Implications for New Physics in $b \to s\mu\mu$ transitions after recent measurements by Belle and LHCb

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based on work with D.Kumar and E.M.Sessolo
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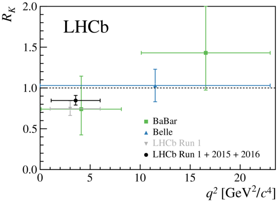
Deviations from the SM in $b \to s$ transitions

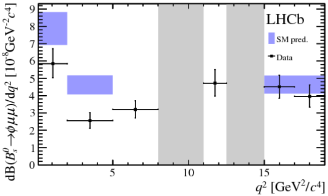
$$R_K = \frac{\mathrm{BR}(B^+ \to K^+ \mu^+ \mu^-)}{\mathrm{BR}(B^+ \to K^+ e^+ e^-)}$$



LHCb (Phys. Rev. Lett. 122 (2019) 191801)

$\sim 2.5\sigma$ NEW!

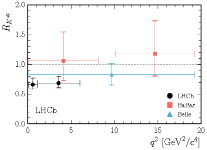
$$\frac{d\mathrm{BR}(B_s^0 \to \phi \mu^+ \mu^-)}{dq^2}$$



LHCb (JHEP 09 (2015) 179)

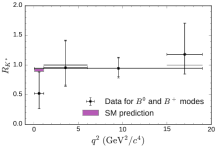
$\sim 3.7\sigma$

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



LHCb (JHEP 08 (2017) 055)

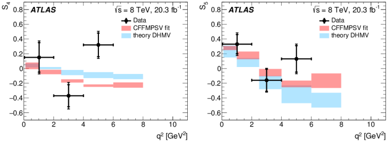
$\sim 2.5\sigma$



Belle (arXiv: 1904.02440)

$\sim 0.5\sigma$ NEW!

angular observables in $B^0 \to K^{*0} \mu^+ \mu^-$



ATLAS (JHEP 10 (2018) 047)

$\sim 3.0\sigma$

Effective field theory approach

- The effective Hamiltonian for $b \to sll$ transitions

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_{i,l} (C_i^l O_i^l + C_i'^l O_i'^l) + \text{h.c.}$$

- We assume the presence of NP in **semileptonic operators**:

$$O_9^l = (\bar{s}_L \gamma^\mu b_L)(\bar{l}\gamma_\mu l), \qquad O_9'^l = (\bar{s}_R \gamma^\mu b_R)(\bar{l}\gamma_\mu l),$$
$$O_{10}^l = (\bar{s}_L \gamma^\mu b_L)(\bar{l}\gamma_\mu \gamma_5 l), \qquad O_{10}'^l = (\bar{s}_R \gamma^\mu b_R)(\bar{l}\gamma_\mu \gamma_5 l)$$

- NP in scalar and pseudoscalar operators $O_S^{(\prime)}$ and $O_P^{(\prime)}$ are severely contrained by the $B_s \to \mu^+\mu^-$ measurements.

  R. Alonso et al. PRL 113(2014) 241802, W. Altmannshofer et al. JHEP 05 (2017) 076.

- NP in electromagnetic dipole operator $O_7^{(\prime)}$ is tightly constrained by radiative decays.

  A. Paul et al. JHEP 04 (2017) 027

- other recent fits: J. Aebischer et al. arXiv 1903.10434, M. Alguero et al., arXiv:1903.09578, A. K. Alok et al., arXiv:1903.09617, M. Ciuchini et al., arXiv:1903.09632, A. Datta et al. arXiv:1903.10086, A. Arbey et al. arXiV:1904.08339

Fit methodology

- Bayes' theorem

$$\mathbf{p(m|d)} = \frac{p(d|\xi(m))\pi(m)}{p(d)}$$

- **posterior pdf** (*probability density function*)

$$p(\psi_{i=1,..,r}|d) = \int p(m|d)d^{n-r}m$$

- likelihood function

$$p(d|\xi(m)) \equiv \mathcal{L}(m) =$$
$$\exp\left\{-\frac{1}{2}\left[\mathcal{O}_{\rm th}(m) - \mathcal{O}_{\rm exp}\right]^T \left(\mathcal{C}^{\rm exp} + \mathcal{C}^{\rm th}\right)^{-1}\left[\mathcal{O}_{\rm th}(m) - \mathcal{O}_{\rm exp}\right]\right\}$$

- evidence $\rightarrow$ comparison of different models through the *Bayes factor*

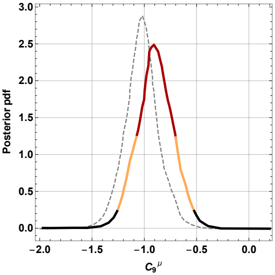
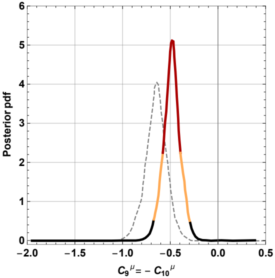
$$p(d)_{\mathcal{M}_1}/p(d)_{\mathcal{M}_2}$$

Fit methodology

140 observables included in the likelihood function ($B^0 \to K^{*0} l^+ l^-$, $B^+ \to K^+ l^+ l^-$, $B^+ \to K^{*+} \mu^+\mu^-$, $B^0 \to K^0 \mu^+\mu^-$, $B_s^0 \to \phi\mu^+\mu^-$, $\Lambda_b^0 \to \Lambda\mu^+\mu^-$, $\mathrm{BR}(B_s^0 \to X_s l^+ l^-)$, $\overline{\mathrm{BR}}(B_s^0 \to \mu^+\mu^-)$)

Parameter	Range	Prior
C_9^μ	$(-3, 3)$	Flat
$C_9^\mu = -C_{10}^\mu$	$(-3, 3)$	Flat
$C_9^\mu,\ C_{10}^\mu$	$(-3, 3)$	Flat
$C_9^\mu,\ C_9^{\prime\mu}$	$(-3, 3)$	Flat
$C_9^\mu,\ C_{10}^\mu,\ C_9^{\prime\mu},\ C_{10}^{\prime\mu}$	$(-3, 3)$	Flat
$C_9^\mu,\ C_{10}^\mu,\ C_9^e,\ C_{10}^e$	$(-3, 3)$	Flat
$C_9^\mu,\ C_9^{\prime\mu},\ C_9^e,\ C_9^{\prime e}$	$(-3, 3)$	Flat
$C_9^\mu,\ C_9^{\prime\mu},\ C_{10}^\mu,\ C_{10}^{\prime\mu}$ $C_9^e,\ C_9^{\prime e},\ C_{10}^e,\ C_{10}^{\prime e}$	$(-3, 3)$	Flat
CKM matrix element V_{cb}	$(4.22, 0.08) \times 10^{-2}$	Gaussian

1 Wilson coefficient

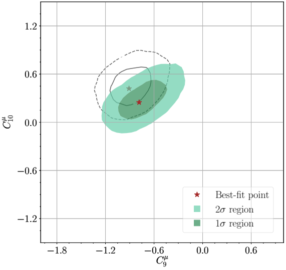
$\mathbf{C_9^\mu}$	$\mathbf{C_9^\mu = -C_{10}^\mu}$
	
$-\ln\mathcal{Z} = \mathbf{77.3}$, pull $\mathbf{4.7}\,\boldsymbol{\sigma}$ (5.0 σ)	$-\ln\mathcal{Z} = \mathbf{77.5}$, pull $\mathbf{4.8}\,\boldsymbol{\sigma}$ (5.3 σ)
$\overline{\mathrm{BR}}(B_s^0 \to \mu^+\mu^-) = 3.5 \times 10^{-9}$	$\overline{\mathrm{BR}}(B_s^0 \to \mu^+\mu^-) = 2.8 \times 10^{-9}$
$\chi^2_{R_K} = 0.3,\ \chi^2_{R_{K^*}} = 8.9$	$\chi^2_{R_K} = 1.6,\ \chi^2_{R_{K^*}} = 7.0$

both predict $R_K \approx R_{K^*}$

$$\text{Bayes factor } \frac{\mathcal{Z}_{C_9^\mu}}{\mathcal{Z}_{C_9^\mu=-C_{10}^\mu}} = 1.2\ (1/4)$$

2 Wilson coefficients

C_9^μ, C_{10}^μ

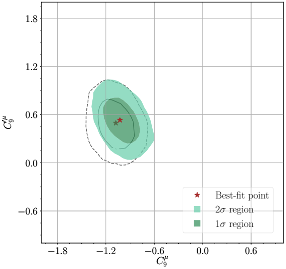


$-\ln \mathcal{Z} = \mathbf{77.6}$, pull $\mathbf{4.7}\,\sigma$ $(5.3\,\sigma)$

$\chi^2_{R_K} = 1.5,\ \chi^2_{R_{K*}} = 7.6$

$R_K \approx R_{K*}$ (tension arises)

C_9^μ, $C_9'^\mu$



$-\ln \mathcal{Z} = \mathbf{75.8}$, pull $\mathbf{5.0}\,\sigma$ $(5.2\,\sigma)$

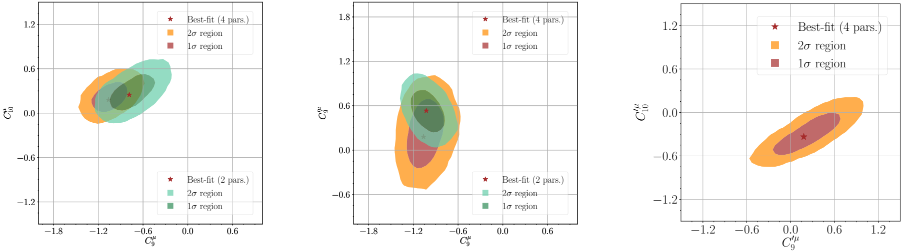
$\chi^2_{R_K} = 0.5,\ \chi^2_{R_{K*}} = 7.3$

$R_K \not\approx R_{K*}$

Bayes factor $\frac{\mathcal{Z}_{C_9^\mu, C_9'^\mu}}{\mathcal{Z}_{C_9^\mu, C_{10}^\mu}} = 6$ (positive) (old: 1/2)

4 vs. 2 Wilson coefficients

$\mathbf{C_9^\mu, C_{10}^\mu, C_9'^\mu, C_{10}'^\mu}$



- perfect fit in R_K and $R_{K*}^{[1.1,6]}$ ($\chi^2_{R_K} = 0.0$, $\chi^2_{R_{K*}} = 6.8$)
- $\overline{\mathrm{BR}}(B_s^0 \to \mu^+\mu^-) = 2.8 \times 10^{-9}$
- larger negative C_9^μ w.r.t. (C_9^μ, C_{10}^μ)
- $C_9'^\mu \leq 0$ allowed w.r.t. $(C_9^\mu, C_9'^\mu)$

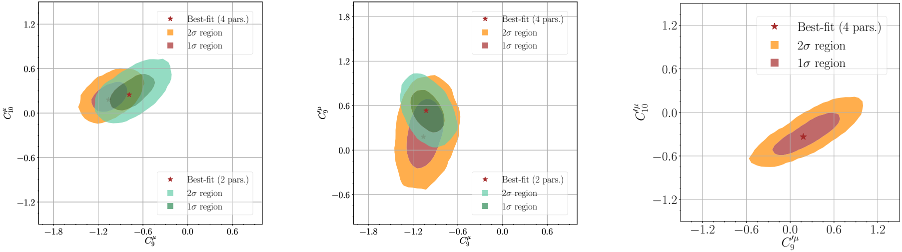
G.Hiller,M.Schmaltz JHEP 02 (2015) 055

$$R_K \approx 1 + 0.24\,(C_9^\mu - C_{10}^\mu + C_9'^\mu - C_{10}'^\mu)$$

$$R_{K*} \approx 1 + 0.24\,(C_9^\mu - C_{10}^\mu) - 0.17\,(C_9'^\mu - C_{10}'^\mu)$$

4 vs. 2 Wilson coefficients

$\mathbf{C_9^\mu, C_{10}^\mu, C_9'^\mu, C_{10}'^\mu}$



$$-\ln \mathcal{Z} = \mathbf{76.0}, \text{ pull } \mathbf{5.1}\,\sigma$$

$$\frac{\mathcal{Z}_{C_9^\mu, C_{10}^\mu, C_9'^\mu, C_{10}'^\mu}}{\mathcal{Z}_{C_9^\mu, C_{10}^\mu}} = 5.0 \quad \text{(positive)}$$

$$\frac{\mathcal{Z}_{C_9^\mu, C_9'^\mu}}{\mathcal{Z}_{C_9^\mu, C_{10}^\mu, C_9'^\mu, C_{10}'^\mu}} = 1.2 \quad \text{(barely worth mentioning)}$$

Impact of $C_{9,10}^{(\prime)e}$

Input parameters	$-\ln \mathcal{Z}$	Pull	$\chi^2_{\rm TOT}$	$\frac{\chi^2_{\rm TOT}}{d.o.f}$	χ^2_μ	$\chi^2_{R_K}$	$\chi^2_{R_{K^*}}$
$C_9^\mu,\ C_{10}^\mu$	77.6	$4.7\,\sigma$	146.1	1.05	130.3	1.5	7.6
$C_9^\mu,\ C_9^{\prime\mu}$	75.8	$5.0\,\sigma$	142.3	1.02	127.6	0.5	7.3
$C_9^\mu,\ C_{10}^\mu,\ C_9^{\prime\mu},\ C_{10}^{\prime\mu}$	76.0	$5.1\,\sigma$	136.8	1.00	123.2	0.0	6.8
$C_9^\mu,\ C_{10}^\mu,\ C_9^e,\ C_{10}^e$	78.0	$4.5\,\sigma$	142.7	1.04	129.8	0.1	5.8
$C_9^\mu,\ C_9^e,\ C_9^{\prime\mu},\ C_9^{\prime e}$	77.7	$4.6\,\sigma$	141.6	1.03	127.2	0.2	6.7
$C_9^\mu,\ C_{10}^\mu,\ C_9^{\prime\mu},\ C_{10}^{\prime\mu}$ $C_9^e,\ C_{10}^e,\ C_9^{\prime e},\ C_{10}^{\prime e}$	78.3	$4.4\,\sigma$	135.4	1.02	123.3	0.2	5.4

No improvement w.r.t fit with the muon-only Wilson coefficients

Heavy Z'

- the most generic Lagrangian, parametrizing couplings of Z' to b, s, μ

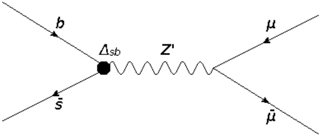
$$\mathcal{L} \supset Z'_\alpha \left(\Delta_L^{sb}\, \bar{s}_L \gamma^\alpha\, b_L + \Delta_R^{sb}\, \bar{s}_R \gamma^\alpha\, b_R + \mathrm{H.c.} \right) + Z'_\alpha \left(\Delta_L^{\mu\mu}\, \bar{\mu}_L \gamma^\alpha \mu_L + \Delta_R^{\mu\mu}\, \bar{\mu}_R \gamma^\alpha \mu_R \right)$$

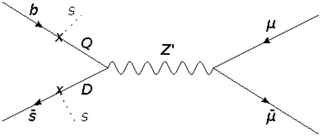
- the corresponding Wilson coefficients

$$C^\mu_{9,\mathrm{NP}} = -\frac{\Delta_L^{sb}(\Delta_L^{\mu\mu} + \Delta_R^{\mu\mu})}{V_{tb} V_{ts}^*} \left(\frac{\Lambda_v}{m_{Z'}} \right)^2 \qquad C'^\mu_{9,\mathrm{NP}} = -\frac{\Delta_R^{sb}(\Delta_L^{\mu\mu} + \Delta_R^{\mu\mu})}{V_{tb} V_{ts}^*} \left(\frac{\Lambda_v}{m_{Z'}} \right)^2$$

$$C^\mu_{10,\mathrm{NP}} = -\frac{\Delta_L^{sb}(\Delta_R^{\mu\mu} - \Delta_L^{\mu\mu})}{V_{tb} V_{ts}^*} \left(\frac{\Lambda_v}{m_{Z'}} \right)^2 \qquad C'^\mu_{10,\mathrm{NP}} = -\frac{\Delta_R^{sb}(\Delta_R^{\mu\mu} - \Delta_L^{\mu\mu})}{V_{tb} V_{ts}^*} \left(\frac{\Lambda_v}{m_{Z'}} \right)^2$$

- Z' is the gauge boson of $\mathrm{U}(1)_X$ $\rightarrow$ its couplings to the gauge eigenstates must be flavor-conserving $\rightarrow$ Δ_L^{sb} and Δ_R^{sb} from VLF





Model 1 P.Fox et al. Phys. Rev. D84 (2011) 115006, C. Bobeth et al. JHEP 04 (2017) 079

- VL quarks $Q^{(\prime)} : (\mathbf{3}, \mathbf{2}, 1/6, -1)$, $D^{(\prime)} : (\bar{\mathbf{3}}, \mathbf{1}, 1/3, -1)$
- scalar singlet $S : (\mathbf{1}, \mathbf{1}, 0, -1)$
- SM leptons: $Q(e) = 0$, $Q(\mu_{R/L}) = -1/1$, $Q(\tau_{L/R}) = -1/1$

SM and BSM mixing given by

$$\mathcal{L} \supset \left(-\lambda_{Q,i} S Q' q_i - \lambda_{D,i} S D' d_{R,i} + \mathrm{H.c.}\right) - M_Q Q' Q - M_D D' D$$

effective Wilson coefficients ($v_S = m_{Z'}/g_X$)

$$C_{9,\mathrm{NP}}^{\mu} = \frac{2\Lambda_v^2}{V_{tb} V_{ts}^*} \frac{\lambda_{Q,2}\lambda_{Q,3}}{2M_Q^2 + \left(\lambda_{Q,2}^2 + \lambda_{Q,3}^2\right) v_S^2}, \qquad C_{10,\mathrm{NP}}^{\mu} = 0$$

$$C_{9,\mathrm{NP}}^{\prime\mu} = -\frac{2\Lambda_v^2}{V_{tb} V_{ts}^*} \frac{\lambda_{D,2}\lambda_{D,3}}{2M_D^2 + \left(\lambda_{D,2}^2 + \lambda_{D,3}^2\right) v_S^2}, \qquad C_{10,\mathrm{NP}}^{\prime\mu} = 0$$

Heavy Z' with $L_\mu - L_\tau$ symmetry

Model 2 W. Altmannshofer et al. Phys. Rev. D94 no. 9, (2016) 095026

- VL quarks $Q^{(\prime)} : (\mathbf{3}, \mathbf{2}, 1/6, -1)$, $E^{(\prime)} : (\mathbf{1}, \mathbf{1}, 1, 0)$
- scalar singlet $S : (\mathbf{1}, \mathbf{1}, 0, -1)$
- SM leptons: $Q(e) = 0$, $Q(\mu_{R/L}) = -1/1$, $Q(\tau_{L/R}) = -1/1$

SM and BSM mixing given by

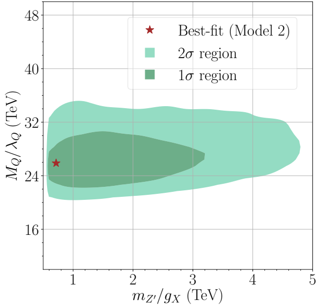
$$\mathcal{L} \supset \left(-\lambda_{E,2} S^* E' \mu_R - \lambda_{E,3} S E' \tau_R - \widetilde{Y}_E \phi^\dagger l_1 E + \mathrm{H.c.}\right) - M_E E' E$$

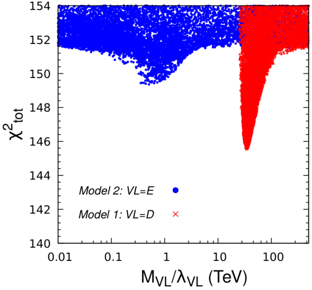
effective Wilson coefficients ($v_S = m_{Z'}/g_X$)

$$C_{9,\mathrm{NP}}^{\mu} = \frac{\Lambda_v^2}{V_{tb} V_{ts}^*} \left(\frac{\lambda_{Q,2}\lambda_{Q,3}}{2M_Q^2 + \left(\lambda_{Q,2}^2 + \lambda_{Q,3}^2\right) v_S^2} \right) \left(1 + \frac{2M_E^2}{2M_E^2 + \lambda_{E,2}^2 v_S^2} \right), \qquad C_{9,\mathrm{NP}}^{\prime\mu} = 0$$

$$C_{10,\mathrm{NP}}^{\mu} = \frac{\Lambda_v^2}{V_{tb} V_{ts}^*} \left(\frac{\lambda_{Q,2}\lambda_{Q,3}}{2M_Q^2 + \left(\lambda_{Q,2}^2 + \lambda_{Q,3}^2\right) v_S^2} \right) \left(-1 + \frac{2M_E^2}{2M_E^2 + \lambda_{E,2}^2 v_S^2} \right), \qquad C_{10,\mathrm{NP}}^{\prime\mu} = 0$$

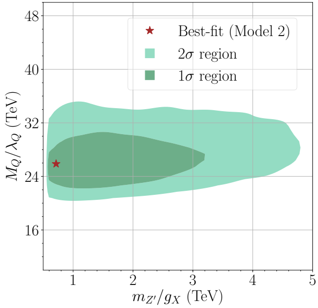
Heavy Z' with $L_\mu - L_\tau$ symmetry

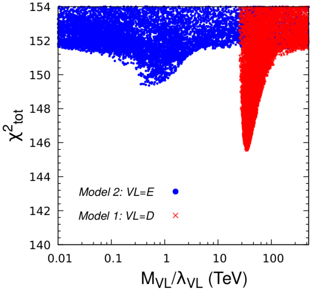




- VLQ mass range is determined by the 2σ range in $C^{\mu}_{9,\mathrm{NP}}$
- VLD and VLE mass is unbounded from the above at the 2σ level ($C'^{\mu}_{9,\mathrm{NP}}$ (model 1) and $C^{\mu}_{10,\mathrm{NP}}$ (model 2) are consistent with the zero at the 2σ)
- $m_{Z'}/g_X$ is limited to values below 5 TeV as a result of the B_s mixing constraint

Heavy Z' with $L_\mu - L_\tau$ symmetry





Z' + VL	$-\ln \mathcal{Z}$	Pull	$m_{Z'}/g_X$	M_Q/λ_Q	$M_{\rm VL}/\lambda_{\rm VL}$
Model 1	78.4	$4.5\,\sigma$	0.7 TeV	24.4 TeV	34.2 TeV
Model 2	80.0	$4.1\,\sigma$	0.7 TeV	24.7 TeV	0.5 TeV

$$\frac{\mathcal{Z}_{\rm Model\ 1}}{\mathcal{Z}_{\rm Model\ 2}} = 5.0 \qquad \text{(positive)}$$

Summary

- Global Bayesian analysis of NP effects with new measurements of R_K and R_{K^*} in Morionod 2019.
- R_K shifts closer to SM predicitons hence (C_9^μ, C_{10}^μ) shifts slightly towards zero.
- Pull w.r.t. SM still at $5\,\sigma$ (!).
- $(C_9^\mu, C_9'^\mu)$ and $(C_9^\mu, C_{10}^\mu, C_9'^\mu, C_{10}'^\mu)$ are favored by the data.