Protection symmetries for TeV-scale leptoquarks

Admir Greljo

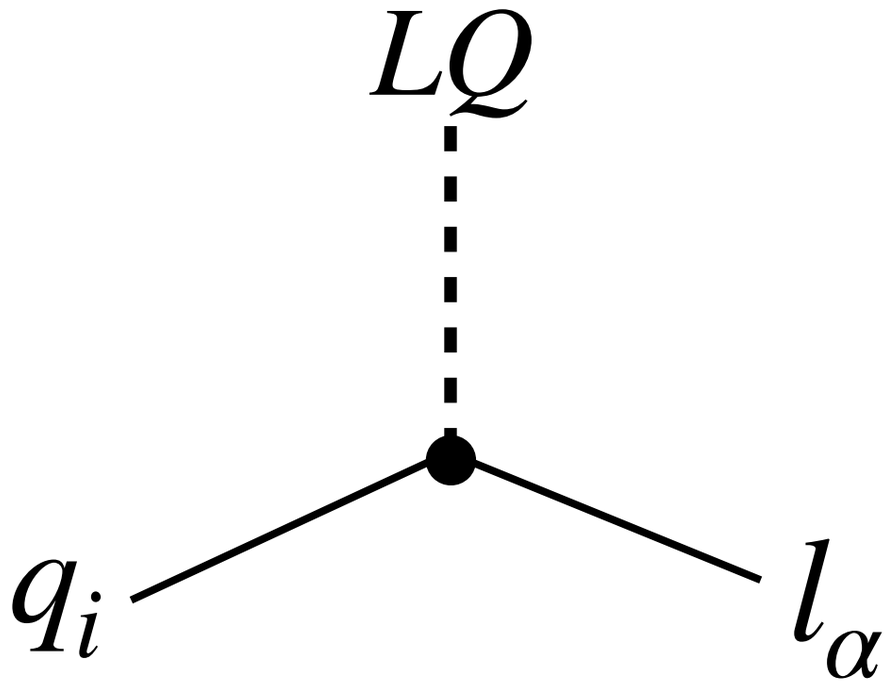
UNIVERSITÄT BERN → University of Basel

FNSNF Swiss National Science Foundation
Eccellenza, Project-186866

11.01.2023, Zurich Phenomenology Workshop 2023

Leptoquarks at the TeV scale?

Doršner, Fajfer, AG, Kamenik, Košnik; 1603.04993 (Physics Reports Review)

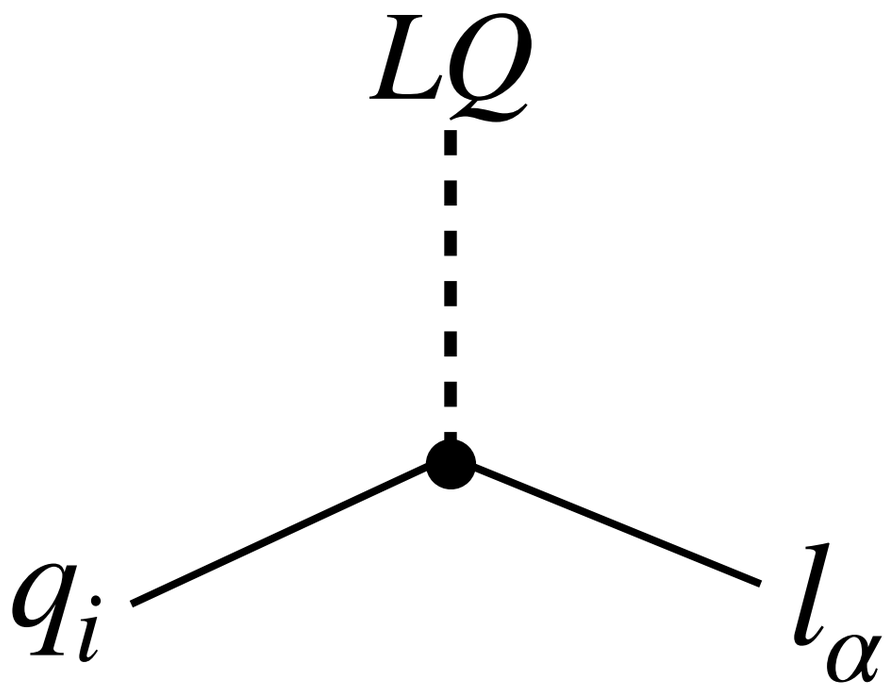


Wanted:

- A LQ with a TeV-scale mass and (some) $\mathcal{O}(1)$ couplings

Leptoquarks at the TeV scale?

Doršner, Fajfer, AG, Kamenik, Košnik; 1603.04993 (Physics Reports Review)



Wanted:

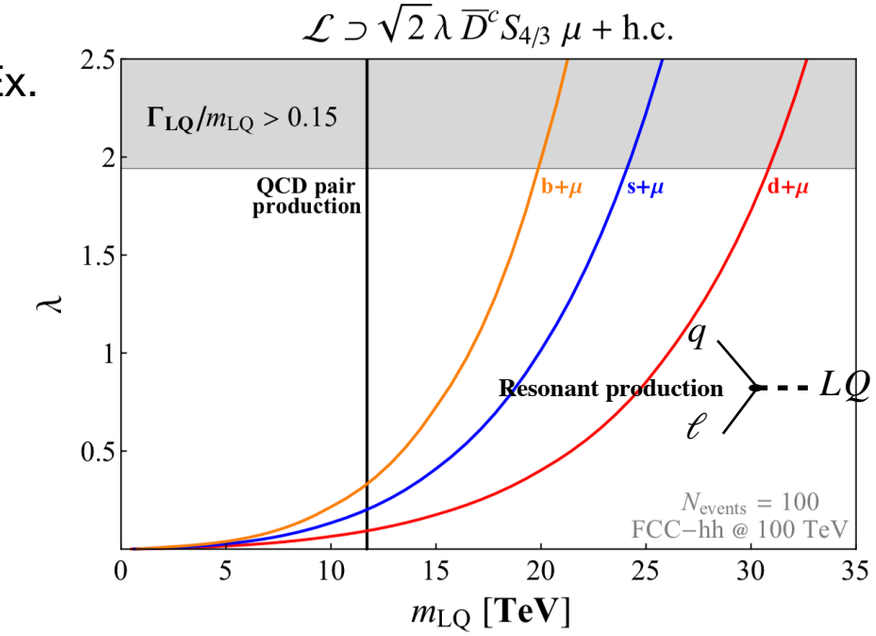
- A LQ with a TeV-scale mass and (some) $\mathcal{O}(1)$ couplings

Why?

Phenomenology

- Rich collider and flavor pheno?

Ex.



Buonocore, AG, Krack, Nason, Selimovic, Tramontano, Zanderighi; 2209.02599

Theory

- Quark-lepton unification!

Pati-Salam, SU(5), SO(10) GUT predict LQs but generically not in this mass-coupling range.
New model building directions…

Outline

PART I

Theory

- A model building direction: Gauged flavour

PART II

Phenomenology

- Interpretation of $b \to s\ell\ell$ anomalies after the recent LHCb update

Accidental Symmetries in the SM

$$q_i, \ell_i, U_i, D_i, E_i \quad \textit{flavour } i = 1,2,3$$

$\mathscr{L}_{\rm SM}$ sans Yukawa: $U(3)_q \times U(3)_\ell \times U(3)_U \times U(3)_D \times U(3)_E$

$$-\mathscr{L}_{\rm Yuk} = \bar{q} V^\dagger \hat{Y}_u \tilde{H} U + \bar{q} \hat{Y}_d H D + \bar{\ell} \hat{Y}_e H E$$

[$U(3)^5$ transformation and a singular value decomposition theorem]

$$\mathscr{L}_{\rm SM}: \quad U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$$

- $B - L$ and $L_i - L_j$ are exact
- $B + L$ is anomalous: non-perturbative dynamics implies a selection rule $\Delta B = \Delta L = 0 \,(\mathrm{mod}\, 3)$

TeV-scale BSM?

- A viable model at the TeV-scale should not (*excessively*) violate the accidental symmetries.
- Not a generic case!

Example: **Leptoquarks**

$\dim[\mathcal{O}] = 4$

$\mathcal{L}_4 \mathrel{+}= y_{ij}\, q^i L^j S + z_{ij}\, q^i q^j S^\dagger$

$B(S) = -\frac{1}{3}$ $\qquad$ $B(S) = \frac{2}{3}$

~~$U(1)_B$~~ Proton decay $[z \cdot y]$ $\qquad \tau_p \gtrsim 10^{34}$ years

~~$U(1)_e \times U(1)_\mu \times U(1)_\tau$~~ $\qquad \mu \to e\,\gamma$ $[i \neq j]$ $\qquad BR(\mu \to e\gamma) \lesssim 10^{-13}$

- Generic TeV-scale LQs are dead!

Gauged $\mathrm{U}(1)_X$ + leptoquarks

The storyline

- Selection rules for a TeV-scale leptoquark
- Neutrino masses
- Proton stability
- Unification

A $U(1)_X$ model

- The initial model $U(1)_{B-3L_\mu}$ AG, Stangl, Thomsen; 2103.13991

- The generalisation

$$X = 3m(B-L) - n\left(2L_\mu - L_e - L_\tau\right) , \quad \gcd(m,n) = 1$$

Davighi, AG, Thomsen; 2202.05275

A $U(1)_X$ model

- The initial model $U(1)_{B-3L_\mu}$ AG, Stangl, Thomsen; 2103.13991

- The generalisation

$$X = 3m(B-L) - n\,(2L_\mu - L_e - L_\tau)\ , \qquad \gcd(m,n) = 1$$

Davighi, AG, Thomsen; 2202.05275

	Fields	$\mathrm{U}(1)_X$
Quarks	$q_i,\ u_i,\ d_i$	m
Electrons and taus	$\ell_{1,3},\ e_{1,3},\ \nu_{1,3}$	$n-3m$
Muons	$\ell_2,\ e_2,\ \nu_2$	$-2n-3m$
Higgs	H	0
Leptoquarks $(\bar{\mathbf{3}},\mathbf{3/1})_{1/3}$	$S_3,\ S_1$	$2m+2n$
Scalars (SM singlets)	$\phi_{e\tau}$	$6m-2n$
	ϕ_μ	$6m+n$

Selection rules

Gauge symmetry selection rules:

✓ $q\mu S$

✗ $qqS^\dagger, qeS, q\tau S$

"Muoquark"

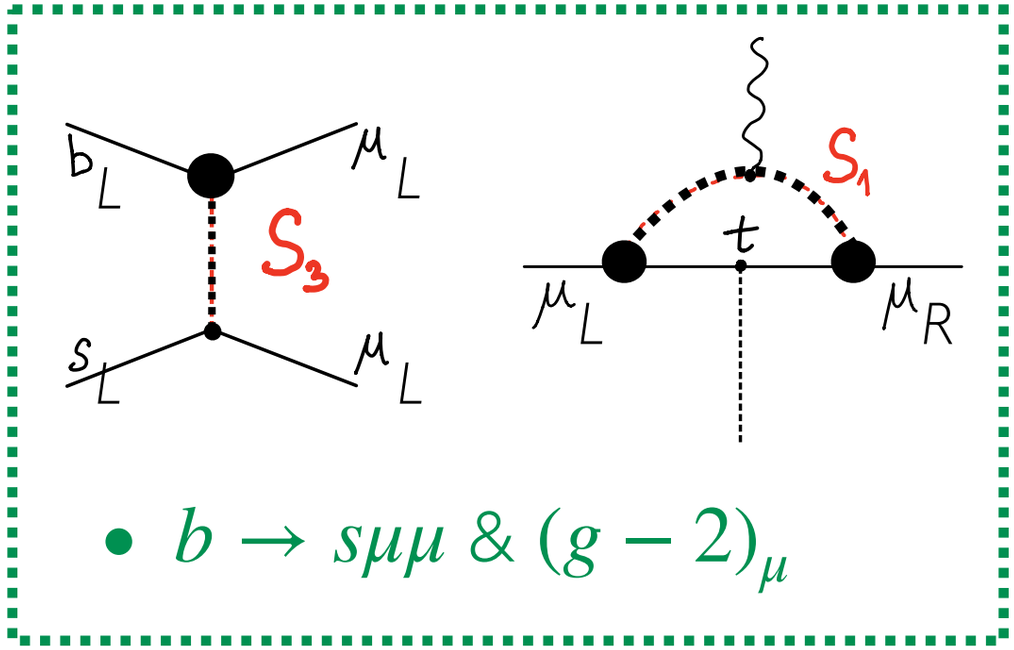
$\Longrightarrow$ The accidental symmetry of $\mathscr{L}_{LQ}$ is $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$ and the LQ charge is $(-1/3, 0, -1, 0)$

Selection rules

Gauge symmetry selection rules:

✔ $q\mu S$

✘ $qqS^\dagger, qeS, q\tau S$



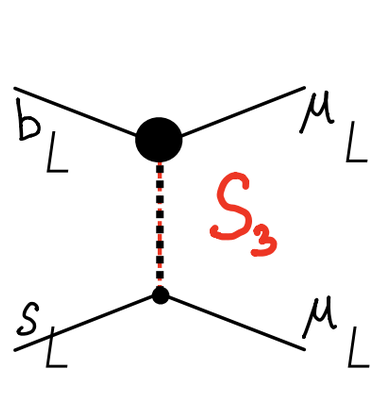
- $b \to s\mu\mu$ & $(g-2)_\mu$

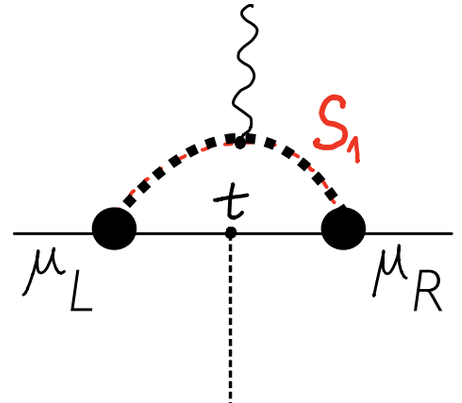
Selection rules

Gauge symmetry selection rules:

✔ $q\mu S$

✘ $qqS^\dagger, qeS, q\tau S$

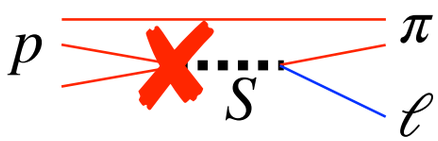




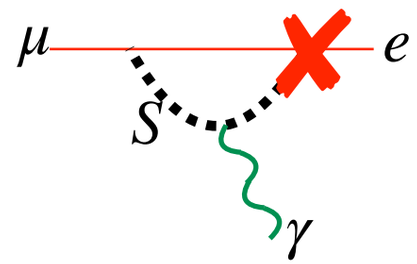
- $b \to s\mu\mu$ & $(g-2)_\mu$

- No proton decay & cLFV

$\tau_p \gtrsim 10^{34}$ years

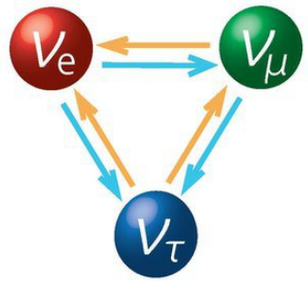


$BR(\mu \to e\gamma) \lesssim 10^{-13}$



...

Neutrino Masses



- The PMNS is full of $\mathcal{O}(1)$ elements.
- The correct neutrino masses and mixings dictate the $U(1)_X$ breaking.

- A *dense* Majorana mass matrix needs two SM-singlet scalar fields with charges $6m - 2n$ and $6m + n$ to get a VEV

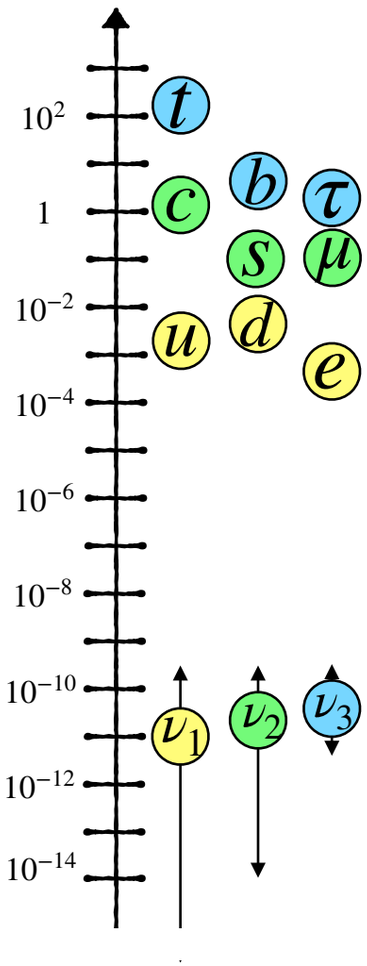
Type-I seesaw mechanism

$$Y_\nu \sim \begin{pmatrix} \times & 0 & \times \\ 0 & \times & 0 \\ \times & 0 & \times \end{pmatrix} \quad ; \quad \mathcal{L} \supset \bar{\nu}_{\rm R}^{i\,c} \nu_{\rm R}^{j} (\xi_{e\tau}^{ij} \phi_{e\tau} + \xi_{\mu}^{ij} \phi_{\mu}) \implies \frac{M_\nu}{v_X} \sim \begin{pmatrix} \times & \times & \times \\ \times & 0 & \times \\ \times & \times & \times \end{pmatrix}$$

- More general than two-zero minor structure type D_1^R Asai; 1907.04042
- This is enough to accommodate for:
  - *Neutrino oscillations data,*
  - *The Planck limit on the sum of neutrino masses,*
  - *The absence of neutrinoless double beta decay.*

AG, Stangl, Thomsen; 2103.13991
Davighi, AG, Thomsen; 2202.05275

Neutrino Masses



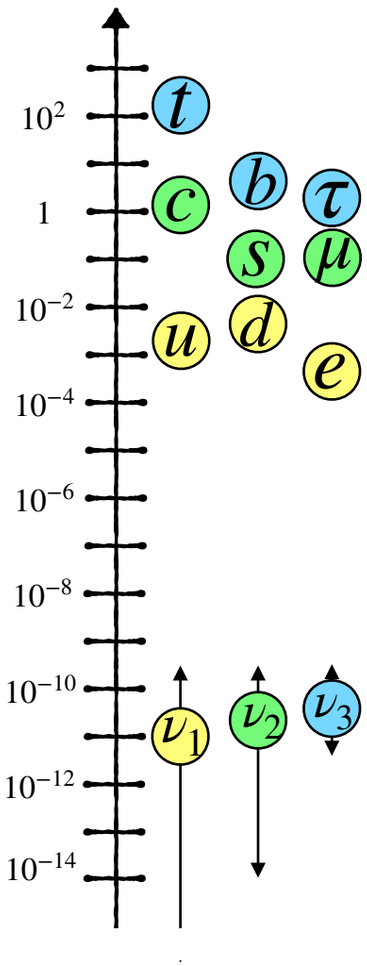
$U(1)_X$ breaking at the high scale?

The mass gap is explained if $\langle \phi_{e\tau} \rangle, \langle \phi_{\mu} \rangle \gg \langle H \rangle$

Standard thermal leptogenesis at high scale

Davighi, AG, Thomsen; 2202.05275

Neutrino Masses



$U(1)_X$ breaking at the high scale?

The mass gap is explained if $\langle \phi_{e\tau} \rangle, \langle \phi_{\mu} \rangle \gg \langle H \rangle$

Standard thermal leptogenesis at high scale

but

In the $U(1)_X$ broken phase one can ***naively*** write renormalisable terms qqS^* and $q_i \ell_j S$ that violate $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$

- What happens?
- Is there proton decay? cLFV?

Davighi, AG, Thomsen; 2202.05275

The IR: discrete gauge subgroup

$\phi_{e\tau}$	$6m-2n$
ϕ_{μ}	$6m+n$

- Fixed by neutrinos

Davighi, AG, Thomsen; 2202.05275

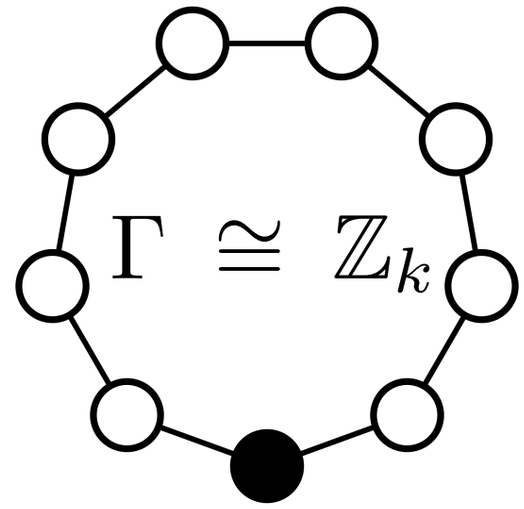
The IR: discrete gauge subgroup

$\phi_{e\tau}$	$6m - 2n$
ϕ_μ	$6m + n$

- Fixed by neutrinos

$$k = \gcd\big([\phi_{e\tau}]_X, [\phi_\mu]_X\big)$$

$$e^{i\frac{2\pi}{k}[\phi]_X}\phi = \phi$$



- The scalars $\phi_{e\tau}$ and ϕ_μ are Γ singlets
- An unbroken discrete subgroup $\Gamma \subset U(1)_X$ acting on matter in the IR

Davighi, AG, Thomsen; 2202.05275

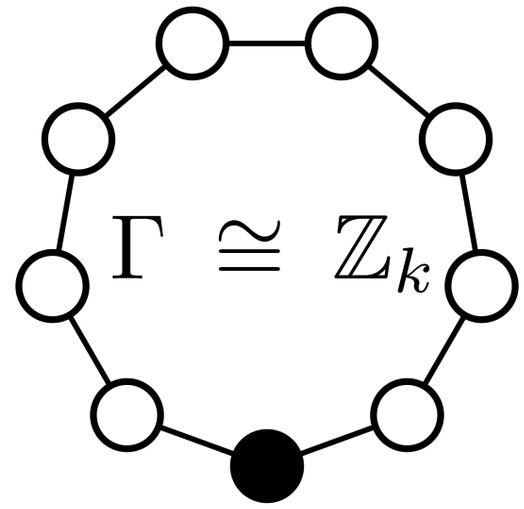
The IR: discrete gauge subgroup

$\phi_{e\tau}$	$6m-2n$
ϕ_μ	$6m+n$

- Fixed by neutrinos

$$k = \gcd\big([\phi_{e\tau}]_X,\, [\phi_\mu]_X\big)$$

$$e^{i\frac{2\pi}{k}[\phi]_X}\phi = \phi$$



- The scalars $\phi_{e\tau}$ and ϕ_μ are Γ singlets
- An unbroken discrete subgroup $\Gamma \subset U(1)_X$ acting on matter in the IR

- The diquark operators qqS^* are banned by Γ when:

$$\boxed{\begin{aligned}&(m,\, n) = \big(3a + r,\, 9b + 3r\big), \quad \text{for} \quad r \in \{1,\, 2\},\\ &(a,\, b) \in \mathbb{Z}^2, \text{ and } \gcd\big(3a + r,\, b - a\big) = 1\,.\end{aligned}}$$

$$\Gamma \cong \begin{cases}\mathbb{Z}_9, & \text{for } b + r \in 2\mathbb{Z} + 1\\ \mathbb{Z}_{18}, & \text{for } b + r \in 2\mathbb{Z}\end{cases}$$

Davighi, AG, Thomsen; 2202.05275

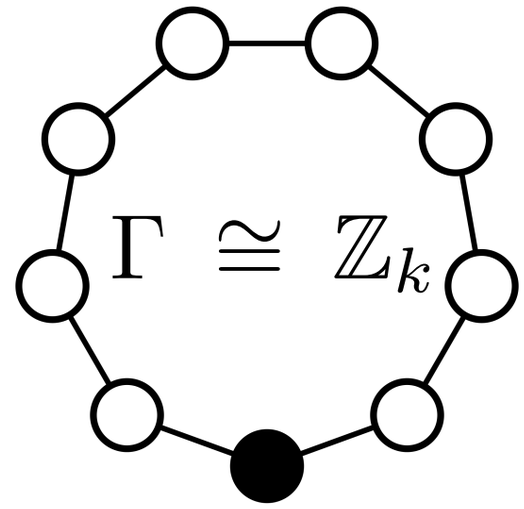
The IR: discrete gauge subgroup

$\phi_{e\tau}$	$6m-2n$
ϕ_μ	$6m+n$

- Fixed by neutrinos

$$k = \gcd\big([\phi_{e\tau}]_X,\, [\phi_\mu]_X\big)$$

$$e^{i\frac{2\pi}{k}[\phi]_X}\phi = \phi$$



- The scalars $\phi_{e\tau}$ and ϕ_μ are Γ singlets
- An unbroken discrete subgroup $\Gamma \subset U(1)_X$ acting on matter in the IR

- The diquark operators qqS^* are banned by Γ when:

$$\boxed{\begin{aligned}&(m,\, n) = \big(3a + r,\, 9b + 3r\big), \quad \text{for} \quad r \in \{1,\, 2\},\\ &(a,\, b) \in \mathbb{Z}^2, \text{ and } \gcd\big(3a + r,\, b - a\big) = 1\,.\end{aligned}}$$

$$\Gamma \cong \begin{cases}\mathbb{Z}_9, & \text{for } b + r \in 2\mathbb{Z} + 1\\ \mathbb{Z}_{18}, & \text{for } b + r \in 2\mathbb{Z}\end{cases}$$

- No proton decay!

- Both B − L and the lepton-flavoured factor required! $\quad X = 3m(B-L) - n\,(2L_\mu - L_e - L_\tau)$

Davighi, AG, Thomsen; 2202.05275

The IR: discrete gauge subgroup

$b+r \pmod 2$	Γ	ℓ	q	S	$qS\ell$	qS^*q
0	$\mathbb{Z}_{18}$	$9(b-a)$	$3a+r$	$6a+8r$	0	$12r$
1	$\mathbb{Z}_9$	0	$3a+r$	$6a+8r$	0	$3r$

Charges under the remnant discrete symmetry Γ

Davighi, AG, Thomsen; 2202.05275

The IR: discrete gauge subgroup

$b+r \pmod 2$	Γ	ℓ	q	S	$qS\ell$	qS^*q
0	$\mathbb{Z}_{18}$	$9(b-a)$	$3a+r$	$6a+8r$	0	$12r$
1	$\mathbb{Z}_9$	0	$3a+r$	$6a+8r$	0	$3r$

Charges under the remnant discrete symmetry Γ

- The Γ protection goes beyond just banning the diquark operators. Integrate out S. Selection rule:

$$\Delta B = 0 \pmod 3$$

Exact proton stability to all orders in the SMEFT!

✘ $qqq\ell$ and so on

Davighi, AG, Thomsen; 2202.05275

The IR: discrete gauge subgroup

$b+r \pmod 2$	Γ	ℓ	q	S	$qS\ell$	qS^*q
0	$\mathbb{Z}_{18}$	$9(b-a)$	$3a+r$	$6a+8r$	0	$12r$
1	$\mathbb{Z}_9$	0	$3a+r$	$6a+8r$	0	$3r$

Charges under the remnant discrete symmetry Γ

- The Γ protection goes beyond just banning the diquark operators. Integrate out S. Selection rule:

$$\Delta B = 0 \pmod 3$$

Exact proton stability to all orders in the SMEFT!

✗ $qqq\ell$ and so on

- Neutron—antineutron oscillations also forbidden
- ΔB = 3 processes are allowed, in analogy to sphalerons.

Davighi, AG, Thomsen; 2202.05275

What about cLFV?

- Γ is lepton flavour universal, otherwise no PMNS.
- cLFV through higher-dim. operators in the $U(1)_X$-invariant effective theory:

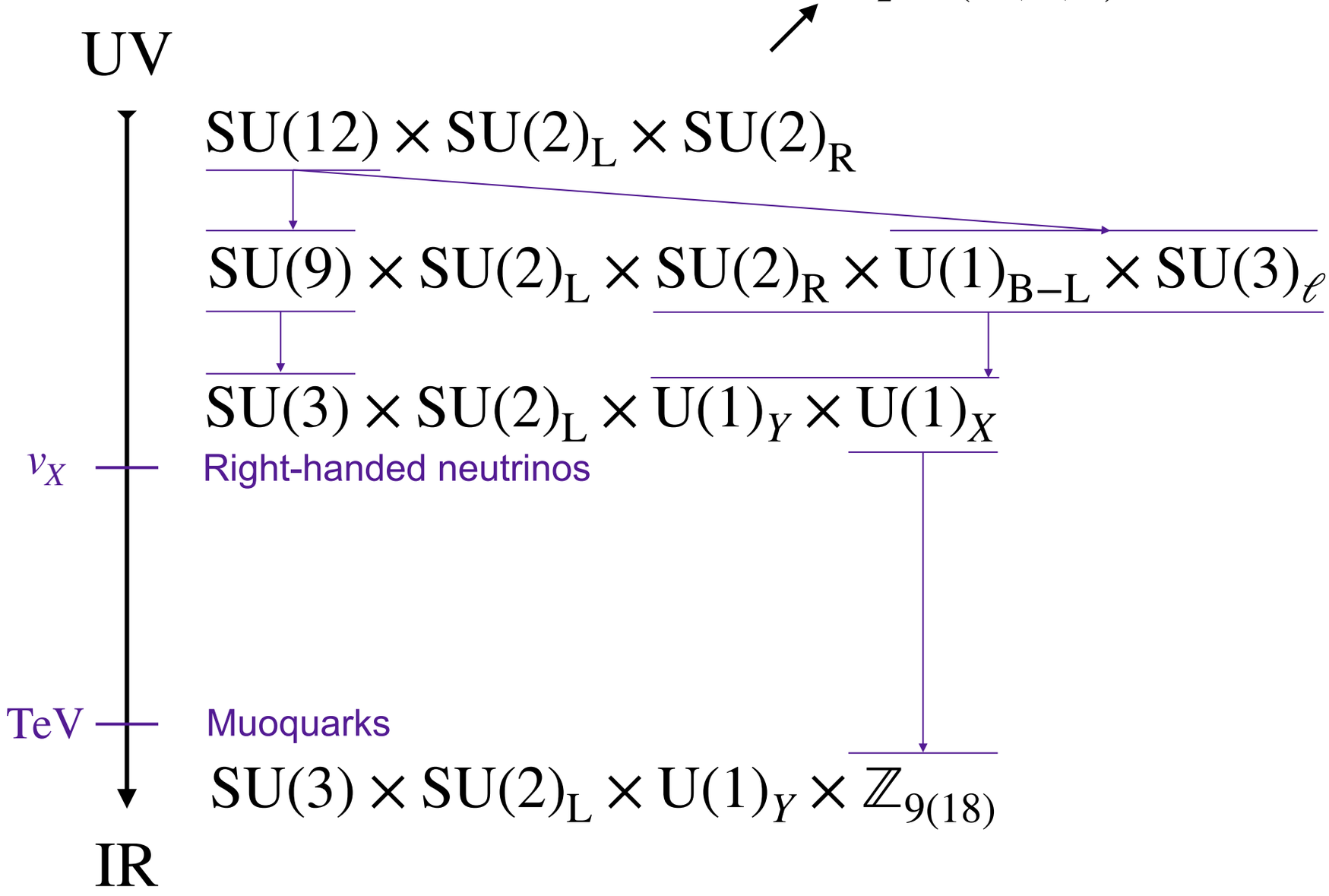
$$\frac{1}{\Lambda^2}\phi_{e\tau}\phi_\mu^*\, qS_{1/3}\ell_{1,3} \qquad \frac{1}{\Lambda^2}\phi_{e\tau}\phi_\mu^*\, uS_1 e_{1,3}$$

- A modest scale separation is sufficient to suppress cLFV processes to a level compatible with current bounds.

Davighi, AG, Thomsen; 2202.05275

Deeper into the UV: Unification

All 3 families of fermions fit into:
$\Psi_L \sim (\mathbf{12}, \mathbf{2}, \mathbf{1})$ $\Psi_R \sim (\mathbf{12}, \mathbf{1}, \mathbf{2})$



Tentative gauge–flavour unification scenario.

Davighi, AG, Thomsen; 2202.05275

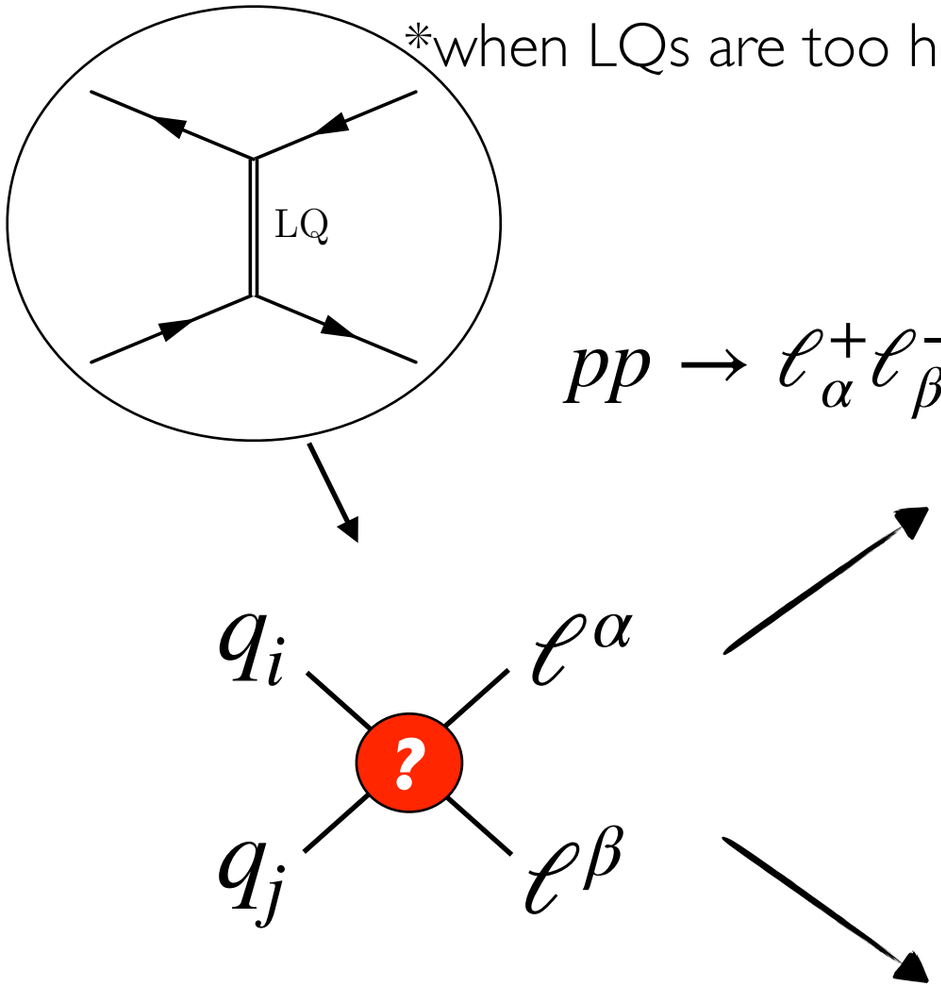
PART II

Comments on $R_{K^{(*)}}$

The storyline

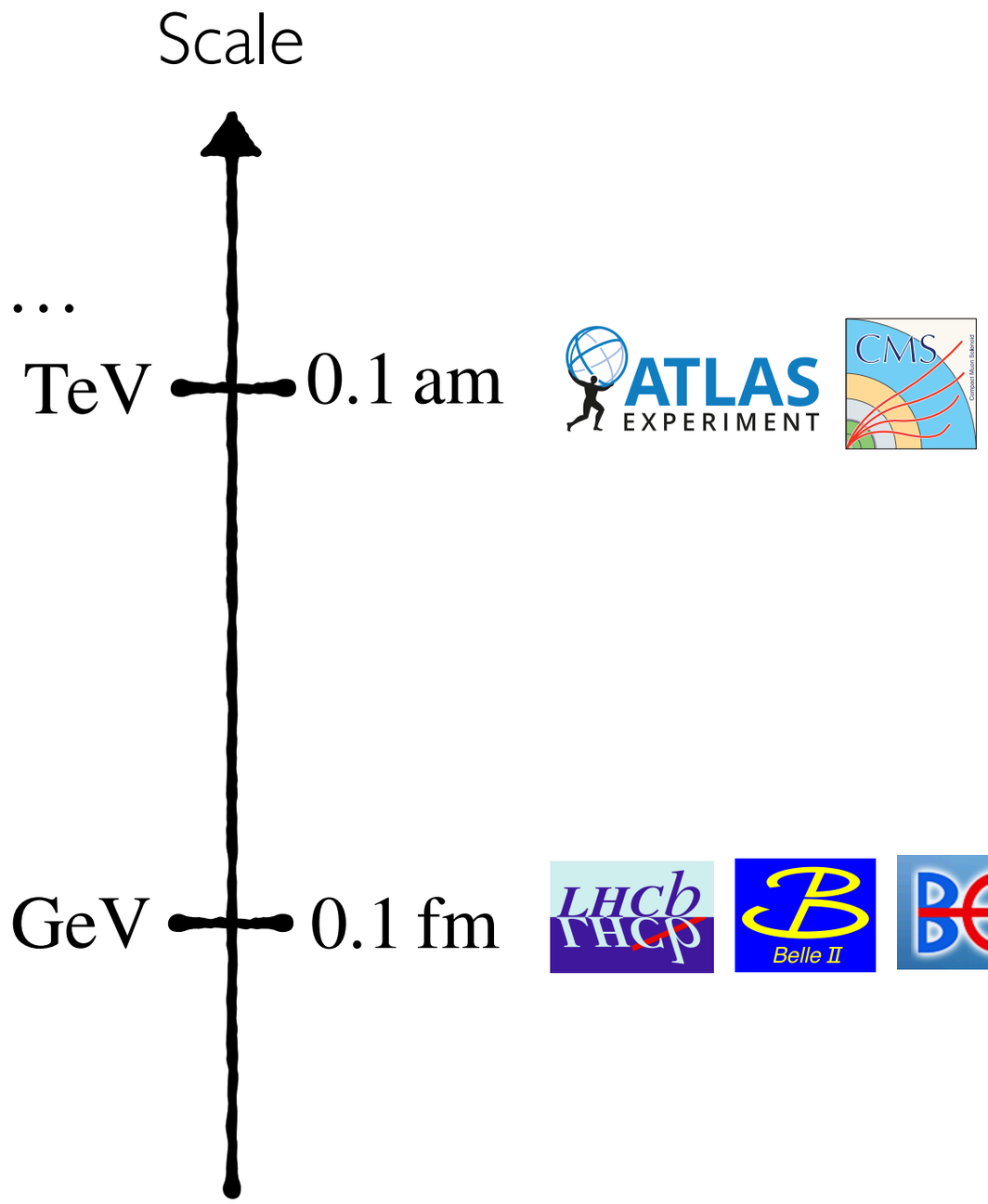
- Interpretation of $b \to s\ell\ell$ anomalies after the recent LHCb update

Drell-Yan versus B-decays



*when LQs are too heavy

$$pp \to \ell^+_\alpha \ell^-_\beta (j), \ \ldots$$



Example: $b \to s\mu\mu$ vs Drell-Yan

AG, Marzocca; 1704.09015

Systematic SMEFT study using `flavio`

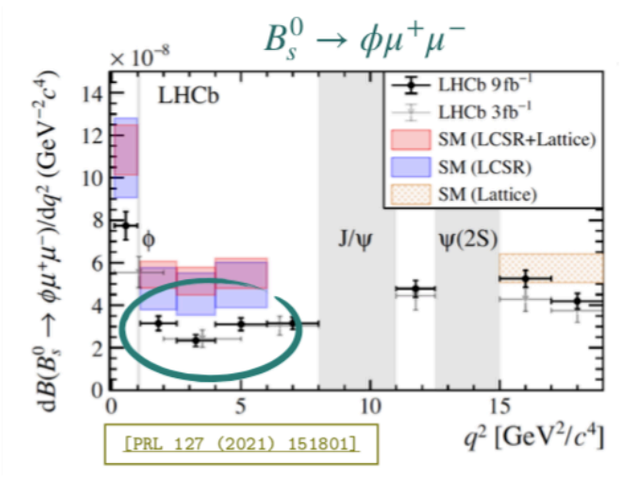
AG, Salko, Smolkovic, Stangl; 2212.10497

The status of $b \to s\ell\ell$ anomalies

cf. Renato Quagliani, CERN seminar 20.12.2022.

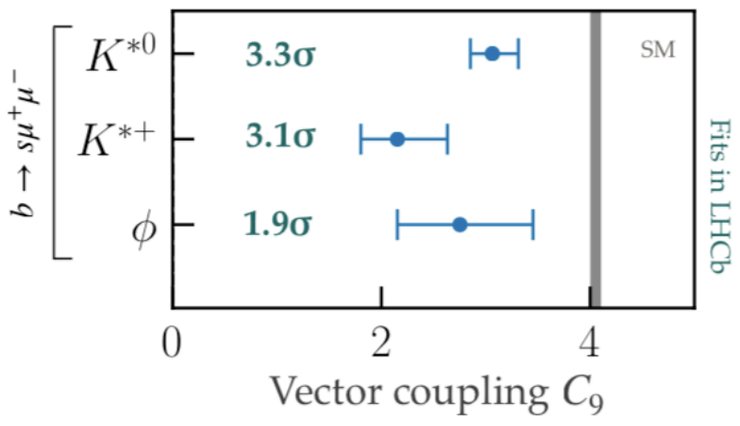
- Anomalies in $b \to s\mu\mu$

$b \to s\mu^+\mu^-$ *differential decay rates*



+ …

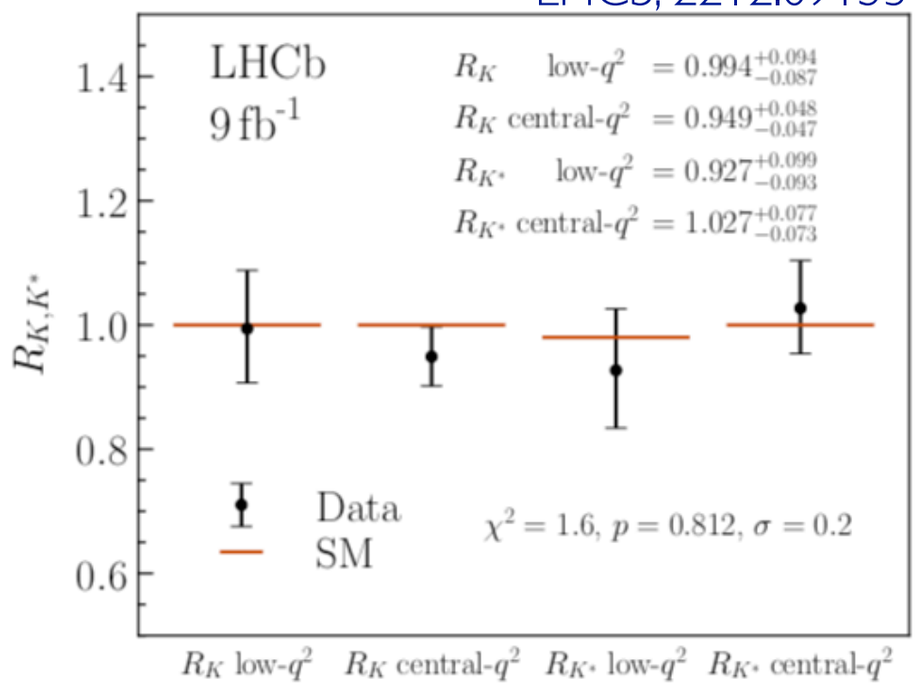
$b \to s\mu^+\mu^-$ *angular analyses*



- Intriguing coherent and consistent pattern
  - However, *charm-loops* can mimic shift in C_9

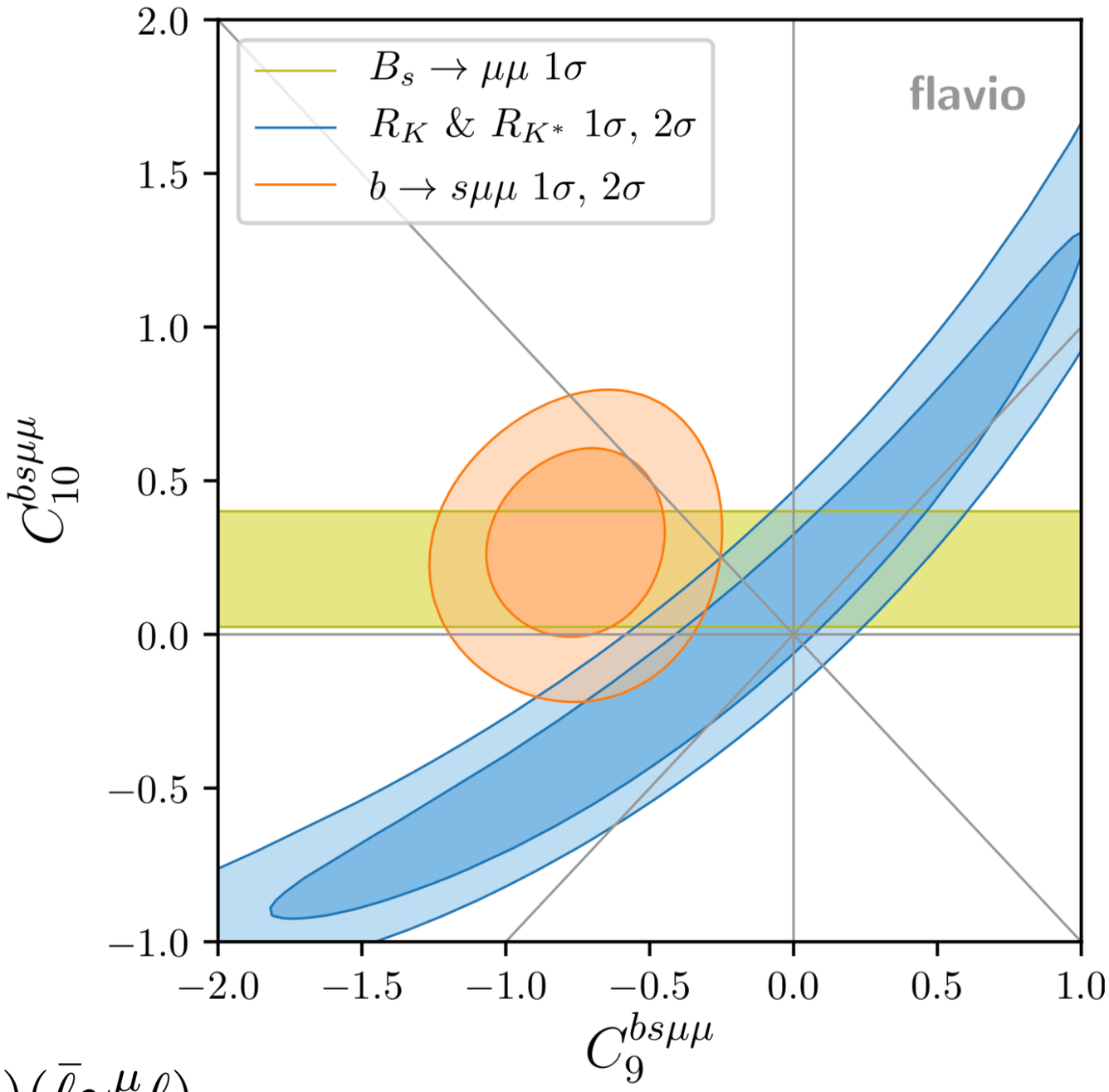
- But **L**epton **F**lavor **U**niversality ratios are SM-like

LHCb, 2212.09153



The EFT fit

AG, Salko, Smolkovic, Stangl; 2212.10497



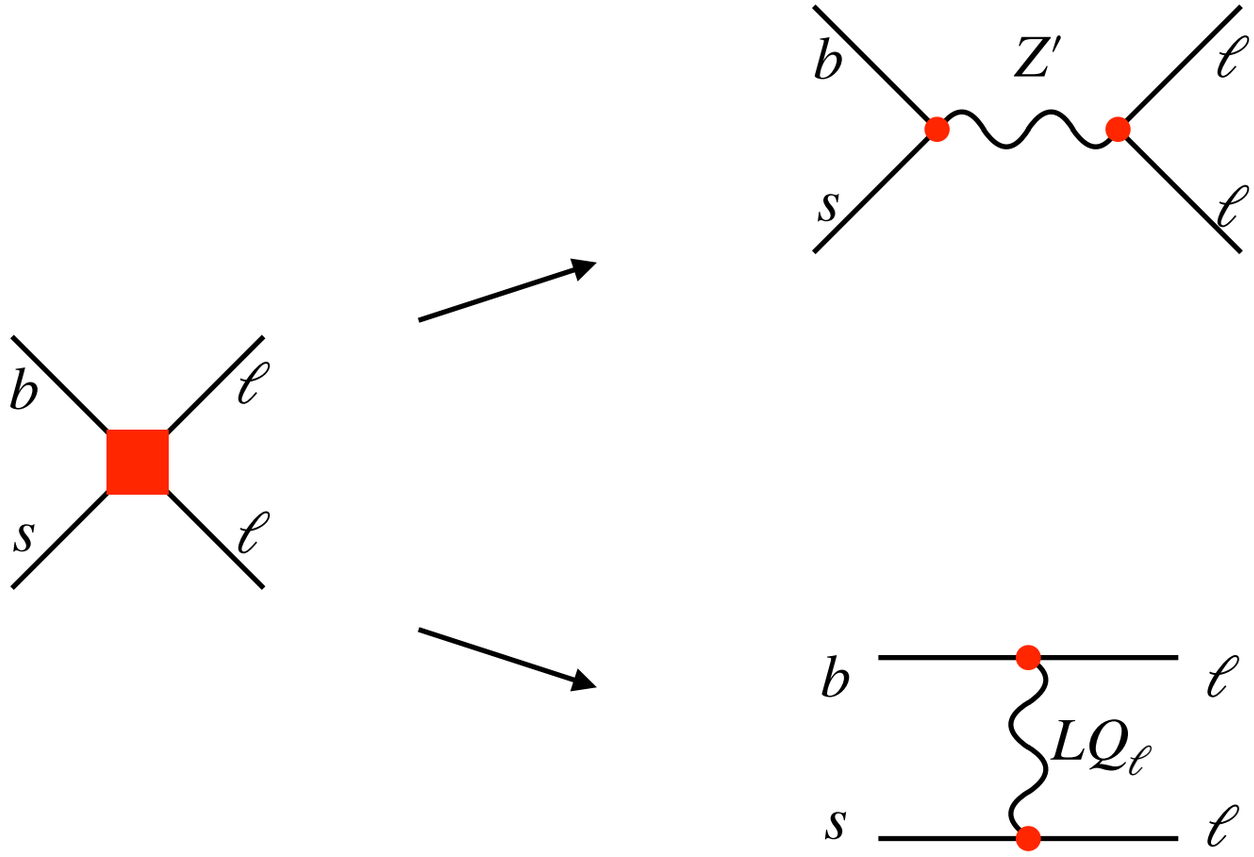
Tension!

$$O_9^{bq\ell\ell} = (\bar{q}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,,$$

$$O_{10}^{bq\ell\ell} = (\bar{q}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5 \ell)$$

LFU models for $b \to s\ell\ell$

Tree-level models



- LFU Z'

$$U(1)_{B-L}$$

$$U(1)_{3B_3-L}$$

...

- LFU LQ

$$(\bar{\mathbf{3}}, \mathbf{3}, 1/3) \times \mathbf{2} = LQ_e + LQ_\mu$$

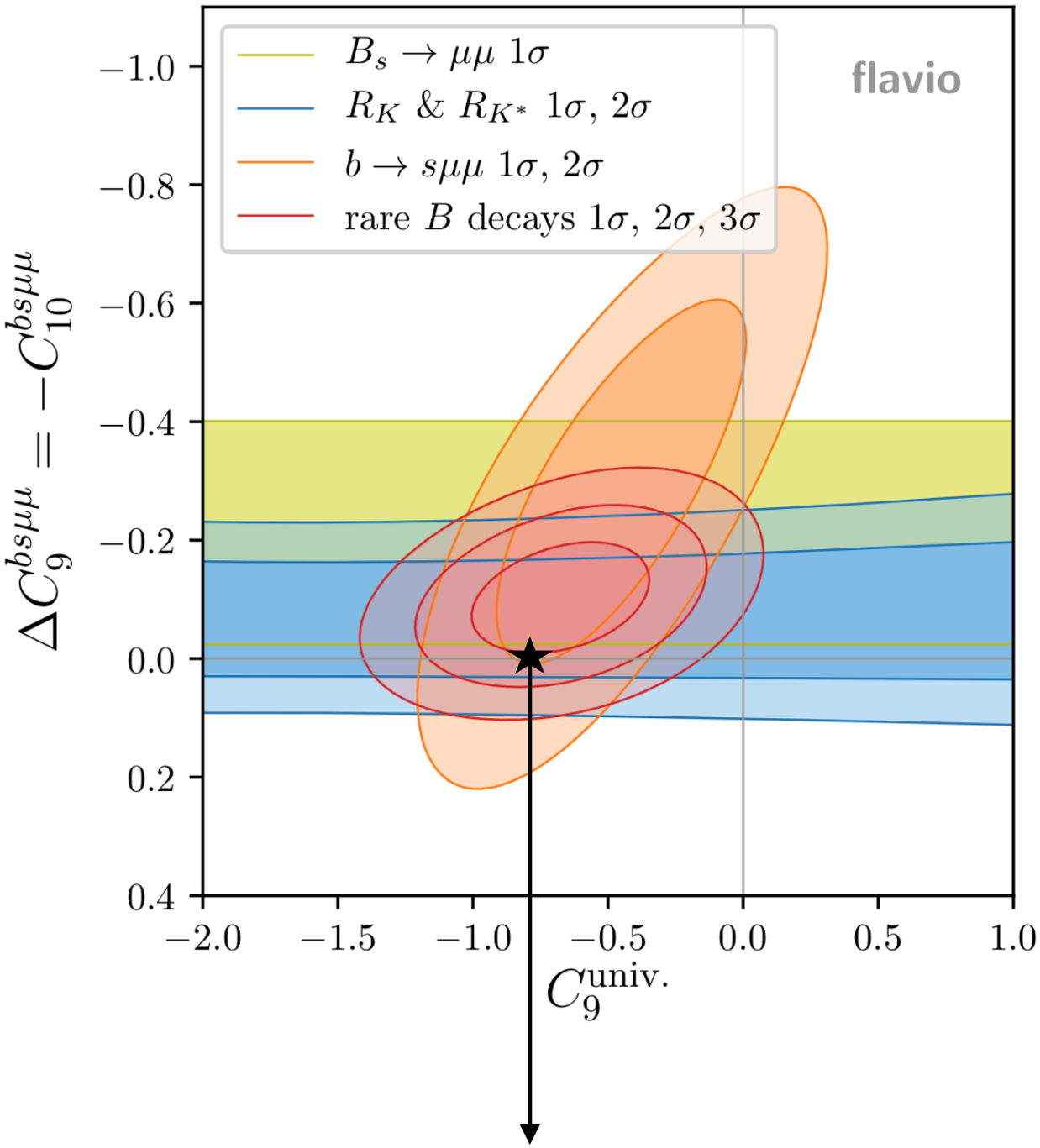
$$U(1)_e \times U(1)_\mu \times Z_2^{\rm LFU}$$

$$LQ_e \leftrightarrow LQ_\mu$$
$$e \leftrightarrow \mu$$

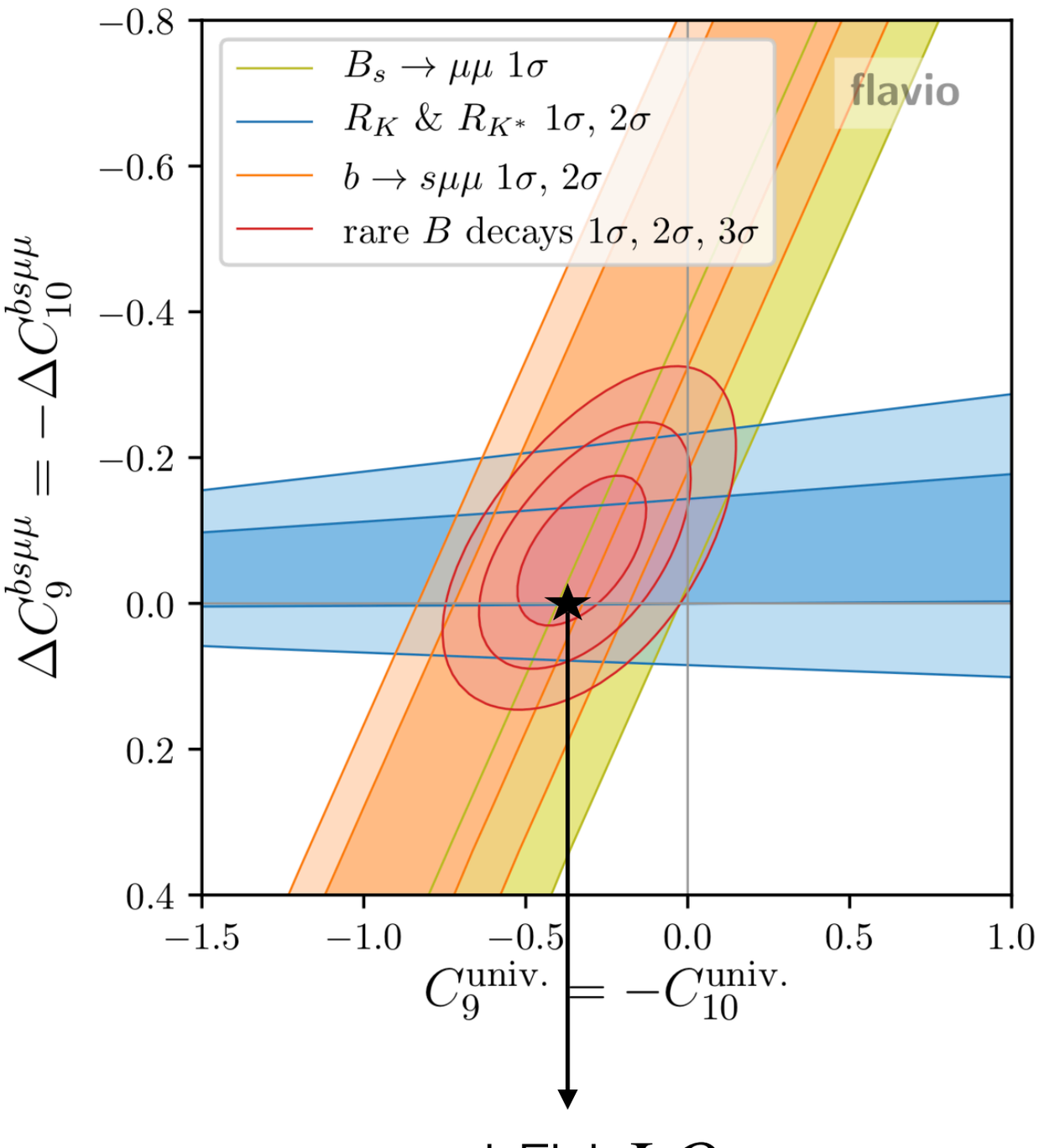
Mass/Coupling degeneracy
Gauged flavour (Part I) ?

The EFT fit

AG, Salko, Smolkovic, Stangl: 2212.10497



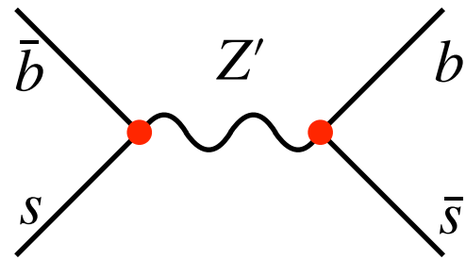
• LFU Z'



• LFU LQ

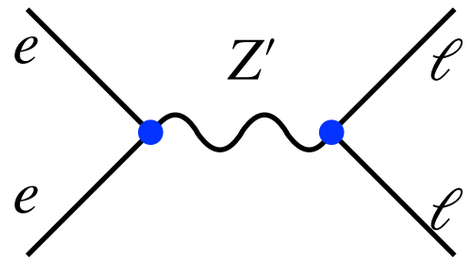
LFU models: Z'

- The bounds from



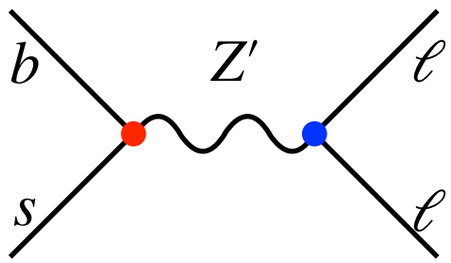
Meson mixing

+



LEP II

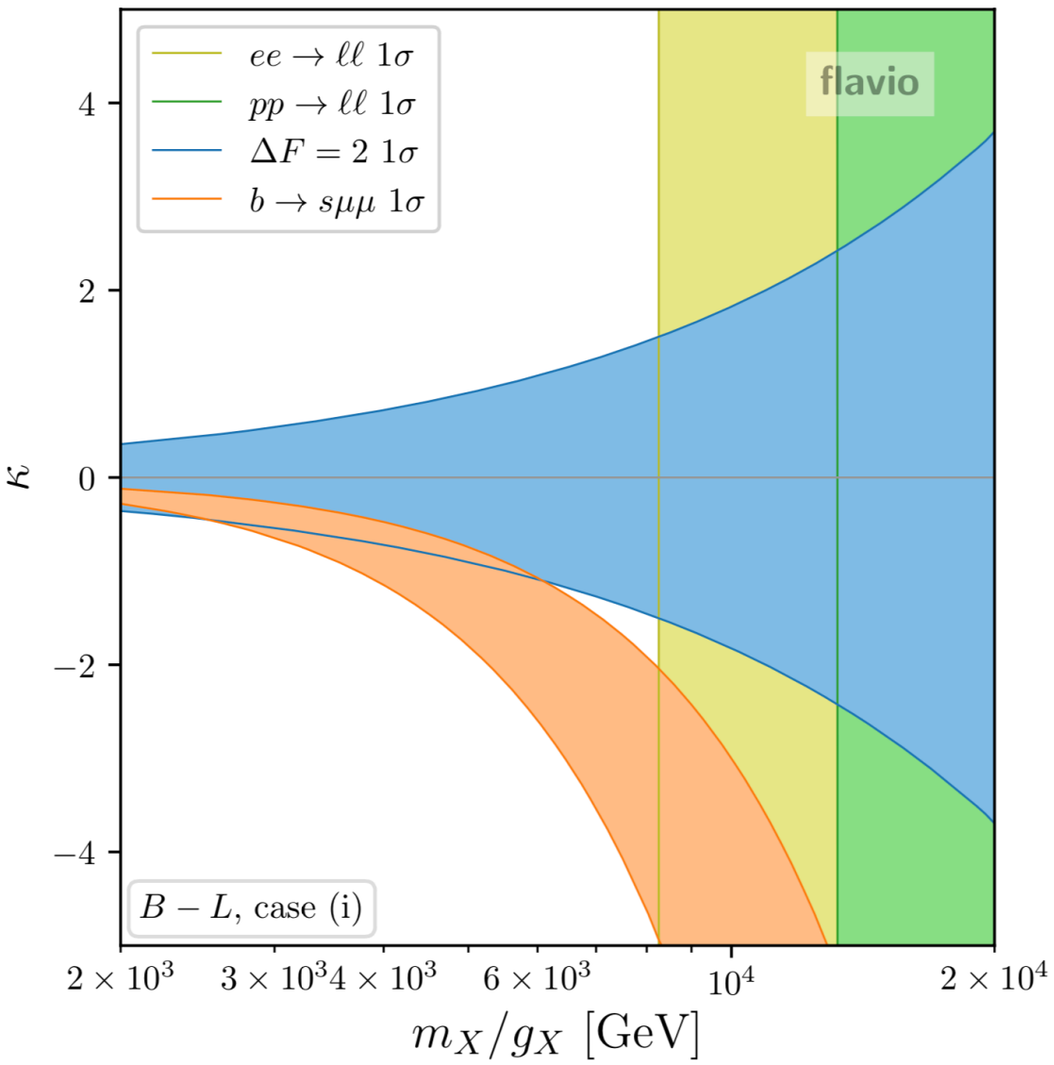
are constraining



!

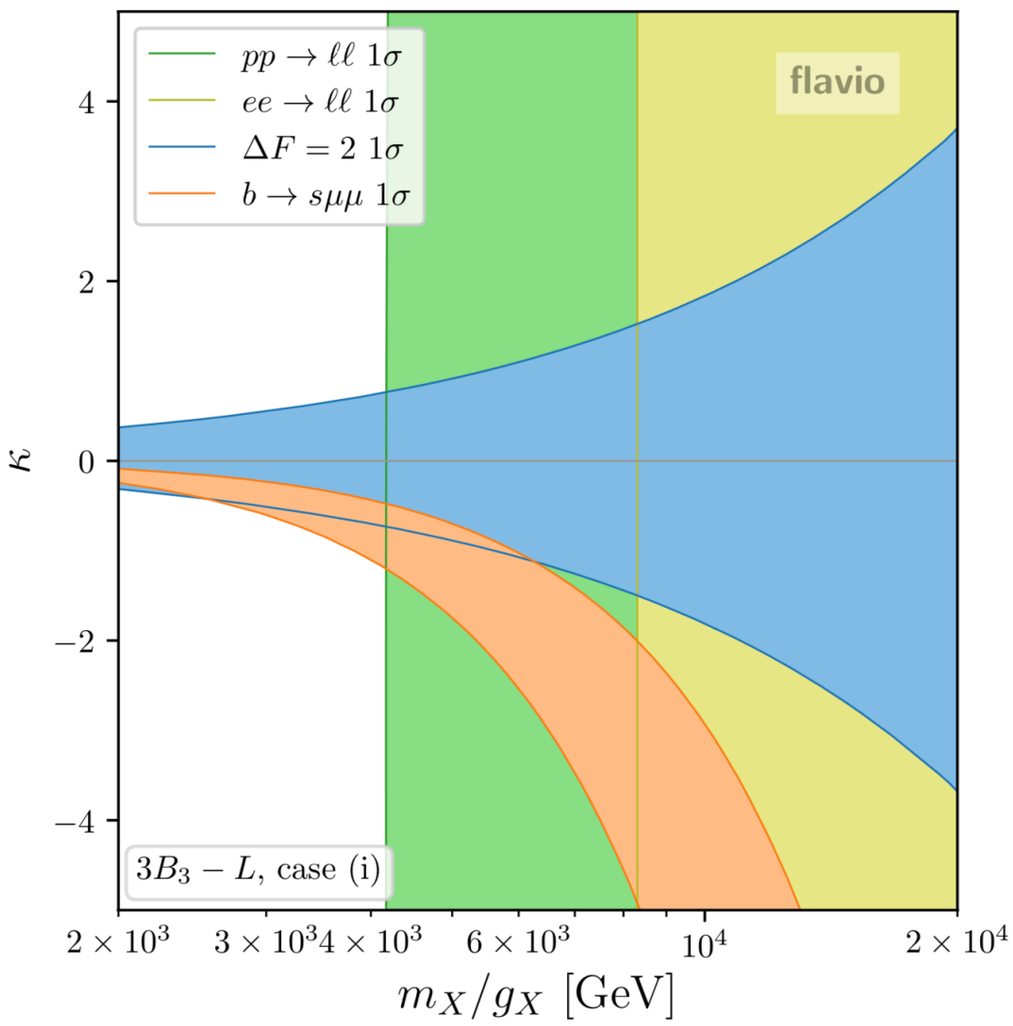
LFU models: Z'

$B - L$



$$J^\mu_X = J^\mu_{B-L} + \frac{1}{3}\epsilon_{ij}\,\bar{q}_i\gamma^\mu q_j$$

$3B_3 - L$



$$J^\mu_X = J^\mu_{3B_3-L} + \frac{1}{3}\epsilon_{ij}\,\bar{q}_i\gamma^\mu q_j$$

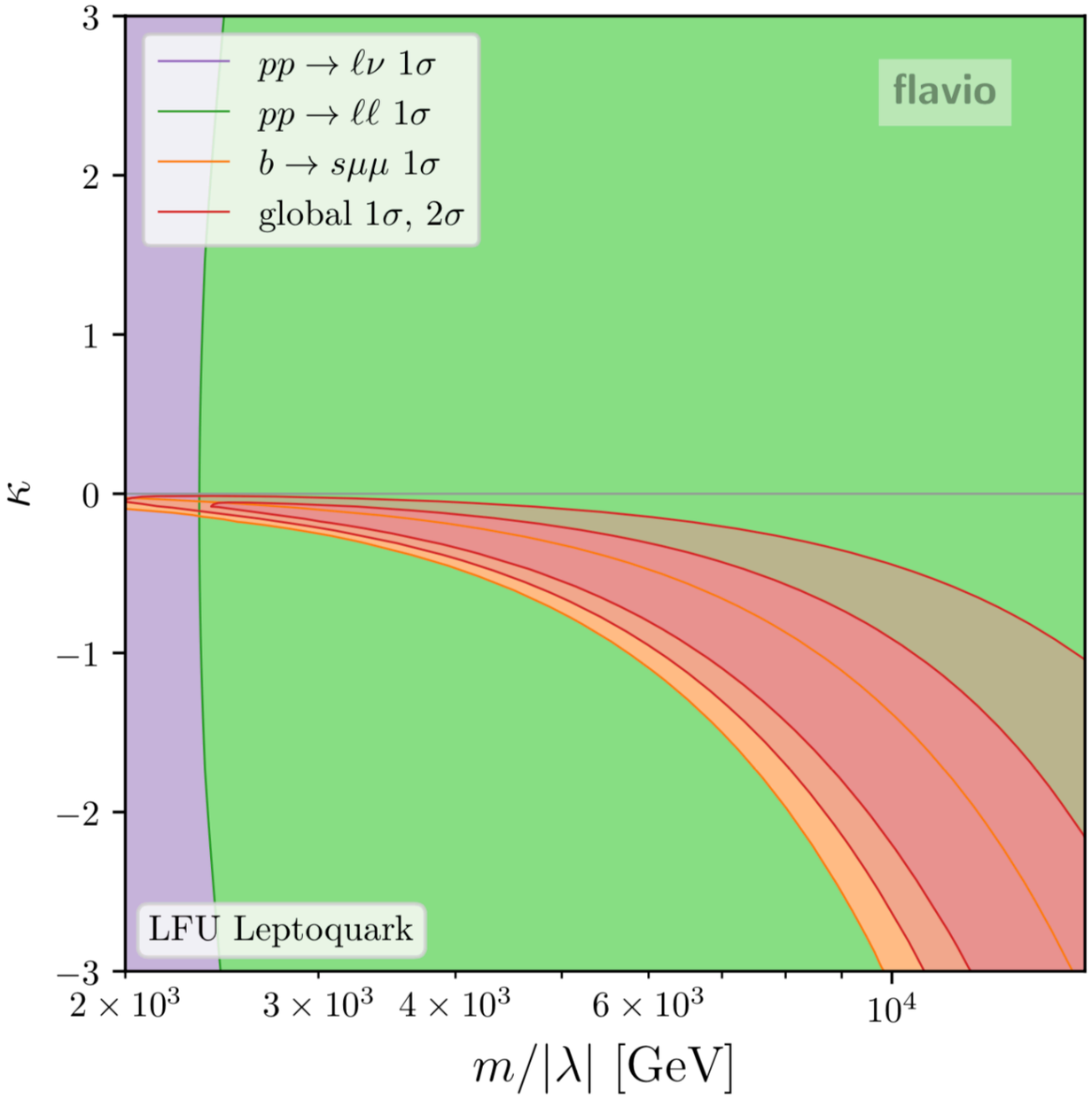
$$\epsilon_{ij} = -\kappa\,|V_{ts}|(\delta_{i2}\delta_{j3} + \delta_{i3}\delta_{j2})$$

Tension!

LFU leptoquark

$$\mathcal{L} \supset (D_\mu S^\alpha)^\dagger (D^\mu S^\alpha) - m^2 S^{\alpha\dagger} S^\alpha - (\lambda_i \, \bar{q}_i^c l_\alpha S^\alpha + \text{h.c.})$$

$$\lambda_i = \lambda \, (\kappa V_{td}, \kappa V_{ts}, 1)$$



- Tree-level $2q2\ell$,
- Loop-suppressed $4q$ and 4ℓ ✓

Conclusions

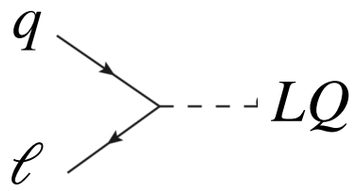
- Gauged lepton flavour $\Longrightarrow$ Selection rules for TeV-scale Leptoquarks
- A mechanism to render the proton ***exactly*** stable to all orders in EFT:

  Spontaneously broken lepton-flavoured gauged $U(1)$ in the UV to generate neutrino masses, leaving a discrete symmetry in the IR
- Complementarity between high-mass Drell-Yan tails and B decays
- Status of $b \to s\ell\ell$ anomalies after the $R_{K^{(*)}}$ update

Backup

Rich pheno example: $pp \to LQ$

- Novel production mechanism:
  using lepton PDF inside the proton

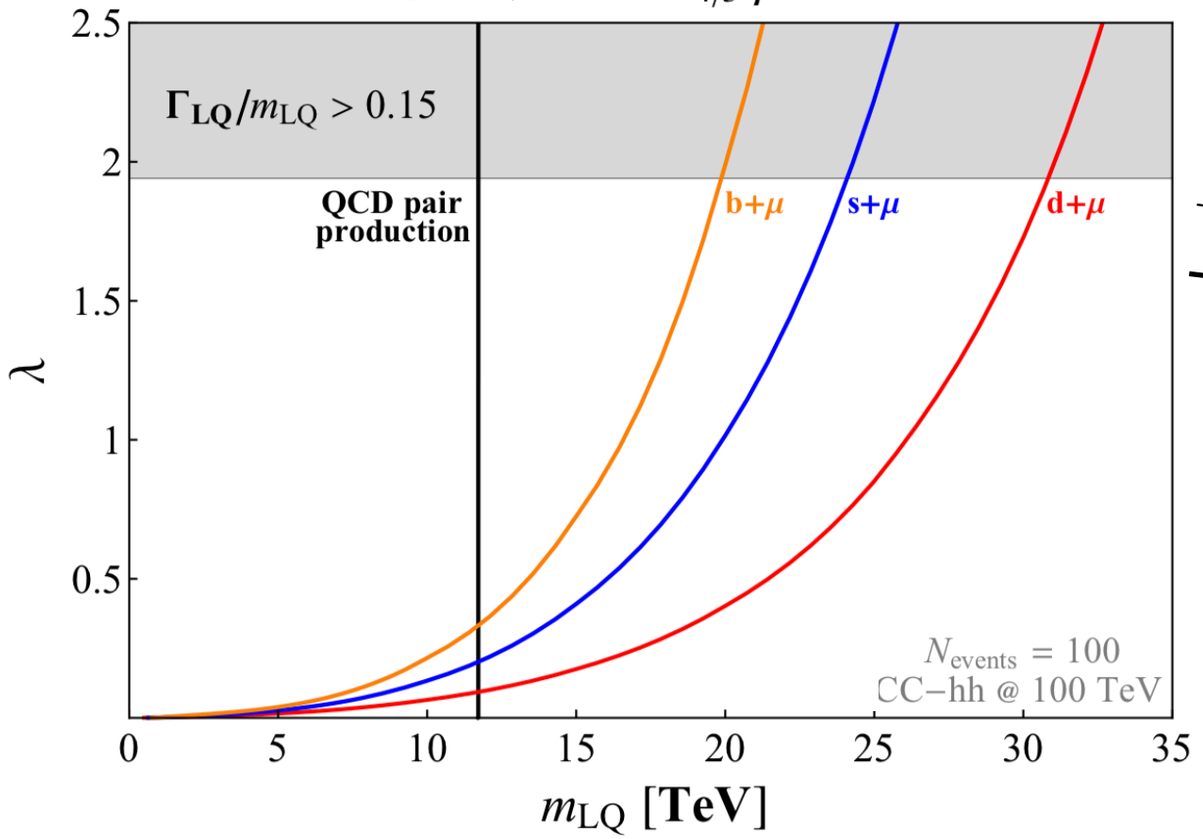


Buonocore, Haisch, Nason, Tramontano, Zanderighi; 2005.06475
AG, Selimovic; 2012.02092
Haisch, Polesello; 2012.11474

- NLO QCD + QED matched to parton shower:
  POWHEG + HERWIG implementation

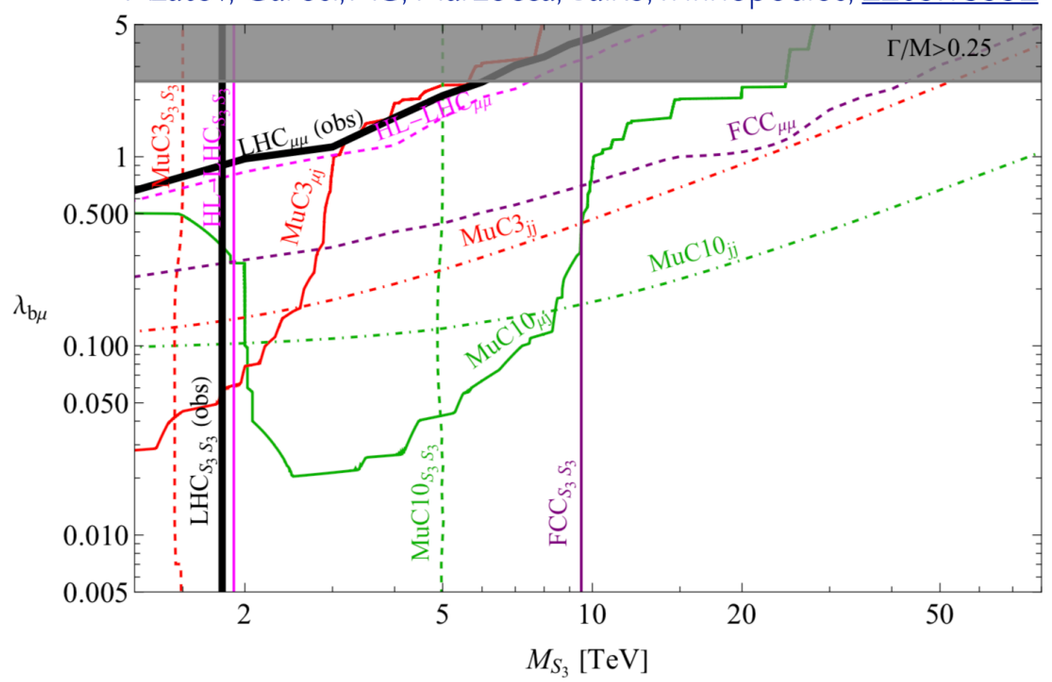
Buonocore, AG, Krack, Nason, Selimovic, Tramontano, Zanderighi; 2209.02599

$$\mathcal{L} \supset \sqrt{2}\,\lambda\,\overline{D}^{c} S_{4/3}\,\mu + \text{h.c.}$$



To be added

Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; 2205.13552



$\lambda_{ql} \sim \mathcal{O}(1)$

The $U(1)_X$ atlas

- 18 chiral fermions

$$Q_i \sim (\mathbf{3},\mathbf{2},\tfrac{1}{6},X_{Q_i}), \qquad U_i \sim (\mathbf{3},\mathbf{1},\tfrac{2}{3},X_{U_i}), \qquad D_i \sim (\mathbf{3},\mathbf{1},-\tfrac{1}{3},X_{D_i}),$$
$$L_i \sim (\mathbf{1},\mathbf{2},-\tfrac{1}{2},X_{L_i}), \qquad E_i \sim (\mathbf{1},\mathbf{1},-1,X_{E_i}), \qquad N_i \sim (\mathbf{1},\mathbf{1},0,X_{N_i}).$$

- Six anomaly cancelation conditions:

$$\mathrm{SU}(3)_C^2 \times \mathrm{U}(1)_X : \ \sum_{i=1}^{3}(2X_{Q_i} - X_{U_i} - X_{D_i}) = 0 \ ,$$
$$\mathrm{SU}(2)_L^2 \times \mathrm{U}(1)_X : \ \sum_{i=1}^{3}(3X_{Q_i} + X_{L_i}) = 0 \ ,$$
$$\mathrm{U}(1)_Y^2 \times \mathrm{U}(1)_X : \ \sum_{i=1}^{3}(X_{Q_i} + 3X_{L_i} - 8X_{U_i} - 2X_{D_i} - 6X_{E_i}) = 0 \ ,$$
$$\mathrm{Gravity}^2 \times \mathrm{U}(1)_X : \ \sum_{i=1}^{3}(6X_{Q_i} + 2X_{L_i} - 3X_{U_i} - 3X_{D_i} - X_{E_i} - X_{N_i}) = 0 \ ,$$
$$\mathrm{U}(1)_Y \times \mathrm{U}(1)_X^2 : \ \sum_{i=1}^{3}(X_{Q_i}^2 - X_{L_i}^2 - 2X_{U_i}^2 + X_{D_i}^2 + X_{E_i}^2) = 0 \ ,$$
$$\mathrm{U}(1)_X^3 : \ \sum_{i=1}^{3}(6X_{Q_i}^3 + 2X_{L_i}^3 - 3X_{U_i}^3 - 3X_{D_i}^3 - X_{E_i}^3 - X_{N_i}^3) = 0 \ .$$

- Integer charges: $-10 \leq X_{F_i} \leq 10$ Allanach, Davighi, Melville; 1812.04602

  21'546'920 inequivalent solutions (up to flavour permutation, etc)

Lepton-flavoured catalog

Quark flavour universal class

$$-10 \leq X_{F_i} \leq 10$$

- $Y_{u,d}$ are allowed => $X_{Q_i} = X_{U_j} = X_{D_k}$ [276 inequivalent solutions]

$$(X_H = 0)$$

- Muoquark requirement

  eg. S_3 LQ: $X_{L_2} \neq \{X_{L_{1,3}}, -3X_q\}$ [273 inequivalent solutions]

- Further classification:

  Y_e allowed => $\mathbf{vector\ category}: \quad X_{L_i} = X_{E_i}$ [252 inequivalent solutions]

  $\mathbf{chiral\ category}: \quad \text{the rest.}$ [21 inequivalent solutions]

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518