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

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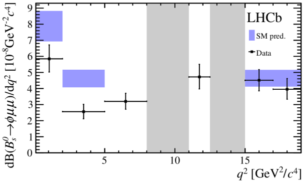
$b \to s$ anomalies

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

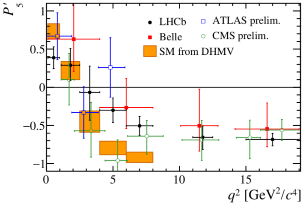


2.2σ away from SM

Form Factor uncertainties

Charm loops

- $B \to K^*\mu^+\mu^-$



2.4-3σ away from SM

Charm loops

$b \to s$ anomalies

- R_K and R_{K^*}

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

LHCb data

$$R_{K,[1,6]} = 0.745 \pm 0.090$$

$$R_{K^*,[0.045,1.1]} = 0.66^{+0.11}_{-0.07}$$

$$R_{K^*,[1.1,6]} = 0.69^{+0.12}_{-0.08}$$

2.2-2.6σ away from SM

clean SM prediction

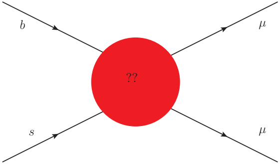
Operator Product Expansion

- Effective Hamiltonian and Wilson Coefficients

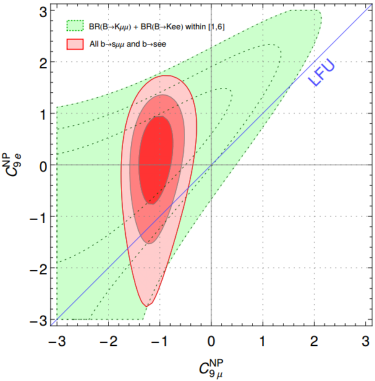
$$\mathcal{H}^{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts} \left(C_9 \mathcal{O}_9 + C_{10} \mathcal{O}_{10} + C_P \mathcal{O}_P + C_S \mathcal{O}_S \ldots \right)$$

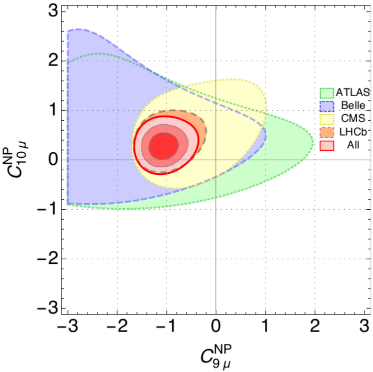
$$\mathcal{O}_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma_\mu \ell) \qquad \mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma_\mu \gamma_5 \ell)$$

- $\ell = \mu$



Data Fit



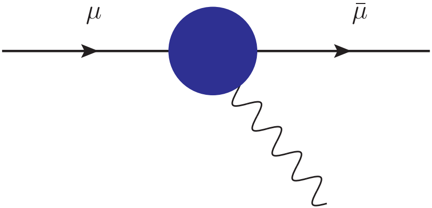


Fits point to scenarios:[Matias et al.]

- $C_9^\mu = -1.1$
- $C_9^\mu = -C_{10}^\mu = -0.61$

Muon Anomalous Magnetic Moment

- $(g-2)_\mu$

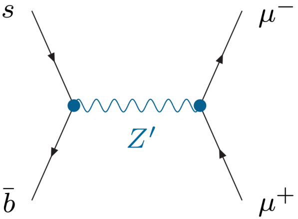


$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (236 \pm 87)10^{-11}$$

2.7σ away from SM

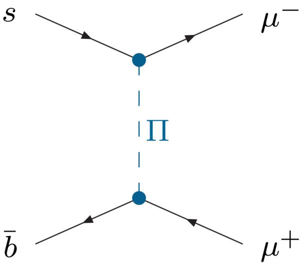
NP Models

- Z'



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

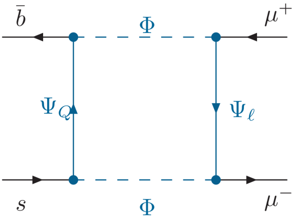
- Leptoquarks



Hiller,Schmaltz;
Bečirević,Košnik,Fajfer;
Gripaios,Nardecchia,Renner; ...

NP Models

- New Heavy Scalars and Fermions



NP CONTRIBUTIONS BOTH APPEAR AT LOOP LEVEL

New Scalars and Fermions

Minimal model

$$\mathcal{L}_{\text{int}}^{a)} = \Gamma_i^Q \bar{Q}_i P_R \Psi \Phi_Q + \Gamma_i^L \bar{L}_i P_R \Psi \Phi_\ell + \text{h.c.}.$$

$$\mathcal{L}_{\text{int}}^{b)} = \Gamma_i^Q \bar{Q}_i P_R \Psi_Q \Phi + \Gamma_i^L \bar{L}_i P_R \Psi_\ell \Phi + \text{h.c.}.$$

- Left-handed fermions $\rightarrow C_9 = -C_{10}$
- Minimal number of new couplings: $\Gamma_s \Gamma_b^*$ Γ_μ
- Different representations

New Scalars and Fermions

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

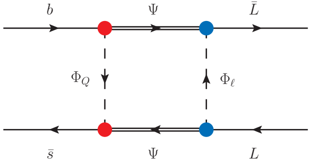
$SU(3)$	Φ_Q, Ψ_Q	Φ_ℓ, Ψ_ℓ	Ψ, Φ
A	3	1	1
B	1	$\bar{3}$	3
C	3	8	8
D	8	$\bar{3}$	3

Y	Φ_Q, Ψ_Q	Φ_ℓ, Ψ_ℓ	Ψ, Φ
	$1/6 + X$	$-1/2 + X$	$-X$

New Scalars and Fermions

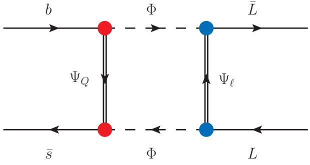
- $b \to s\ \mu^+\mu^-$

Model a)



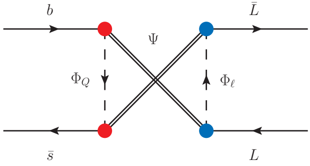
$a)$

Model b)

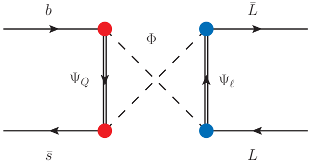


$b)$

Some Representations



$a)$



$b)$

New Scalars and Fermions

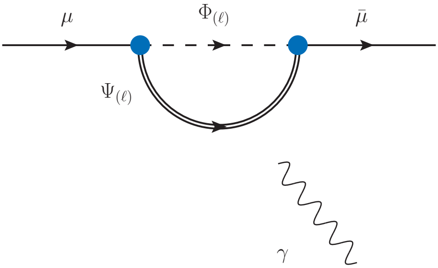
- $b \to s\ \mu^+\mu^-$
  generates $C_9 = -C_{10}$

$$-0.81 \leq C_9 = -C_{10} \leq -0.51 \quad (\text{at } 1\,\sigma)\,,$$
$$-0.97 \leq C_9 = -C_{10} \leq -0.37 \quad (\text{at } 2\,\sigma)\,,$$
$$-1.14 \leq C_9 = -C_{10} \leq -0.23 \quad (\text{at } 3\,\sigma)\,.$$

[Matias et al.]

New Scalars and Fermions

- $(g-2)_\mu$



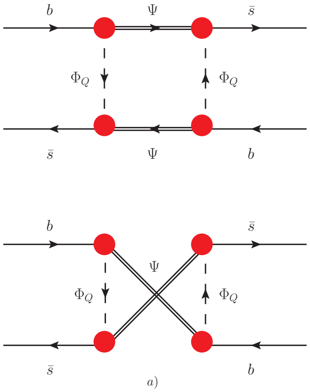
$$\mathcal{H}_{\text{eff}}^{a_\mu} = -a_\mu \frac{e}{4m_\mu}(\bar{\mu}\sigma^{\mu\nu}\mu)\, F_{\mu\nu},$$

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (236 \pm 87) \times 10^{-11},$$

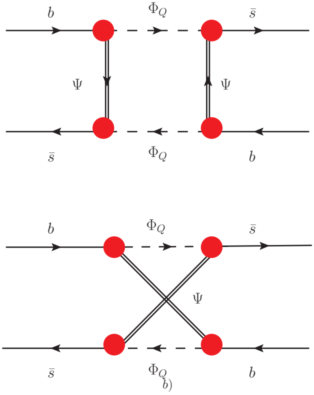
New Scalars and Fermions

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

Model a)



Model b)



New Scalars and Fermions

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

$$\mathcal{H}_{\rm eff}^{B\bar{B}} = C_{B\bar{B}} (\bar{s}_\alpha \gamma^\mu P_L b_\alpha) \, (\bar{s}_\beta \gamma^\mu P_L b_\beta) \, ,$$

$$C_{B\bar{B}}(\mu_H) \in \quad [-2.1, 0.6] \times 10^{-5} \, \mathrm{TeV}^{-2} \quad (\text{at } 2 \, \sigma),$$
$$C_{B\bar{B}}(\mu_H) \in \quad [-2.8, 1.3] \times 10^{-5} \, \mathrm{TeV}^{-2} \quad (\text{at } 3 \, \sigma) \, .$$

Fermilab, MILC 16

- $b \to s \; \nu^+ \nu^-$
- $b \to s\gamma$
- $\mu \to e\gamma$
- $Z \to \mu^+ \mu^-$

Analysis

- Non Degenerate case: 5 independent parameters

$$\Gamma_b^*\Gamma_s \quad \Gamma_\mu$$

$$m_\Psi(m_\Phi)\ ,\ m_{\Phi_Q}(m_{\Psi_Q})\ ,\ m_{\Phi_\ell}(m_{\Psi_\ell})$$

- Degenerate case: 3 independent parameters

$$\Gamma_b^*\Gamma_s \quad \Gamma_\mu \quad m_\Psi(m_\Phi)$$

Analysis

- Degenerate case
  - $B_s - \bar{B}_s$ constrains $\Gamma_b^* \Gamma_s$

$$|\Gamma_s^* \Gamma_b| \leq \; 0.15 \, \frac{1}{\sqrt{\xi_{B\bar{B}}}} \, \frac{m_\Psi}{1\,\mathrm{TeV}} \, ,$$

  - $b \to s \; \mu^+ \mu^-$ box

$$|\, C_9^{\rm box} | \leq \; 0.05 \, \frac{\xi_9^{\rm box}}{\sqrt{\xi_{B\bar{B}}}} \, |\Gamma_\mu|^2 \, \frac{1\,\mathrm{TeV}}{m_\Psi} \, ,$$

$$|\Gamma_\mu| \geq 2.1 \, \sqrt{\frac{m_\Psi}{1\,\mathrm{TeV}}} \, .$$

  - $(g-2)_\mu$

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

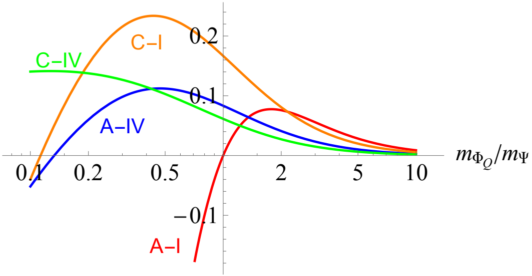
$$|\Gamma_\mu| \geq 2.6(2.1) \, \frac{m_\Psi}{\mathrm{TeV}} \, .$$

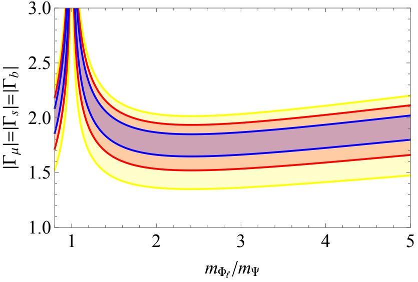
Analysis

- Non degenerate case
  - Case a + Majorana fermion

$$C_{B\bar{B}} \sim \chi_{B\bar{B}}\eta_{B\bar{B}}F(x_Q, x_Q) + 2\chi^{\mathrm{M}}_{B\bar{B}}\eta^{\mathrm{M}}_{B\bar{B}}G(x_Q, x_Q), \quad x_Q = m_{\Phi_Q}/m_{\Psi}$$

If $C_{B\bar{B}} = 0 \longrightarrow$ no bound on $\Gamma_b^* \Gamma_s$



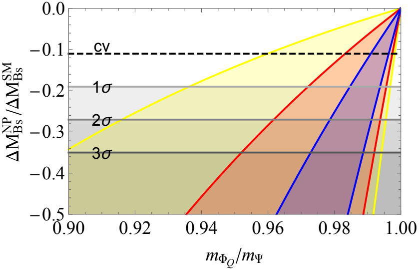


Allowed Regions

$m_{\Phi_Q} = m_\Psi = 1\,\text{TeV}$

Photon penguin still negligible

Couplings smaller



$|\Gamma_\mu| = 2$

$m_{\Phi_\ell} = 2m_\Psi = 2\,\text{TeV}$

Conclusions

- Introduce minimal model a) and b)
- Interact with left-handed SM fermions ($C_9 = -C_{10}$) with all possible representations
- $B_s - \bar{B}_s$ mixing is very stringent (destructive interference)

$$|\Gamma_\mu| \geq 2.1 \sqrt{\frac{m_\Psi}{1\,\mathrm{TeV}}}\,.$$

- Using Majorana rep in model a), can avoid $B_s - \bar{B}_s$ bound
- Muon AMM generates a bound

$$|\Gamma_\mu| \geq 2.6(2.1)\,\frac{m_\Psi}{\mathrm{TeV}}\,.$$