New physics solutions of the flavour anomalies

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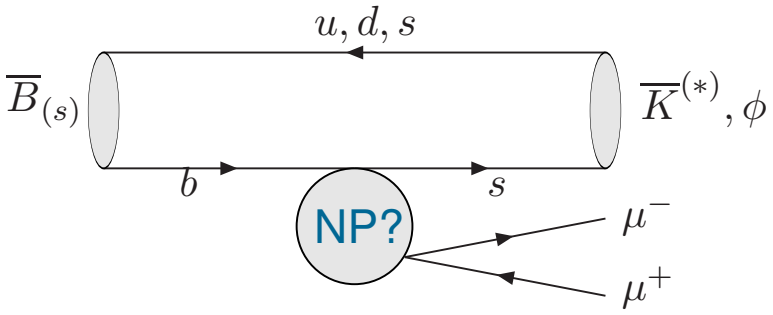
What is behind the anomalies?

none of the anomalies is significant as individual observable ...



but ...
anomalies related to the same quark-level transition $b \to s\ell^+\ell^-$

Possible explanations:

- underestimated form factor uncertainties?
- effect from non-perturbative charm loops?
- new physics (Z'-models, lepto-quarks, ...)?

explanation	$R_{K^{(*)}}$	P_5'	$B_s \to \phi\mu^+\mu^-$
form factors	X	X	✓
charm loop	X	✓	✓
new physics	✓	✓	✓

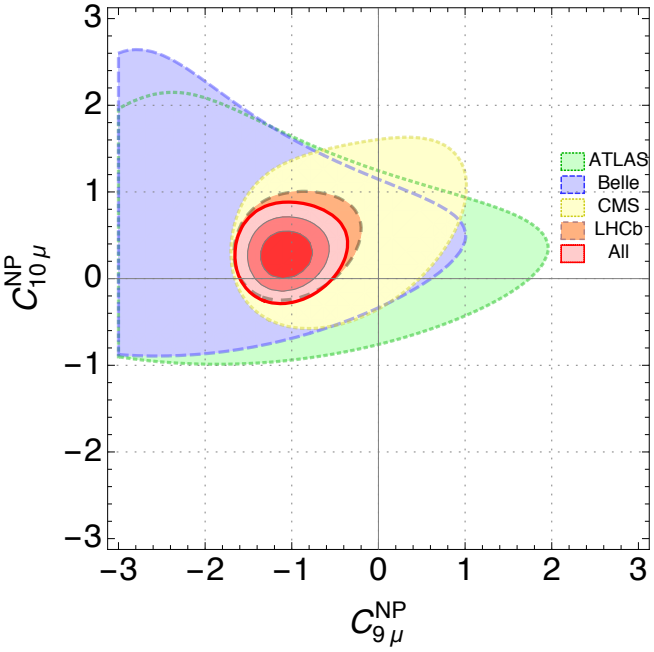
New physics in $b \to s\ell\ell$

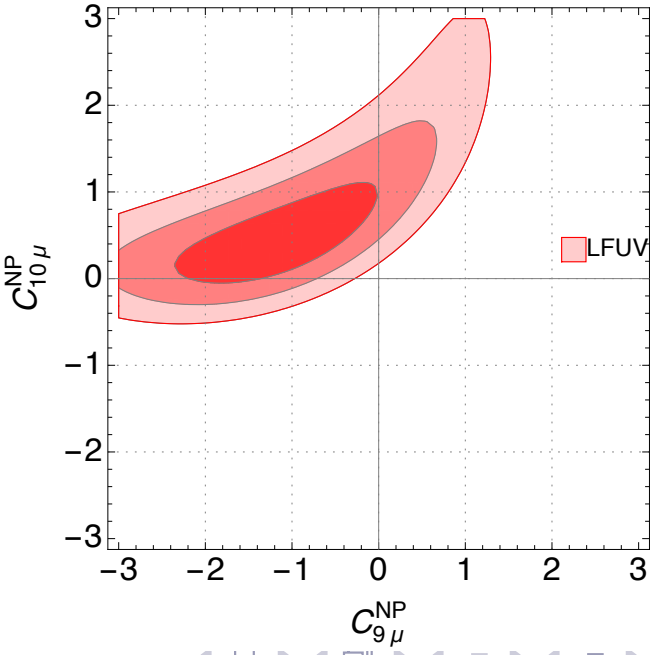
- Relevant effective operators:

$$\mathcal{O}_9^{(\prime)} = \frac{\alpha}{4\pi}[\bar{s}\gamma^\mu P_{L(R)} b][\bar{\mu}\gamma_\mu \mu], \qquad \mathcal{O}_{10}^{(\prime)} = \frac{\alpha}{4\pi}[\bar{s}\gamma^\mu P_{L(R)} b][\bar{\mu}\gamma_\mu \gamma_5 \mu]$$

- Solution of anomalies requires large negative NP-contribution $\mathcal{C}_9$

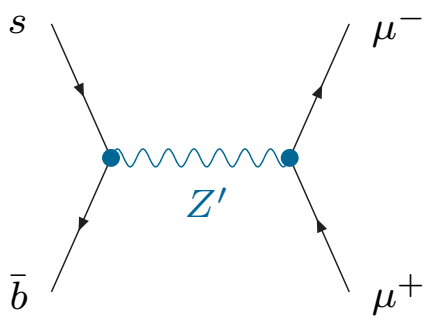
	$\langle P_5' \rangle_{[4,6]}$	$\langle P_5' \rangle_{[6,8]}$	$R_K^{[1,6]}$	$R_{K^*}^{[0.045,1.1]}$	$R_{K^*}^{[1.1,6]}$	$\mathcal{B}^{[2,5]}_{B_s \to \phi\mu\mu}$	$\mathcal{B}^{[5,8]}_{B_s \to \phi\mu\mu}$
SM	-2.9σ	-2.9σ	+2.6σ	+2.3σ	+2.6σ	+2.2σ	+2.2σ
$\mathcal{C}_{9\mu}^{\rm NP} = -1.1$	-1.0σ	-1.3σ	+0.4σ	+1.9σ	+1.2σ	+1.8σ	+1.6σ



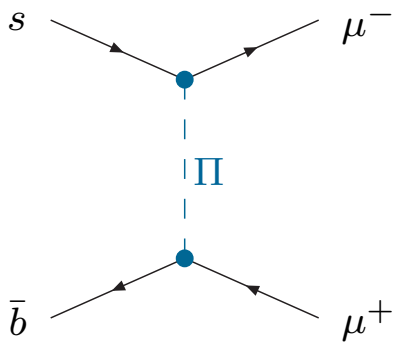


New physics generating $b \to s\mu^+\mu^-$

- tree-level new-physics contributions

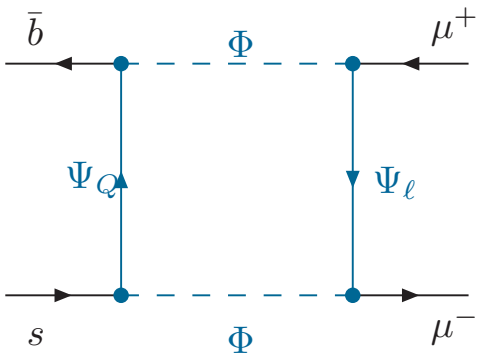


Z' models
Buras,De Fazio,Girrbach;
Altmannshofer,Gori,Pospelov,Yavin;
Crivellin,D'Ambrosio,Heeck; ...



lepto-quarks
Hiller,Schmaltz;
Bečirević,Košnik,Fajfer;
Gripaios,Nardecchia,Renner; ...

- loop-level new-physics contributions



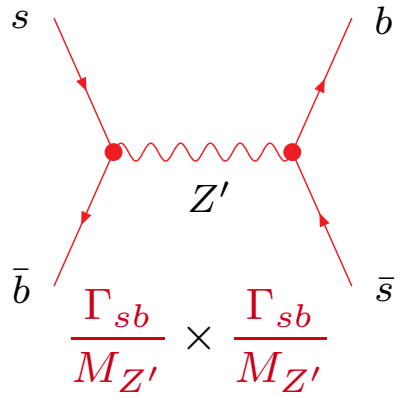
box contributions
Gripaios,Nardecchia,Renner;
Bauer,Neubert;
Arnan,Crivellin,LH,Mescia ...

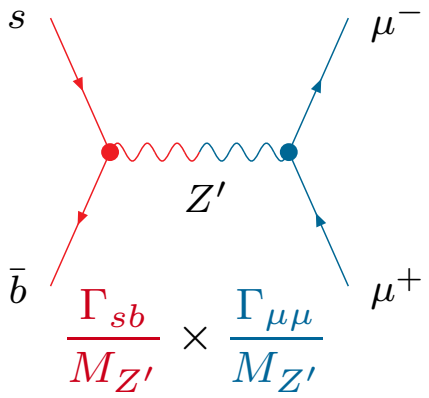
Generic Z' models

- most general framework: arbitrary couplings Γ^L_{sb}, $\Gamma^V_{\mu\mu}$
- zero (or very small) $Z'e^+e^-$ coupling

  + allows to solve R_K + avoids LEP bounds

- constraints from $B_s - \bar{B}_s$ mixing

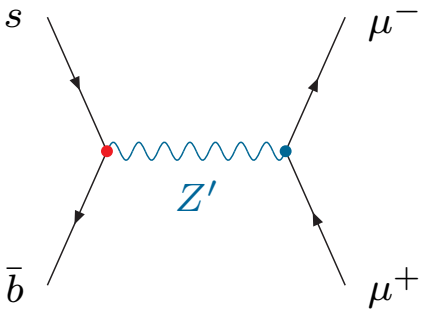


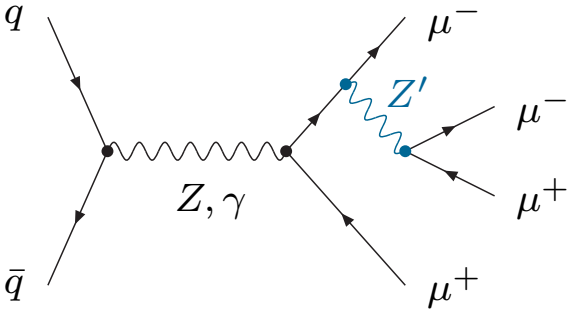


$$\frac{\Gamma_{\mu\mu}}{M_{Z'}} \gtrsim \frac{0.3}{1\text{TeV}}$$

perturbativity:
$M_{Z'} \lesssim 10\text{TeV}$

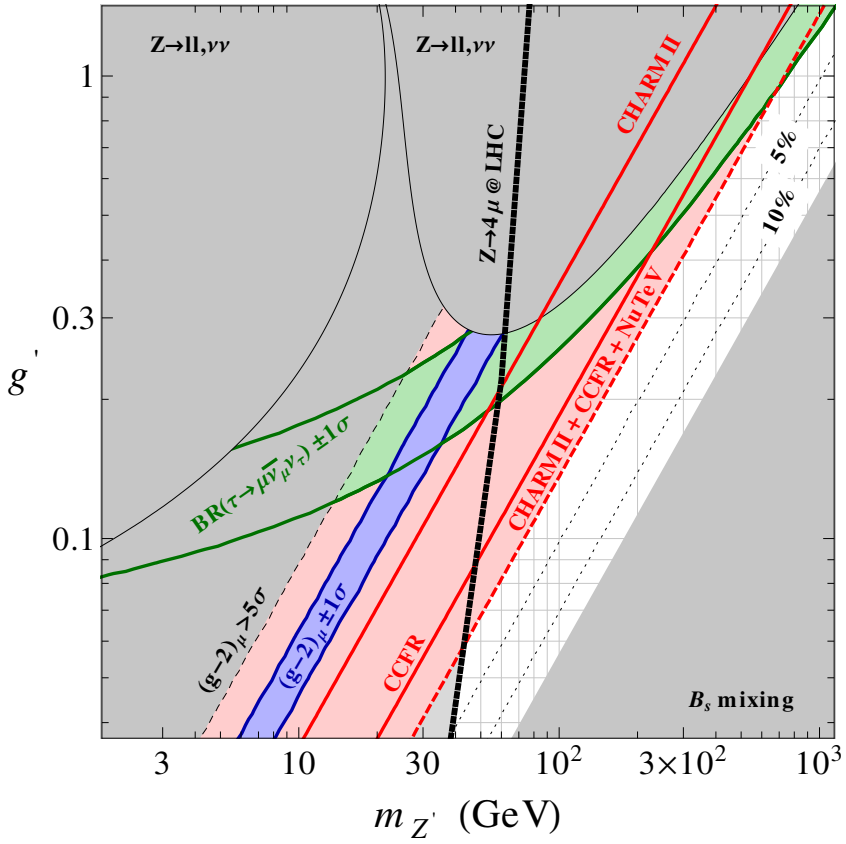
- Collider signatures:





Constraints on Z' models

Generic $Z'\mu^+\mu^-$ coupling:



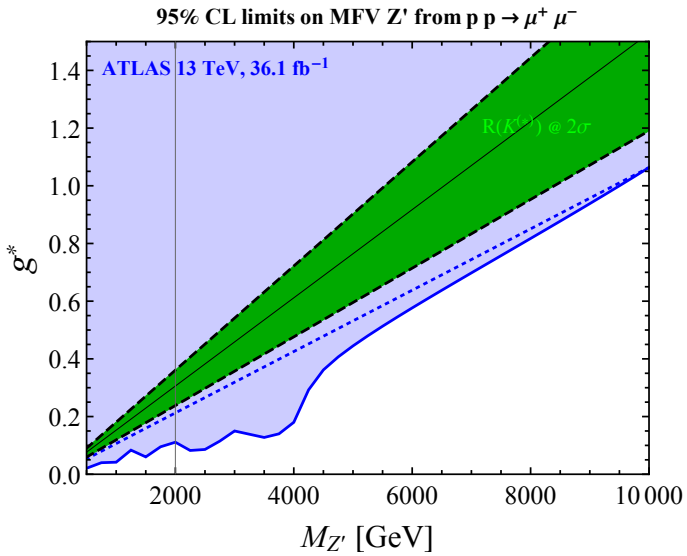
[Altmannshofer,Gori,Pospelov,Yavin'14]

MVF-like $Z'ff$ couplings:

$$\Gamma^L_{\mu\mu} = g_*,\ \Gamma^L_{bs} = V_{ts} g_*$$
$$\Gamma^L_{uu} = \Gamma^L_{dd} = g_*$$

$u\bar{u} \to \mu^+\mu^-,\ u\bar{u} \to \mu^+\mu^-$:

avoid pdf-suppression + CKM-enhancement



[Greljo,Marzocca'17]

Typical $U(1)'$ gauge models

Lepton sector:
$U(1)'$ charges $Q_L = (0, 1, -1)$ $\rightarrow$ gauged $L_\tau - L_\mu$

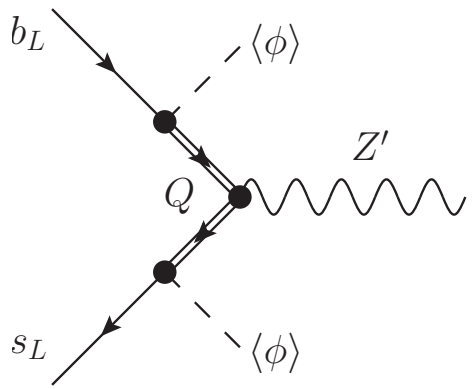
- anomaly free
- good symmetry for PMNS matrix
- no coupling to electrons:
  allows to solve R_K $+$ avoids LEP bounds

Quark sector:
$U(1)'$ charges: $Q_q = (0, 0, 0)$

[Altmannshofer,Gori,Pospelov,Yavin'14]

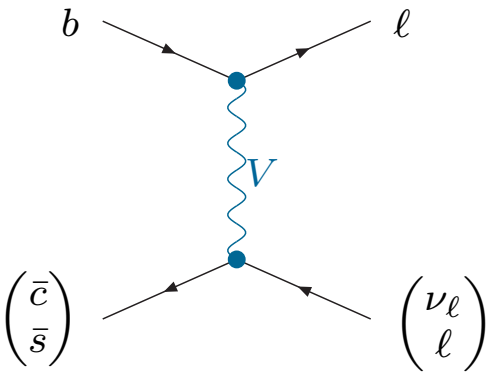
introduce heavy vector-like quark Q and scalar ϕ with charges $Q_Q = Q_\phi$

$\rightarrow$ effective bsZ' coupling



Vector lepto-quarks

- a vector lepto-quark can contribute to both $R_{K^{(*)}}$ and $R_{D^{(*)}}$:



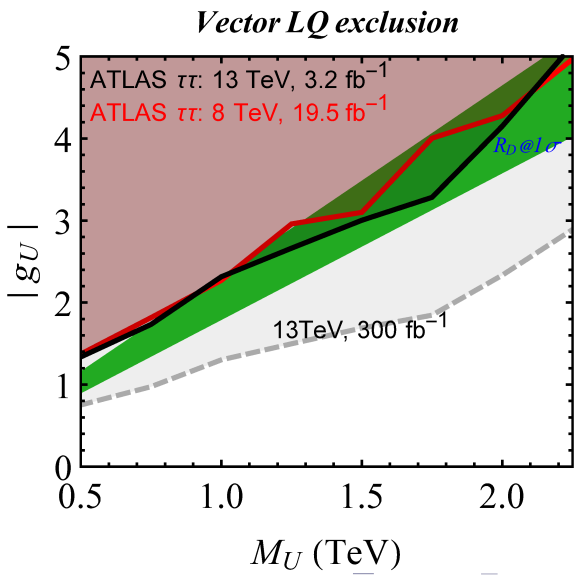
$R_{K^{(*)}}$: NP tree vs. SM loop
$\rightarrow$ can be solved easily

$R_{D^{(*)}}$: NP tree vs. SM tree
$\rightarrow$ solution difficult

- $SU(2)_L$ triplet: $b \rightarrow c\tau\nu$ correlated with $b \rightarrow s\nu\bar{\nu}$
$\rightarrow$ solution of R_{D^*} violates constraint from $B \rightarrow K^{(*)}\nu\bar{\nu}$

- important bounds from
$b\bar{b} \rightarrow \tau^+\tau^-$
[Faroughy,Greljo,Kamenik'16]

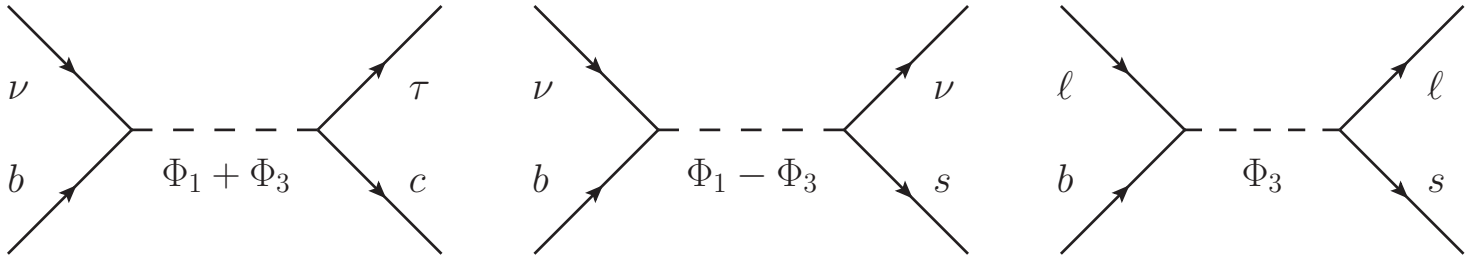
$SU(2)_L$ singlet
$g_{b\tau} = g_U, \quad g_{c\nu_\tau} \sim V_{cb} g_U$



Scalar lepto-quarks

- simultaneous solution of $R_{K^{(*)}}$ and $R_{D^{(*)}}$ requires two scalar lepto-quarks: [Crivellin,Müller,Ota'17]

  Φ_3: $SU(2)_L$ triplet, Φ_1: $SU(2)_L$ singlet



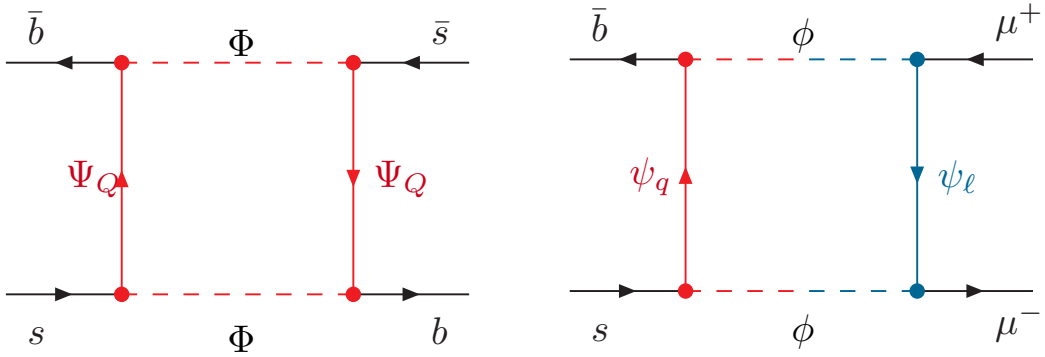
$\rightarrow SU(2)$ singlet Φ_1 needed to cancel contribution to $b \rightarrow s\nu\bar{\nu}$

Further features of lepto-quark models:

- small couplings to electors needed to avoid $\mu \rightarrow e\gamma$ etc.
- m_t-enhancement can allow for solution of $(g-2)_\mu$ anomaly

Box contributions

- tight constraints from box-contributions



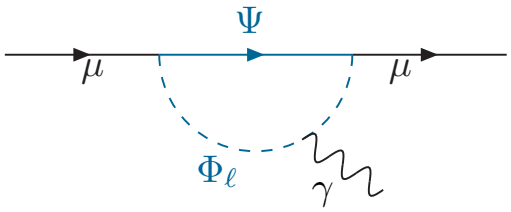
$$\frac{\Gamma_s^* \Gamma_b}{M_{Z'}} \sqrt{\epsilon} \times \frac{\Gamma_s^* \Gamma_b}{M_{Z'}} \sqrt{\epsilon} \qquad \frac{\Gamma_s^* \Gamma_b}{M_\phi} \sqrt{\epsilon} \times \frac{|\Gamma_\mu|^2}{M_\phi} \sqrt{\epsilon}$$

$$\boxed{\frac{\Gamma_\mu}{\sqrt{M_{Z'}}} \gtrsim \frac{3}{\sqrt{1\text{TeV}}}}$$

constraint can be alleviated in the case of Majorana fermions

[Arnan,Crivellin,LH,Mescia'16]

- simultaneous explanation of muon anomalous magnetic moment possible



- Collider signatures:
  similar to sbottom and neutralino searches