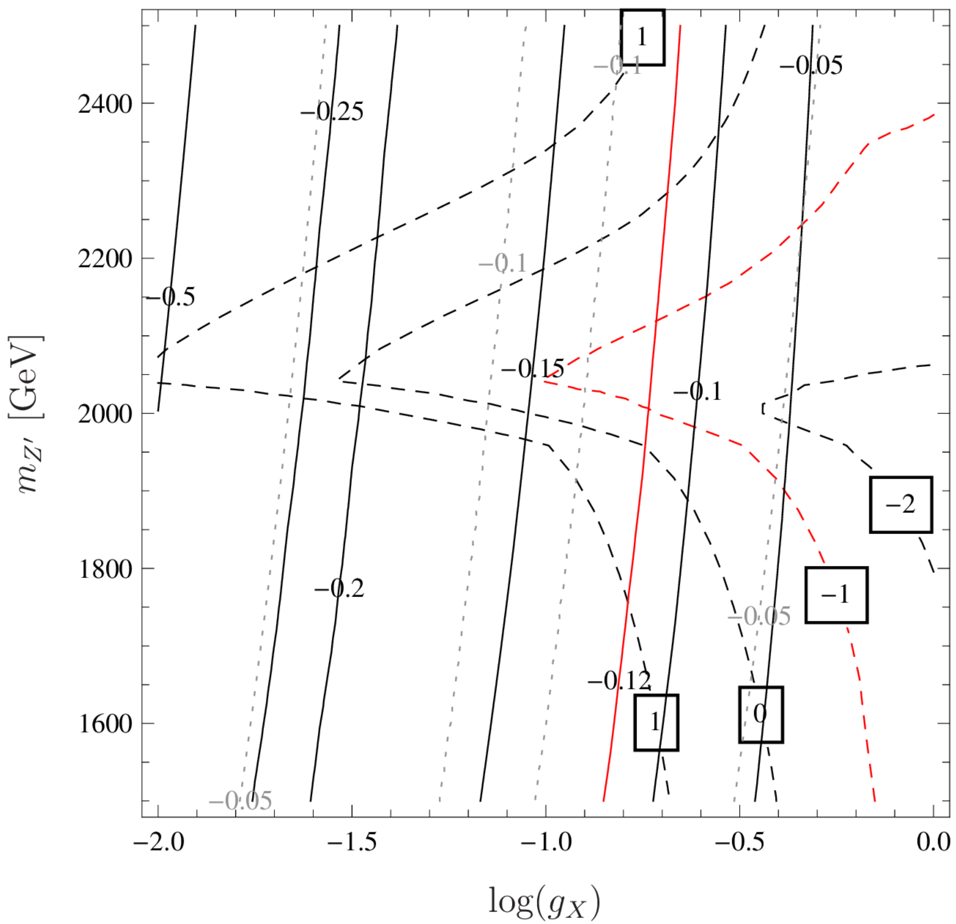
Assumption:

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

# DM and $b \to s$ anomalies

[Aristizabal Sierra, Staub, AV, 2015]

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

# 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 → $X$ | $0$ | $(\mathbf{1}, \mathbf{1}, 0)$ | $-1$ |
| $Q_{L,R}$ | $\frac{1}{2}$ | $(\mathbf{3}, \mathbf{2}, \frac{1}{6})$ | $1$ |
| $L_{L,R}$ | $\frac{1}{2}$ | $(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$ | $1$ |

**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

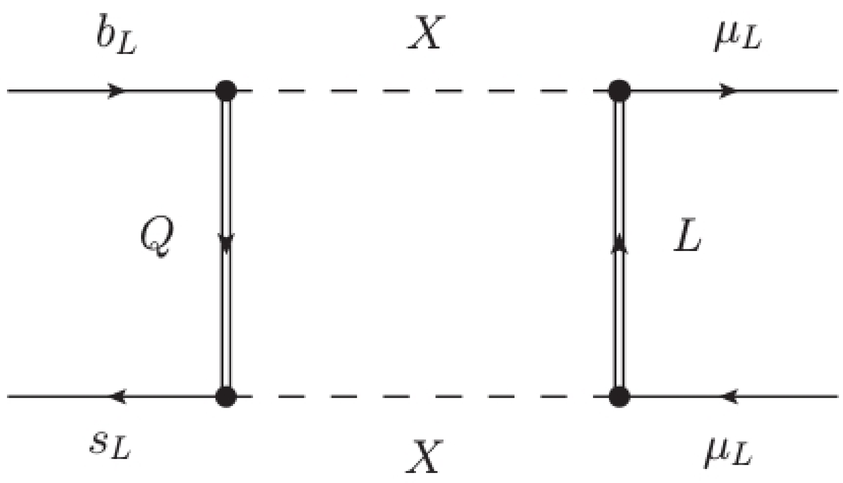
→ Loop explanation to the $b \to s$ anomalies

# Solving the $b \to s$ anomalies

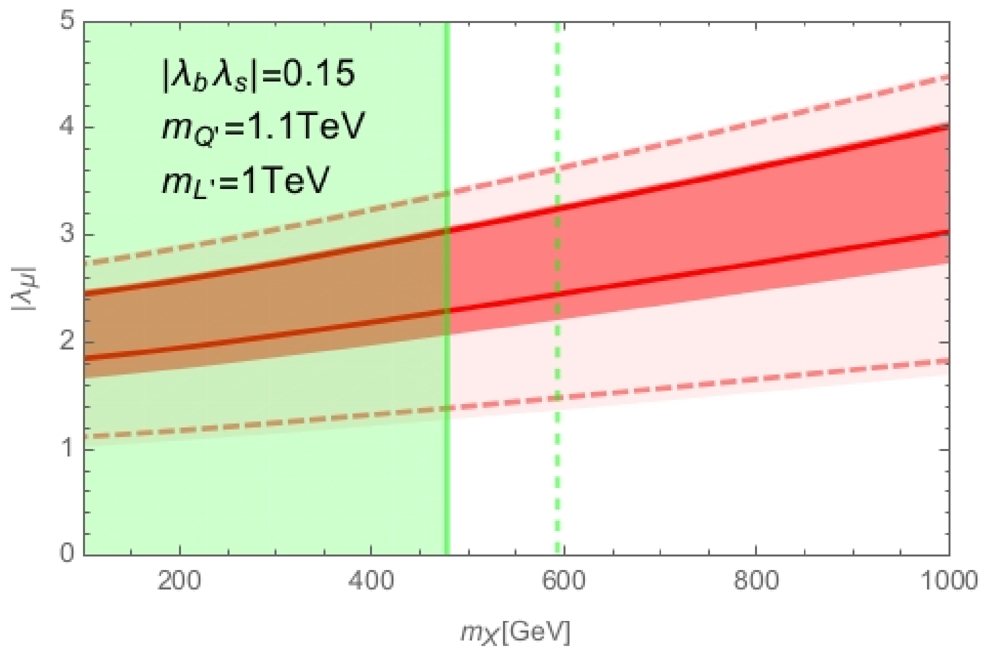
**Scenario A-I, model class b)**
[ 1608.07832 ]

[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

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

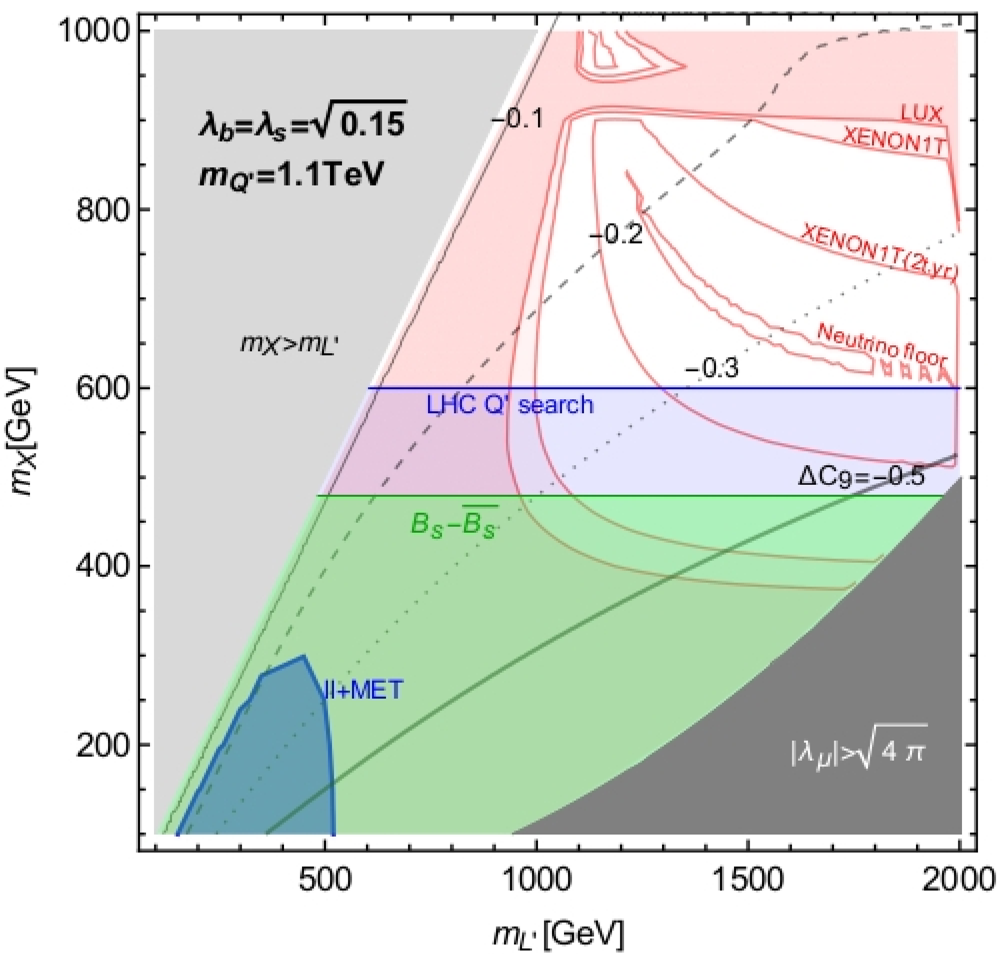
Most relevant annihilation channels for the relic density

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

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

The model explains the anomalies at $2\sigma$

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




# $b \to s$ 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

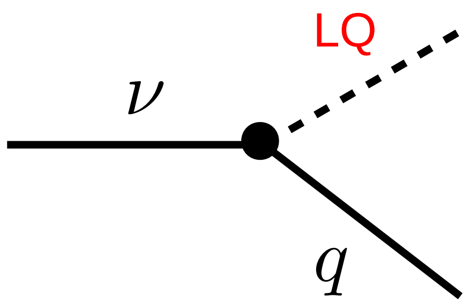
**Why two?**

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

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

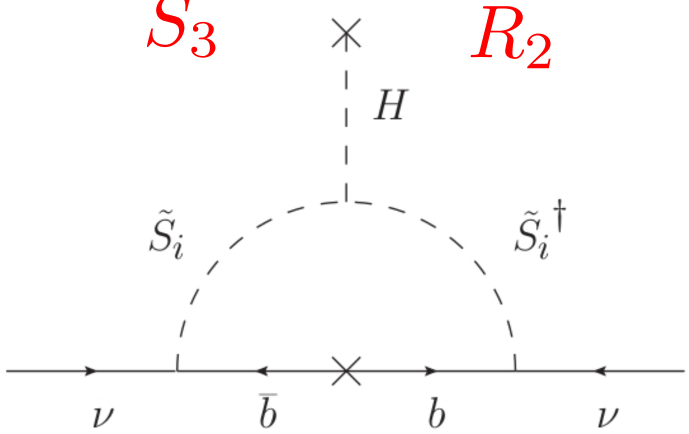
$$\widetilde{d}_R^* \sim S_1$$

# Leptoquarks: the link to neutrinos?

(Some) leptoquark models for the <u>B-anomalies</u> and <u>neutrino masses</u>

Päs, Schumacher
[ 1510.08757 ]

$S_3$ $\widetilde{R}_2$

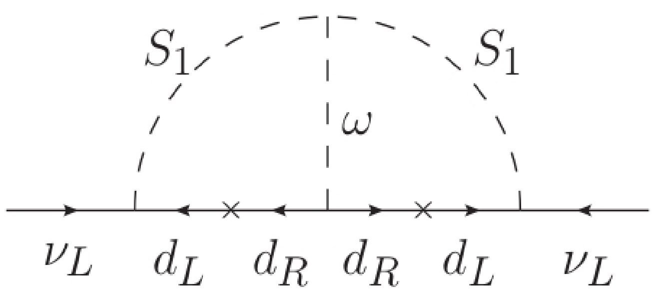



**1-loop**

Version with vector LQs in 1603.07672

Guo et al
[ 1707.00522 ]

$S_3$

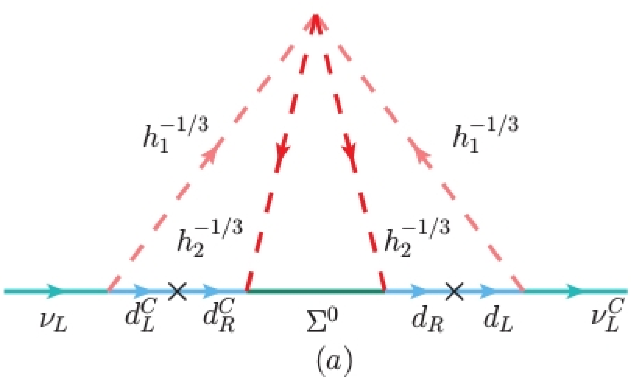



$\omega$ : diquark

**2-loop**

Hati et al
[ 1806.10146 ]

$S_3 \times 2$




**3-loop**


# B-anomalies and strong CP problem

# B-anomalies and strong CP problem

[ Fuentes-Martín, Reig, AV, 2019 ]

UV completions for

$$U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$$

vector leptoquark

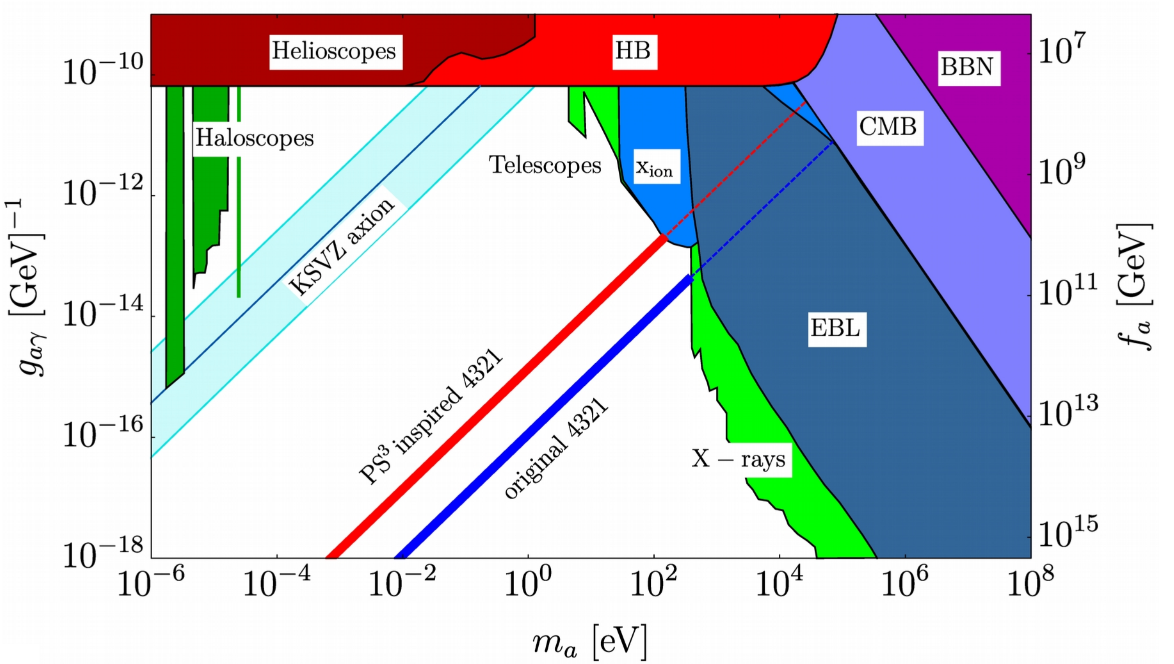
QCD
low-energy emergent interaction

$$\mathrm{SU}(4) \times \mathrm{SU}(3)' \to \mathrm{SU}(3)_c$$

$$\mathcal{L} = \frac{\theta_4 \alpha_4}{8\pi} H^A_{\mu\nu} \tilde{H}^{A\;\mu\nu} + \frac{\theta_3 \alpha_3}{8\pi} C^a_{\mu\nu} \tilde{C}^{a\;\mu\nu}$$

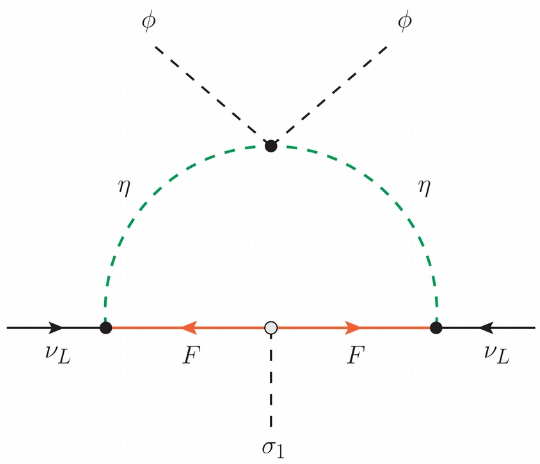
Two axions are required

Phenomenology closely linked to the B-anomalies




Bonus:

$m_\nu$



# Summary

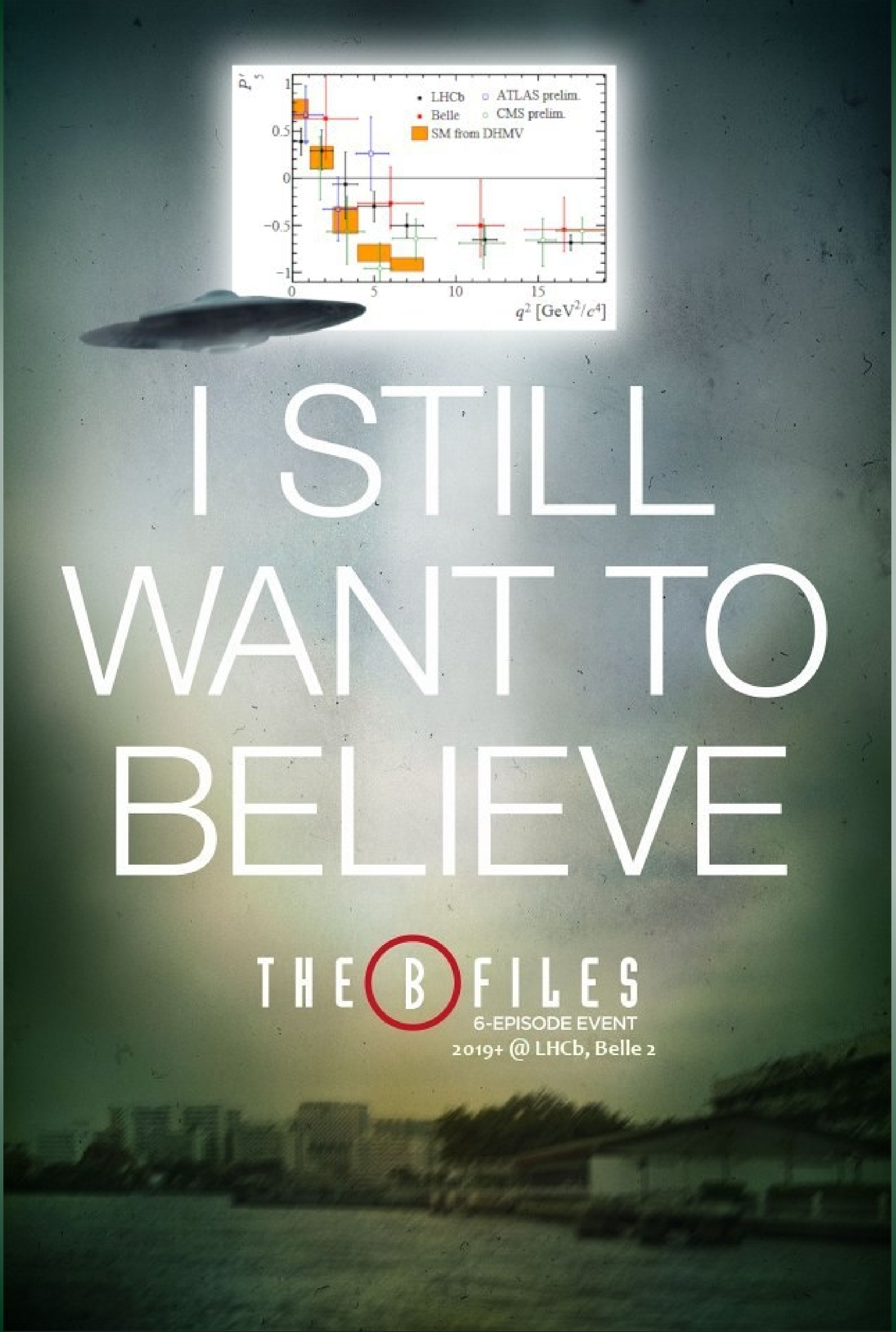
# Summary

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

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

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

Thanks for
your attention!




Poster by
Renato Fonseca

# Backup slides

# Direct searches at the LHC

## $Z'$ boson

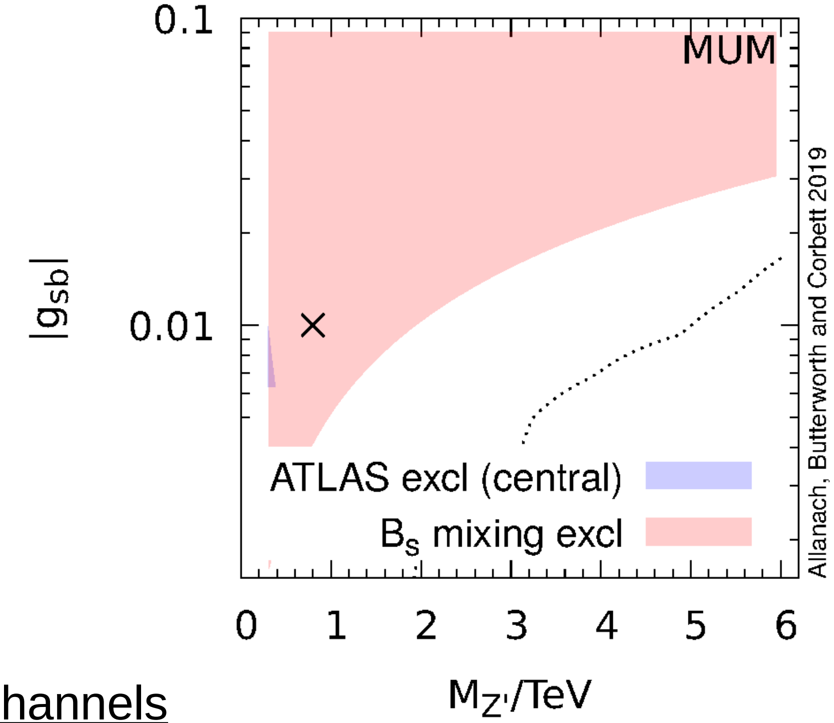
**ATLAS** 13 TeV & 139 fb$^{-1}$

$$pp \to Z' \to \mu^+\mu^-$$

$$\mathcal{L} = \overline{d_L}\,\Lambda_Q\,\gamma^\mu d_L\,Z'_\mu + \overline{e_L}\,\Lambda_L\,\gamma^\mu e_L\,Z'_\mu$$

$$\Lambda_Q = g_{bs}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad \Lambda_L = g_{\mu\mu}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

[Allanach et al, 2019]




## VL fermions

Limits strongly dependent on the dominant decay channels

$$m_Q \gtrsim 1\,\mathrm{TeV}$$ (QCD pair-produced)

$$m_L \gtrsim 500\,\mathrm{GeV}$$ (Drell-Yan pair-produced)

**Talk by Jernej Kamenik**

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

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

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

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

# 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 | $\bar{B} \to X_s \ell^+ \ell^-$ |
| $\tau \to P\,\ell$ | $\bar{B} \to X_{d,s} \nu \bar{\nu}$ |
| $h \to \ell_\alpha \ell_\beta$ | $B \to K \ell^+ \ell^-$ |
| $Z \to \ell_\alpha \ell_\beta$ | $K \to \pi \nu \bar{\nu}$ |
| | $\Delta M_{B_{s,d}}$ |
| | $\Delta M_K$ and $\varepsilon_K$ |
| | $P \to \ell \nu$ |

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

Easily extendable

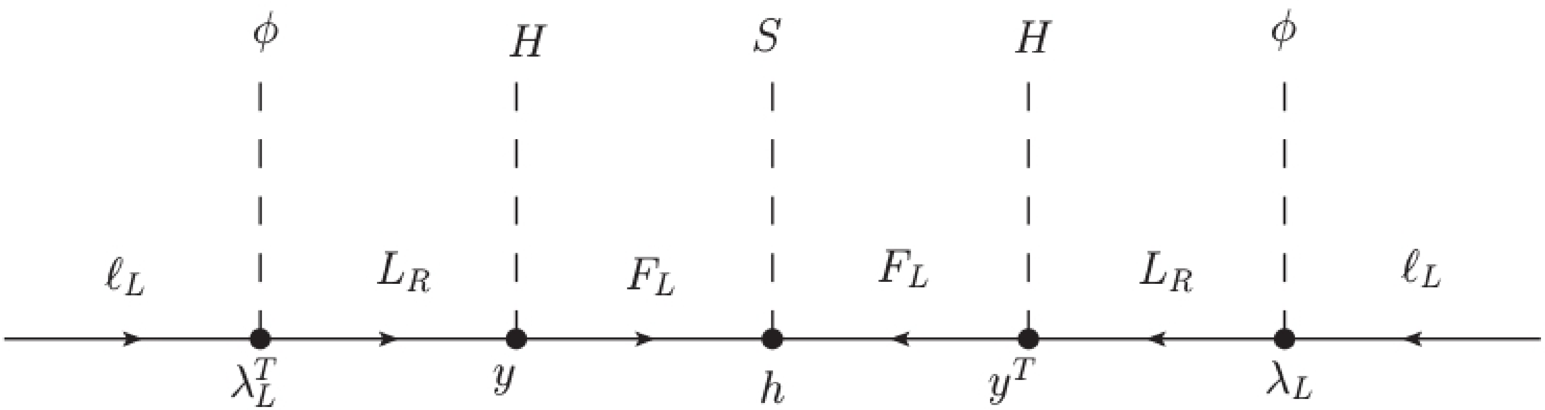
Many observables ready to be computed in your favourite model!

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

# Neutrino masses in DM portal model

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!

# 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.

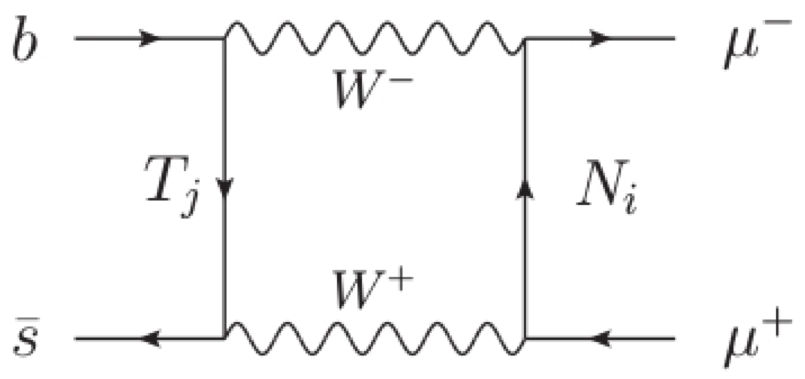
# Heavy neutrinos in loops

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

# 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

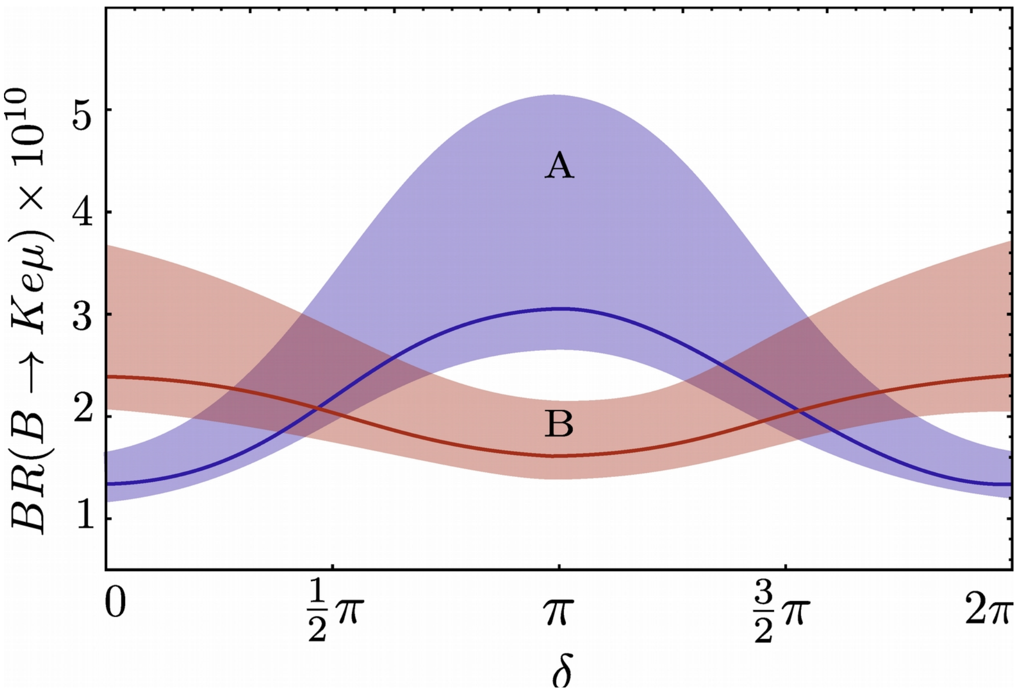
Working hypothesis: What if $U_\ell = K^\dagger$?

[Boucenna, Valle, AV, 2015]

Neutrino oscillations

**Neutrinos ⟷ B-physics**

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




Lines: BF
Bands: $1\sigma$