Loop effects of heavy new scalars and fermions in $b \to s\mu^+\mu^-$

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$b \to s\mu^+\mu^-$ anomalies I

$\bar{B}_d \to \bar{K}^{*0}\mu^+\mu^-$

angular observable P_5'

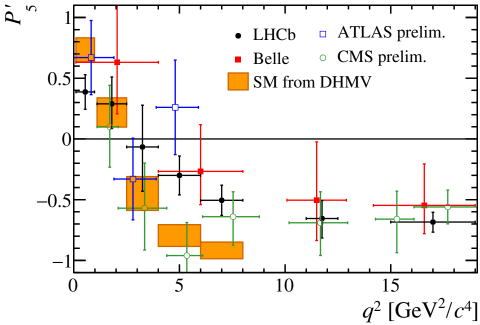
LHCb: $2.8\,\sigma$ in $[4,6]$

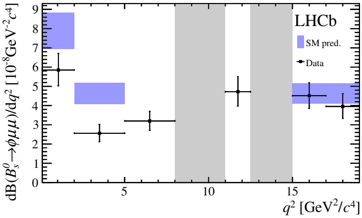
$3.0\,\sigma$ in $[6,8]$

Belle: $2.6\,\sigma$ in $[4,8]$

Atlas: $2.4\,\sigma$ in $[4,6]$

CMS: consistent with SM





$\bar{B}_s \to \phi\mu^+\mu^-$

branching ratio

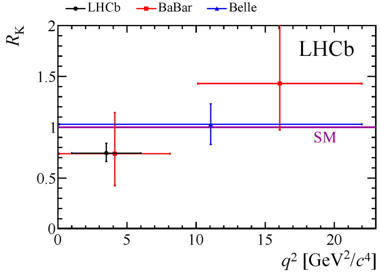
LHCb: $2.2\,\sigma$ in $[2,5]$

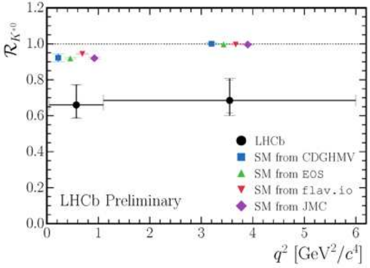
$2.2\,\sigma$ in $[5,8]$

$b \to s\mu^+\mu^-$ anomalies II: LFUV

$$R_{K^{(*)}} = \frac{\mathrm{Br}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{Br}(B \to K^{(*)}e^+e^-)}$$

- clean SM prediction $R_{K^{(*)}} = 1$
- measure lepton-flavour universality violation





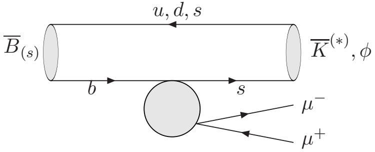
LHCb: 2.6σ in $[1.0, 6.0]$

LHCb: 2.3σ in $[0.045, 1.1]$
2.6σ in $[1.1, 6.0]$

Belle: $P_5'^{\ell}$ $(\ell = \mu, e)$
muons: $2.6\,\sigma$ electrons: $1.1\,\sigma$ $\to$ LFUV?

What is behind the anomalies?

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



but ...

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

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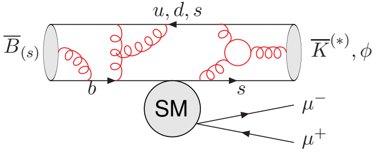

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- underestimated form factor uncertainties?

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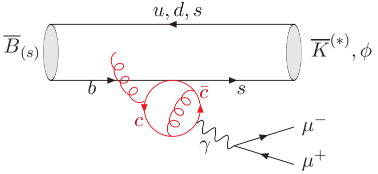

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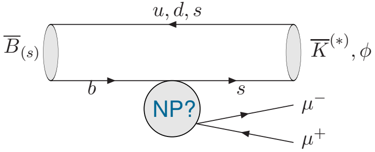

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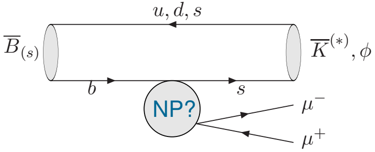

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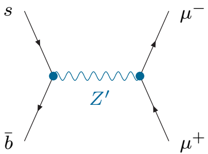
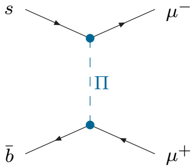
explanation	$R_{K^{(*)}}$	P_5'	$B_s \to \phi\mu^+\mu^-$
form factors	X	X	✓
charm loop	X	✓	✓
new physics	✓	✓	✓

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

- tree-level new-physics contributions

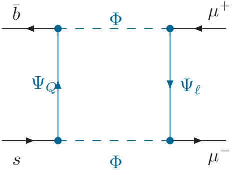


Z' models
Buras,De Fazio,Girrbach;
Altmannshofer,Gori,Pospelov,Yavin;
Crivellin,D'Ambrosio,Heeck; ...



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

- loop-level new-physics contributions

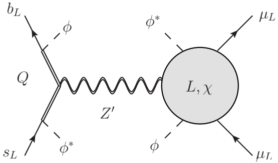


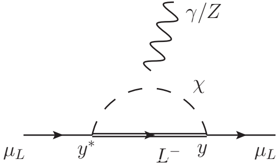
box contributions
Gripaios,Nardecchia,Renner;
Bauer,Neubert;
Arnan,Crivellin,LH,Mescia ...

$b \to s\mu^+\mu^-$ and $(g-2)_\mu$

Simultaneous solution requires loop-contribution to $b \to s\mu^+\mu^-$

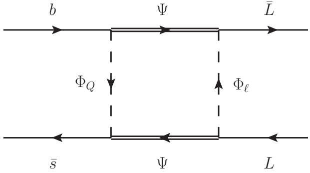
- Z' penguin contribution: [Bélanger,Delaunay,Westhoff'15]

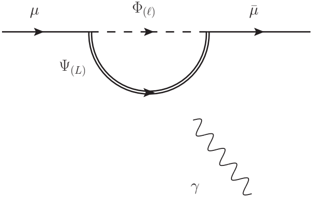




- Box contribution: this talk

[Gripaios,Nardecchia,Renner'15; Arnan,Crivellin,LH,Mescia'16]

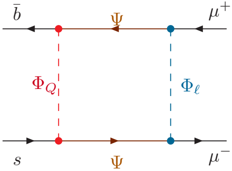




Minimal scenario

- Three new particles:
  - one vector-like fermion Ψ
  - two scalars Φ_Q, Φ_ℓ

  (or vice versa)



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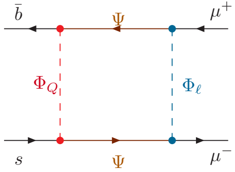

- scenario with left-handed couplings Γ_b^L, Γ_s^L, Γ_μ^L allows for good description of $b \to s\ell^+\ell^-$ data:

	μ_L	μ_R
q_L	$\boldsymbol{\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{10}^{\rm NP}\ (4.6\sigma)}$	$\mathcal{C}_9^{\rm NP} = \mathcal{C}_{10}^{\rm NP}\ (1.0\sigma)$
q_R	$\mathcal{C}_{9'}^{\rm NP} = -\mathcal{C}_{10'}^{\rm NP}\ (0.6\sigma)$	$\mathcal{C}_{9'}^{\rm NP} = \mathcal{C}_{10'}^{\rm NP}\ (0.1\sigma)$

in our analysis: $\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{10}^{\rm NP} \in [-0.97, -0.37]$ (2σ)
new global-fit result (incl. R_{K^*}): $[-0.87, -0.36]$ (2σ)

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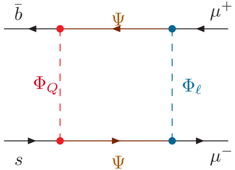

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- Consider $SU(2)$, $SU(3)$ representations present in SM:

$SU(2)$	Φ_Q	Φ_ℓ	Ψ
I	2	2	1
II	1	1	2
III	3	3	2
IV	2	2	3
V	3	1	2
VI	1	3	2

$SU(3)$	Φ_Q	Φ_ℓ	Ψ
A	3	1	1
B	1	$\bar{3}$	3
C	3	8	8
D	8	$\bar{3}$	3

Characteristics of minimal scenario

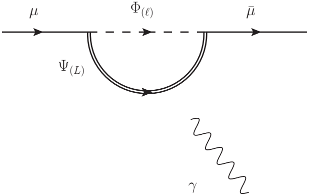
- no additional sources of $SU(2)_{\mathrm{L}}$-breaking:
  - Z-penguin contribution to $b \to s\ell^+\ell^-$ irrelevant (m_b^2/m_Z^2 suppression compared to box contributions)
  - corrections to $Z \to \mu^+\mu^-$ proportional to m_Z^2/m_{NP}^2: 1-2 orders of magn. below the sensitivity of LEP for $m_{\mathrm{NP}} \gtrsim 1$ TeV
  - constraints from $b \to s\gamma$ less important than $B_s - \bar{B}_s$ mixing
- Collider signatures:
  similar to sbottom and neutralino searches
  $\to$ masses $\gtrsim 1$ TeV still viable with current Atlas/CMS data
- Contributions to flavour physics

$B_s - \bar{B}_s$ mixing	$b \to s\mu^+\mu^-$	$(g-2)_\mu$
box: $(\Gamma_b^*\Gamma_s)^2$	box: $(\Gamma_b^*\Gamma_s)\lvert\Gamma_\mu\rvert^2$	penguin: $\lvert\Gamma_\mu\rvert^2$
	penguin: $(\Gamma_b^*\Gamma_s)e^2$	

$(g-2)_\mu$

- 2.7σ tension between experiment and SM:
$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (236 \pm 87) \times 10^{-11}$$

- NP contribution ($m_{\Psi_{(\ell)}} \approx m_{\Phi_{(\ell)}}$)



$$\Delta a_\mu = (5.8\times 10^{-12})\, \xi_{a_\mu}\, |\Gamma_\mu|^2 \left(\frac{1\,\text{TeV}}{m_\Psi}\right)^2$$

ξ_{a_μ}: gauge group factor

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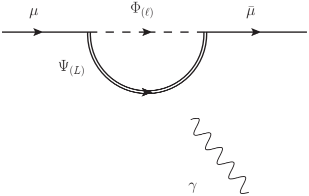


$$\Delta a_\mu = (5.8\times 10^{-12})\, \xi_{a_\mu}\, |\Gamma_\mu|^2 \left(\frac{1\,\text{TeV}}{m_\Psi}\right)^2$$

ξ_{a_μ}: gauge group factor

- maximum enhancement: $\xi_{a_\mu}^{\rm max} = 24$

  for $\Psi = (8,2)$, $\Phi_\ell = (8,1)$, hypercharges $|X| \leq 1$

  $\Rightarrow |\Gamma_\mu| \geq 2.1\, \frac{m_\Psi}{\text{TeV}} \quad (2\sigma)$

- reduction of tension in $(g-2)_\mu$ below 2σ requires $|\Gamma_\mu| \geq 2$
  $\rightarrow$ large but still viable (Landau-pole at $\gtrsim 10^3$ TeV for $|\Gamma_\mu| \leq 2.4$)

$\mu \to e\gamma$

- non-vanishing Γ_e would generate $\mu \to e\gamma$
  $\to$ correlated with $(g-2)_\mu$

$$\mathrm{Br}\left(\mu \to e\gamma\right) = \alpha_{\mathrm{QED}} m_\mu \tau_\mu \left|\frac{\Gamma_e}{\Gamma_\mu}\right|^2 \Delta a_\mu$$

- experimental constraints at 2σ:

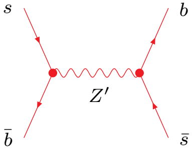
$$\Delta a_\mu^{\mathrm{exp}} = 61 \times 10^{-11}, \qquad \mathrm{Br}^{\mathrm{exp}}\left(\mu \to e\gamma\right) \leq 4.2 \times 10^{-13}$$

$$\Rightarrow \quad |\Gamma_e/\Gamma_\mu| < 2 \times 10^{-5}$$

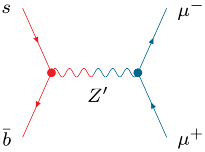
- bound on $|\Gamma_e|$ consistent with $\Gamma_e \sim 0$
  $\to$ coherent with $R_K^{(*)}$

Constraints from $B_s - \overline{B}_s$ mixing

- moderate constraints on Z' models



$$\frac{\Gamma_{sb}}{M_{Z'}} \times \frac{\Gamma_{sb}}{M_{Z'}}$$



$$\frac{\Gamma_{sb}}{M_{Z'}} \times \frac{\Gamma_{\mu\mu}}{M_{Z'}}$$

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

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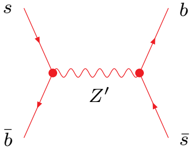

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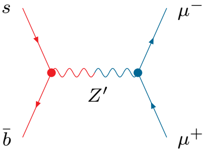

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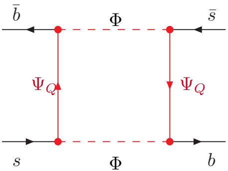
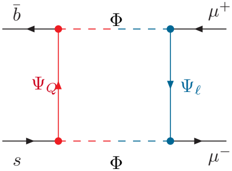
- tight constraints on models with box-contributions



$$\frac{\Gamma_s^*\Gamma_b}{M_\Psi}\sqrt{\epsilon} \times \frac{\Gamma_s^*\Gamma_b}{M_\Psi}\sqrt{\epsilon}$$



$$\frac{\Gamma_s^*\Gamma_b}{M_\Psi}\sqrt{\epsilon} \times \frac{|\Gamma_\mu|^2}{M_\Psi}\sqrt{\epsilon}$$

$$\frac{|\Gamma_\mu|^2}{M_\Psi} \gtrsim \frac{3}{1\text{TeV}}$$

Constraints from $B_s - \overline{B}_s$ mixing

- with Fermilab,MILC'16 lattice results:

$$R_{\Delta B_s} = \frac{\Delta M_{B_s}^{\mathrm{exp}}}{\Delta M_{B_s}^{\mathrm{SM}}} - 1 = -0.09 \pm 0.08$$

$\rightarrow$ experiment slightly below SM prediction

- NP contribution positive for real couplings Γ_b, Γ_s
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- consequence for $b \to s\mu^+\mu^-$:

$$|C_9^{\rm box}| = |C_{10}^{\rm box}| = \tfrac{1}{3}\, \xi_9^{\rm box}\, |\Gamma_s^* \Gamma_b|\, |\Gamma_\mu|^2 \times (1\,{\rm TeV}/m_\Psi)$$
$$\leq 0.05\, \frac{\xi_9^{\rm box}}{\sqrt{\xi_{B\bar{B}}}}\, |\Gamma_\mu|^2 \times (1\,{\rm TeV}/m_\Psi)$$

- size of Γ_μ needed to solve $b \to s\ell^+\ell^-$ anomalies:

less dependent on reps. of new particles: $\left(\frac{\xi_9^{\rm box}}{\sqrt{\xi_{B\bar{B}}}}\right)_{\rm max} \approx 1.7$

$\rightarrow |\Gamma_\mu| \geq 2.1 \frac{m_\Psi}{\rm TeV} \quad (2\sigma)$

$D - \overline{D}$ mixing

- $SU(2)_L$ symmetry: $\Gamma^L_{d,s,b}$ linked to $\Gamma^L_{u,c,t}$ by CKM rotation

$$\begin{aligned} \Gamma_u &= V_{us}\Gamma_s + V_{ub}\Gamma_b \approx V_{us}\Gamma_s \\ \Gamma_c &= V_{cs}\Gamma_s + V_{cb}\Gamma_b \approx \Gamma_s \end{aligned}$$

  $\rightarrow$ contribution to $D - \bar{D}$ mixing generated

- $B_s - \bar{B}_s$ mixing: $\propto |\Gamma_b|^2 \, |\Gamma_s|^2$

  $D - \bar{D}$ mixing: $\propto |V_{us}|^2 \, |\Gamma_s|^4$

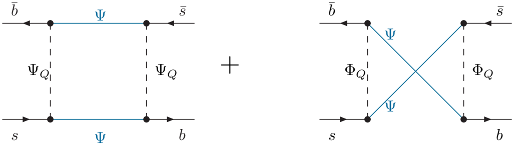
- fulfill $B_s - \bar{B}_s$ mixing constraint with

$$|\Gamma_b| = \mathcal{O}(1), \qquad |\Gamma_s| \ll |\Gamma_b|$$

  $\rightarrow$ $D - \bar{D}$ mixing constraint also fulfilled

Relaxing the $B_s - \overline{B}_s$ bound for box diagrams

consider Majorana fermions in box:



$$= H\left(\frac{m_{\Phi_Q}}{m_\Psi}\right)$$

quantum numbers new particles

$SU(2)$	Φ_Q	Φ_ℓ	Ψ
I	2	2	1
IV	2	2	3

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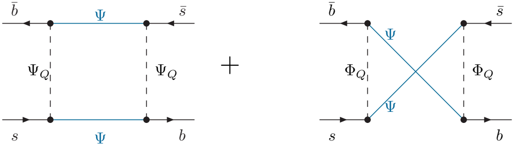

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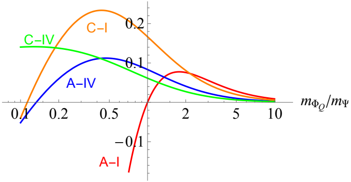
destructive interference:



A-I: Majorana singlets
cancellation for $m_{\Phi_Q} \approx m_\Psi \equiv m$
$\rightarrow$ avoids $B_s - \overline{B}_s$ mixing bound

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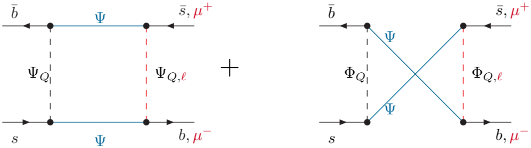

$$= H\left(\frac{m_{\Phi_Q}}{m_\Psi}, \frac{m_{\Phi_\ell}}{m_\Psi}\right)$$

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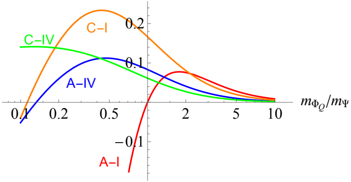

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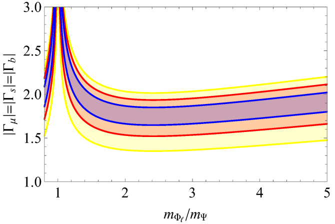
$b \to s\mu^+\mu^-$: avoid cancellation
$\rightarrow$ assume $m_{\Phi_\ell} \gtrsim 1.5m$



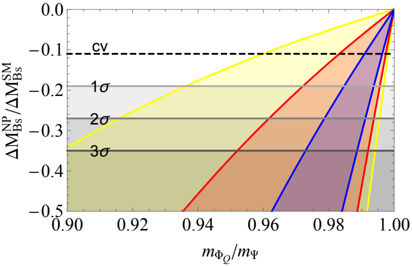
Majorana case

$$\Psi = (1,1), \;\; \Phi_Q = (3,2), \;\; \Phi_\ell = (1,2); \;\; m_\Psi \sim m_{\Phi_Q}, \;\; m_{\Phi_\ell} \sim 2 m_\Psi$$

- absence of bound from $B_s - \bar{B}_s$ mixing for $m_\Psi = m_{\Phi_Q}$ allows solution of $b \to s\ell^+\ell^-$ anomalies at 2σ-level for

$$|\Gamma_b| = |\Gamma_s| = |\Gamma_\mu| \gtrsim 1.6$$

- For $m_{\Phi_Q} \lesssim m_\Psi$ a negative contribution to $B_s - \bar{B}_s$ mixing is generated, as preferred by current lattice data



$1\sigma-$, $2\sigma-$, $3\sigma-$ranges from $b \to s\ell^+\ell^-$

$m_{\Phi_\ell} = 2m_\Psi = 2$ TeV, $\quad \Gamma_\mu = 2$

Conclusions

- we have studied box cotributions to $b \to s\mu^+\mu^-$ from one aditional fermion and two additional scalars (one additional scalar and two additional fermions) for various representations
- left-handed couplings to the SM fermions lead to the scenario $C_9 = -C_{10}$, capable of solving the $b \to s\mu^+\mu^-$ anomalies
- both the $b \to s\mu^+\mu^-$ anomalies and $(g-2)_\mu$ can be solved simultaneously for a rather large coupling to muons: $|\Gamma_\mu| \gtrsim 2$ for new particle masses at the TeV scale
- for $b \to s\mu^+\mu^-$ the requirement of large Γ_μ results from the tight $B_s - \bar{B}_s$ mixing bounds, which can be relaxed in scenarios with Majorana fermions