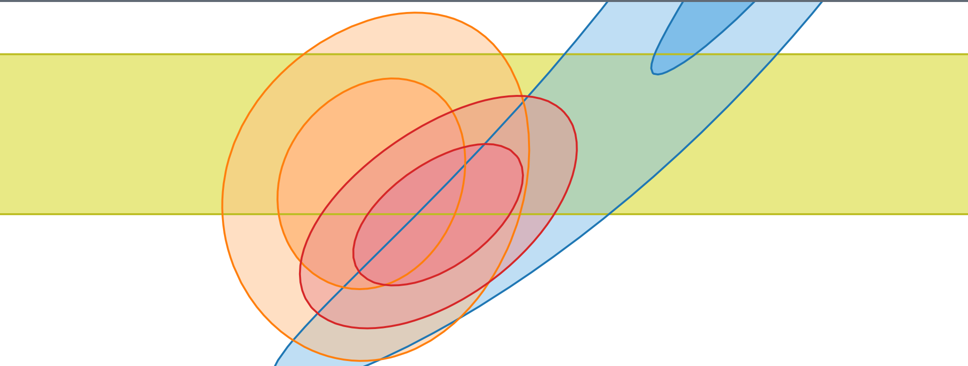
ITP Seminar, Bern, 16 April 2021

Anomalies in B decays after Moriond 2021

Peter Stangl AEC & ITP University of Bern

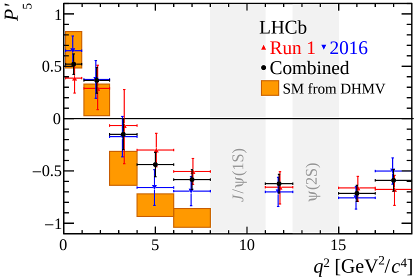


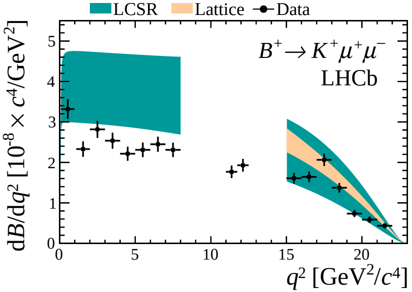
The flavor anomalies

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

Several LHCb measurements deviate from Standard model (SM) predictions by 2-3σ:

- Angular observables in $B \to K^*\mu^+\mu^-$. LHCb, arXiv:2003.04831, arXiv:2012.13241
- Branching ratios of $B \to K\mu^+\mu^-$, $B \to K^*\mu^+\mu^-$, and $B_s \to \phi\mu^+\mu^-$. LHCb, arXiv:1403.8044, arXiv:1506.08777, arXiv:1606.04731



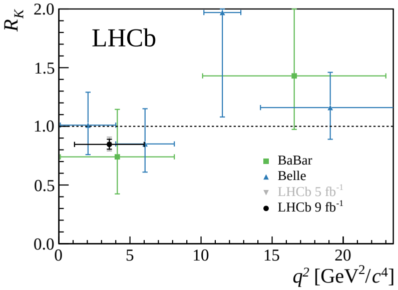


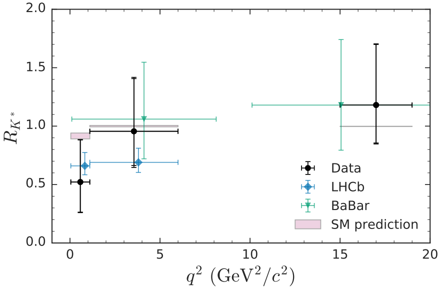
Hints for LFU violation in $b \to s\,\ell^+\ell^-$ decays

Measurements of lepton flavor universality (LFU) ratios $R_{K^*}^{[0.045,1.1]}$, $R_{K^*}^{[1.1,6]}$, $R_K^{[1,6]}$ show deviations from SM by 2.3, 2.5, and 3.1σ.

LHCb, arXiv:1705.05802, arXiv:2103.11769
Belle, arXiv:1904.02440, arXiv:1908.01848

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

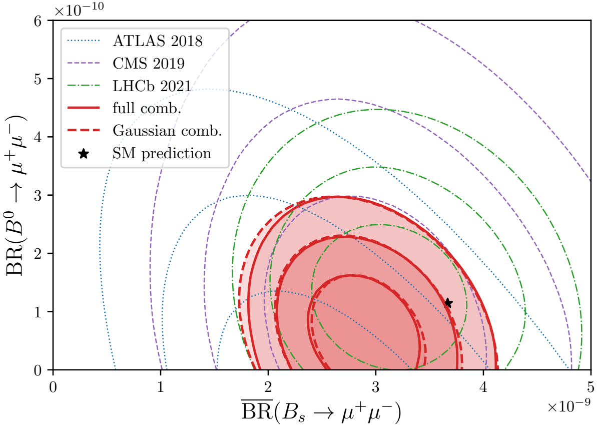




Combination of $B_{s,d} \to \mu^+\mu^-$ measurements

Measurements of BR($B_{s,d} \to \mu^+\mu^-$) by LHCb, CMS, and ATLAS show combined deviation from SM by about 2σ.

ATLAS, arXiv:1812.03017
CMS, arXiv:1910.12127
LHCb seminar 23 March 2021
Altmannshofer, PS, arXiv:2103.13370



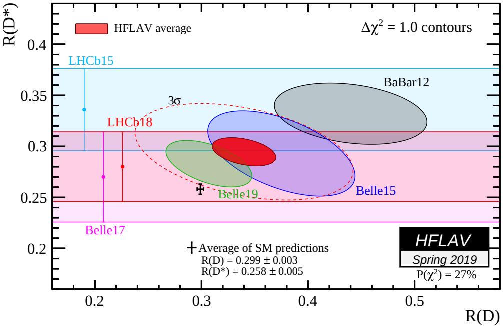
Hints for LFU violation in $b \to c\,\ell\,\nu$ decays

Measurements of LFU ratios R_D and R_{D^*} by BaBar, Belle, and LHCb show combined deviation from SM by about 3-4σ.

BaBar, arXiv:1205.5442, arXiv:1303.0571
LHCb, arXiv:1506.08614, arXiv:1708.08856
Belle, arXiv:1507.03233, arXiv:1607.07923, arXiv:1612.00529, arXiv:1904.08794

$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\ell\nu)}$$

$$\ell \in \{e, \mu\}$$



HFLAV, hflav.web.cern.ch

New physics interpretation

$b \to s\ell\ell$ in the weak effective theory

- Effective Hamiltonian at scale m_b: $\mathcal{H}_{\text{eff}}^{bs\ell\ell} = \mathcal{H}_{\text{eff, SM}}^{bs\ell\ell} + \mathcal{H}_{\text{eff, NP}}^{bs\ell\ell}$

$$\mathcal{H}_{\text{eff, NP}}^{bs\ell\ell} = -\mathcal{N} \sum_{\ell=e,\mu} \sum_{i=9,10,S,P} \left(C_i^{bs\ell\ell} O_i^{bs\ell\ell} + C_i'^{bs\ell\ell} O_i'^{bs\ell\ell} \right) + \text{h.c.}$$

- Operators considered here ($\ell = e, \mu$)

$$\begin{aligned}
O_9^{bs\ell\ell} &= (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, & O_9'^{bs\ell\ell} &= (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)\,,\\
O_{10}^{bs\ell\ell} &= (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,, & O_{10}'^{bs\ell\ell} &= (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,,\\
O_S^{bs\ell\ell} &= m_b(\bar{s}P_R b)(\bar{\ell}\ell)\,, & O_S'^{bs\ell\ell} &= m_b(\bar{s}P_L b)(\bar{\ell}\ell)\,,\\
O_P^{bs\ell\ell} &= m_b(\bar{s}P_R b)(\bar{\ell}\gamma_5\ell)\,, & O_P'^{bs\ell\ell} &= m_b(\bar{s}P_L b)(\bar{\ell}\gamma_5\ell)\,.
\end{aligned}$$

- Not considered here
  - Dipole operators: strongly constrained by radiative decays. e.g. [arXiv:1608.02556]
  - Four quark operators: dominant effect from RG running above m_B.
    Jäger, Leslie, Kirk, Lenz [arXiv:1701.09183]

Setup

- Quantify agreement between theory and experiment by χ^2 function

$$\chi^2(\vec{C}) = \left(\vec{O}_{\text{exp}} - \vec{O}_{\text{th}}(\vec{C})\right)^T \left(C_{\text{exp}} + C_{\text{th}}\right)^{-1} \left(\vec{O}_{\text{exp}} - \vec{O}_{\text{th}}(\vec{C})\right) .$$

- **theory errors** and **correlations** in covariance matrix $\boldsymbol{C}_{\textbf{th}}$
- **experimental errors** and available **correlations** in covariance matrix $\boldsymbol{C}_{\textbf{exp}}$
- Theory errors depend on new physics Wilson coefficients $\boldsymbol{C}_{\textbf{th}}(\vec{\boldsymbol{C}})$
- $\Delta\chi^2$ and pull

$$\text{pull}_{1D} = 1\sigma \cdot \sqrt{\Delta\chi^2}, \qquad \text{where } \Delta\chi^2 = \chi^2(\vec{0}) - \chi^2(\vec{C}_{\text{best fit}}) .$$

$$\text{pull}_{2D} = 1\sigma, 2\sigma, 3\sigma, ... \quad \text{for} \quad \Delta\chi^2 \approx 2.3, 6.2, 11.8, ...$$

- New physics scenarios **Weak Effective Theory (WET)** at scale 4.8 GeV

Setup

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- New physics scenarios **Weak Effective Theory (WET)** at scale 4.8 GeV

Scenarios with a single Wilson coefficients

Wilson coefficient	$b \to s\mu\mu$ best fit	$b \to s\mu\mu$ pull	LFU, $B_s \to \mu\mu$ best fit	LFU, $B_s \to \mu\mu$ pull	all rare B decays best fit	all rare B decays pull
$C_9^{bs\mu\mu}$	$-0.87^{+0.19}_{-0.18}$	4.3σ	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.80^{+0.14}_{-0.14}$	5.7σ
$C_{10}^{bs\mu\mu}$	$+0.49^{+0.24}_{-0.25}$	1.9σ	$+0.60^{+0.14}_{-0.14}$	4.7σ	$+0.55^{+0.12}_{-0.12}$	4.8σ
$C_9^{\prime bs\mu\mu}$	$+0.39^{+0.27}_{-0.26}$	1.5σ	$-0.32^{+0.16}_{-0.17}$	2.0σ	$-0.14^{+0.13}_{-0.13}$	1.0σ
$C_{10}^{\prime bs\mu\mu}$	$-0.10^{+0.17}_{-0.16}$	0.6σ	$+0.06^{+0.12}_{-0.12}$	0.5σ	$+0.04^{+0.10}_{-0.10}$	0.4σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$-0.34^{+0.16}_{-0.16}$	2.1σ	$+0.43^{+0.18}_{-0.18}$	2.4σ	$-0.01^{+0.12}_{-0.12}$	0.1σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.60^{+0.13}_{-0.12}$	4.3σ	$-0.35^{+0.08}_{-0.08}$	4.6σ	$-0.41^{+0.07}_{-0.07}$	5.9σ

Only small pull for

- Coefficients with $\ell = e$ (cannot explain $b \to s\mu\mu$ anomaly and $B_s \to \mu\mu$)
- Scalar coefficients (can only reduce tension in $B_s \to \mu\mu$)

see also similar fits by other groups:
Algueró et al., arXiv:1903.09578 Ciuchini et al., arXiv:2011.01212 Datta et al., arXiv:1903.10086
Kowalska et al., arXiv:1903.10932 Arbey et al., arXiv:1904.08399 Geng et al., arXiv:2103.12738

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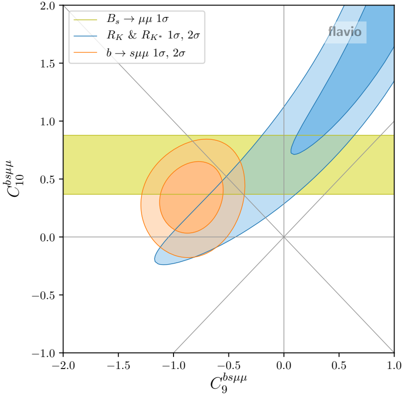
SM err.	$C_9^{bs\mu\mu}$	$-0.96^{+0.19}_{-0.18}$	4.6σ	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.83^{+0.14}_{-0.14}$	5.9σ
	$C_{10}^{bs\mu\mu}$	$+0.51^{+0.22}_{-0.22}$	2.3σ	$+0.60^{+0.14}_{-0.14}$	4.7σ	$+0.56^{+0.12}_{-0.12}$	4.9σ
	$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.64^{+0.16}_{-0.17}$	4.3σ	$-0.35^{+0.08}_{-0.08}$	4.6σ	$-0.41^{+0.07}_{-0.07}$	5.9σ

Visible effect of theory errors depending on new physics

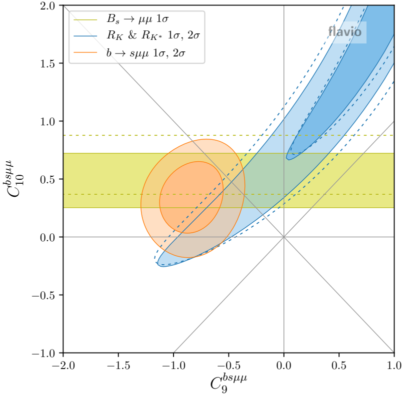
Scenarios with two Wilson coefficients



- **Before Moriond 2021**

WET at 4.8 GeV

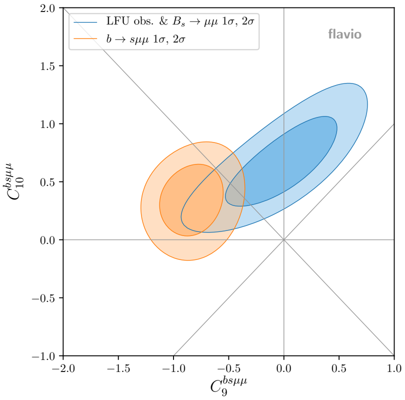
Scenarios with two Wilson coefficients



WET at 4.8 GeV

- **After Moriond 2021**:
  - R_K: smaller uncertainty
  - $B_s \to \mu\mu$: smaller uncertainty, better agreement with $b \to s\mu\mu$

Scenarios with two Wilson coefficients



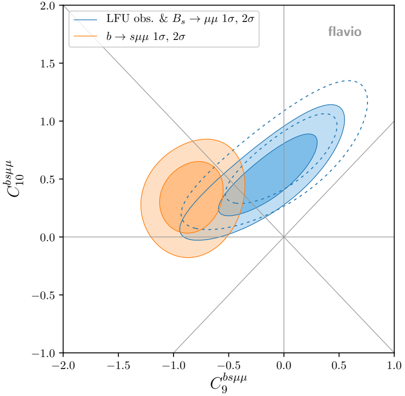
WET at 4.8 GeV

Combination of $B_s \to \mu^+\mu^-$ and NC LFU observables ($R_K, R_{K^*}, D_{P_{4',5'}}$)

- NCLFU obs. & $B_s \to \mu\mu$: very clean theory prediction, insensitive to universal $C_9^{\text{univ.}}$
- $b \to s\mu\mu$ sensitive to univ. coeff. possibly afflicted by underestimated hadr. uncert.

- **Before Moriond 2021**

Scenarios with two Wilson coefficients



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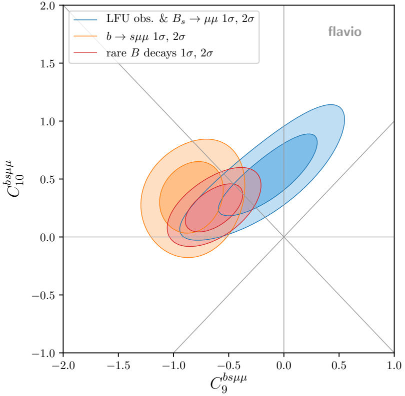
- $b \to s\mu\mu$ sensitive to univ. coeff. possibly afflicted by underestimated hadr. uncert.

- **After Moriond 2021**:
  - **LFU obs. & $B_s \to \mu\mu$**: smaller uncertainty, better agreement with $b \to s\mu\mu$

Scenarios with two Wilson coefficients

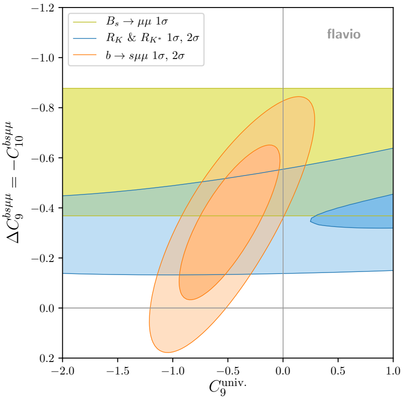


WET at 4.8 GeV

- Global fit in $C_9^{bs\mu\mu}$-$C_{10}^{bs\mu\mu}$ plane prefers negative $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$
- Tension between fits to $b \to s\mu\mu$ observables and R_K & R_{K^*} could be reduced by **LFU** contribution to $\boldsymbol{C_9}$

Scenarios with two Wilson coefficients

- **Before Moriond 2021**



WET at 4.8 GeV

- Perform two-parameter fit in space of $C_9^{\text{univ.}}$ and $\Delta C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$:

$$C_9^{bsee} = C_9^{bs\tau\tau} = C_9^{\text{univ.}}$$
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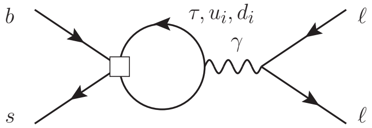
scenario first considered in Algueró et al., arXiv:1809.08447

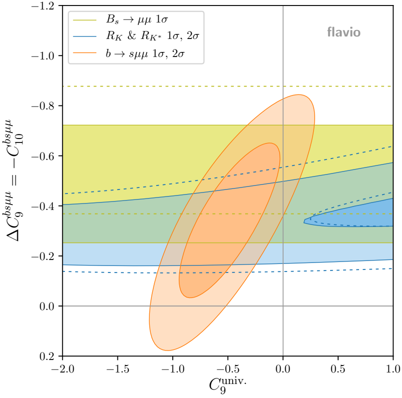
- Preference for **non-zero $C_9^{\text{univ.}}$**
  - could be mimicked by hadronic effects
  - can arise from RG effects:



Bobeth, Haisch, arXiv:1109.1826
Crivellin, Greub, Müller, Saturnino, arXiv:1807.02068

Scenarios with two Wilson coefficients

- **After Moriond 2021**: smaller uncertainty, better agreement between R_K & R_{K^*} and $B_s \to \mu\mu$



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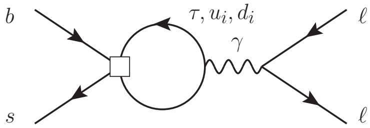

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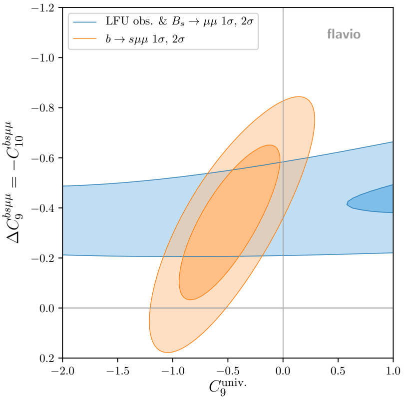

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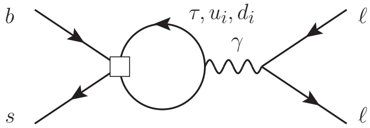

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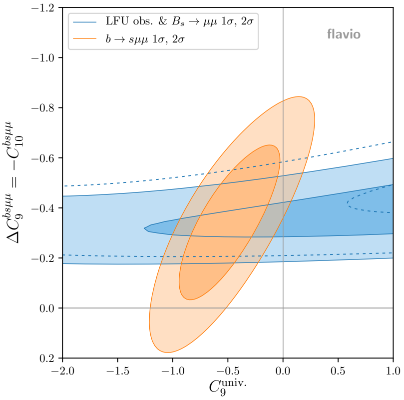
Scenarios with two Wilson coefficients

- **After Moriond 2021**:
  smaller uncertainty, better agreement



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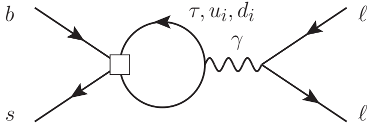

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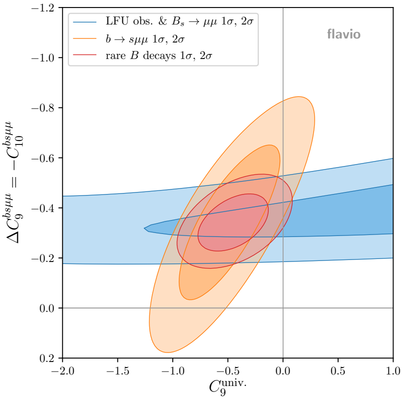

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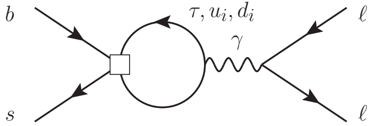

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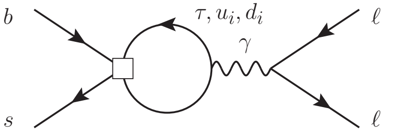
RG effect in SMEFT

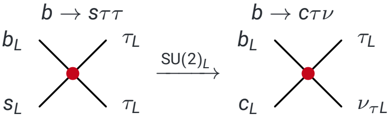
RG effects require scale separation

- Consider **SMEFT**



Possible operators:

- $[O_{lq}^{(3)}]_{3323} = (\bar{l}_3\gamma_\mu\tau^a l_3)(\bar{q}_2\gamma^\mu\tau^a q_3)$:
  Might also **explain $R_{D^{(*)}}$ anomalies!**



- $[O_{lq}^{(1)}]_{3323} = (\bar{l}_3\gamma_\mu l_3)(\bar{q}_2\gamma^\mu q_3)$:
  Strong constraints from $B \to K\nu\nu$ require $[C_{lq}^{(1)}]_{3323} \approx [C_{lq}^{(3)}]_{3323}$

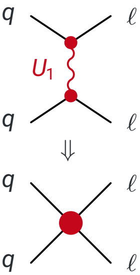
Buras et al., arXiv:1409.4557

- **U_1 vector leptoquark** $(\mathbf{3}, \mathbf{1})_{2/3}$ couples LH fermions

$$\mathcal{L}_{U_1} \supset g_{lq}^{ji} \left(\bar{q}^i\gamma^\mu l^j\right) U_\mu + \text{h.c.}$$

- Generates **semi-leptonic operators at tree-level**

$$[C_{lq}^{(1)}]_{ijkl} = [C_{lq}^{(3)}]_{ijkl} = -\frac{g_{lq}^{jk}\, g_{lq}^{il*}}{2M_U^2}$$



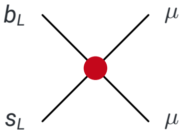
Models for $b \to s\ell\ell$ anomalies

Models for $b \to s\ell\ell$ anomalies

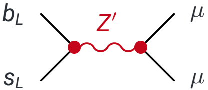
Global fits suggest

$$C_9^\mu - C_{10}^\mu \approx -0.9, \qquad 0 \gtrsim \frac{C_{10}^\mu}{C_9^\mu} \gtrsim -1$$

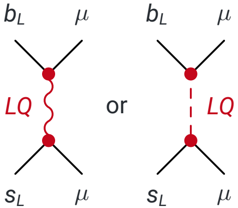
$$O_9^\mu = (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)\,, \quad O_{10}^\mu = (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$$



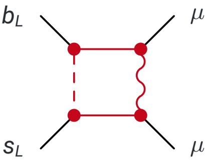
$$\sim \frac{C_9^\mu - C_{10}^\mu}{(34\,\text{TeV})^2}$$



$$\sim \frac{g_{bs}\, g_{\mu\mu}}{m_{Z'}^2}$$

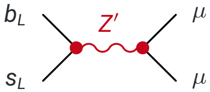


$$\sim \frac{g_{b\mu}\, g_{s\mu}}{m_{LQ}^2}$$

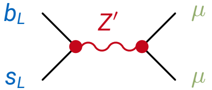


$$\sim \frac{g_b\, g_s\, g_{\mu,1}\, g_{\mu,2}}{16\,\pi^2\, m_{\text{NP}}^2}$$

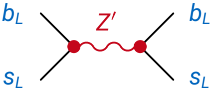
Z'



Z': Constraints from B_s-$\bar{B}_s$ mixing



$\rightarrow$



$$\sim \frac{g_{bs}\, g_{\mu\mu}}{m_{Z'}^2} \sim \frac{1}{(36\,\text{TeV})^2}$$

$$\sim \frac{g_{bs}^2}{m_{Z'}^2} \lesssim \frac{\left|\frac{M_{12}}{M_{12}^{\text{SM}}} - 1\right| \Big/ 10\%}{(244\,\text{TeV})^2}$$

$$\left|\frac{M_{12}}{M_{12}^{\text{SM}}} - 1\right| \approx 10\%$$

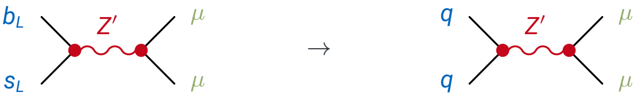
$$\Downarrow$$

$$\frac{g_{\mu\mu}}{m_{Z'}} \gtrsim \frac{1}{5.3\,\text{TeV}}$$

Ways around:

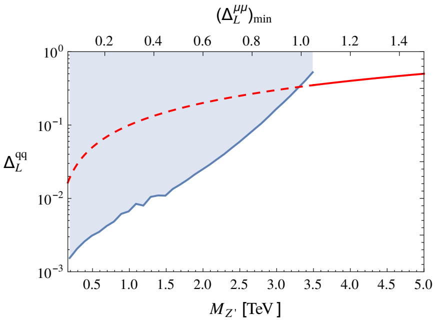
- imaginary part of g_{bs} $\rightarrow$ constraints from *CP* violating observables
- Z' coupling to $(\bar{s}\gamma_\mu P_R b)$ $\rightarrow$ constraint from $R_K \approx R_{K^*}$
- ...

Z': Constraints from $pp \to \mu\mu$

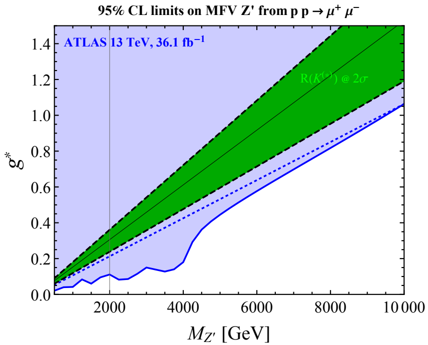


- Direct searches for a Z' resonance
- Searches for quark-lepton contact interactions

Z': Constraints from $pp \to \mu\mu$



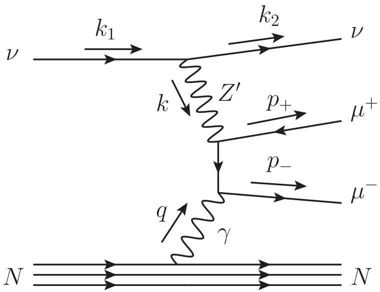
Altmannshofer, Straub, arXiv:1411.3161



Greljo, Marzocca, arXiv:1704.09015

- Couplings to light quarks must be suppressed for $m_{Z'} < 4.5\,\text{TeV}$
- MFV-like Z'-quark couplings already excluded

Z': Constraints from neutrino trident production

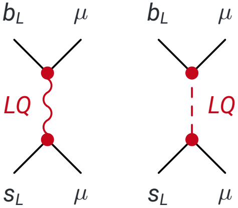


Altmannshofer, Gori, Pospelov, Yavin, arXiv:1406.2332

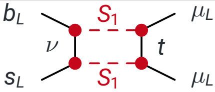
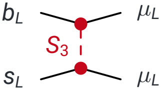
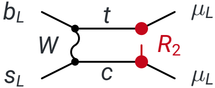
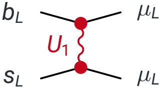
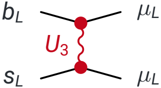
- $\mu^+\mu^-$ production induced by neutrino in Coulomb field of heavy nucleus
- Cross section with Z' contribution

$$\frac{\sigma}{\sigma_{SM}} \simeq \frac{1 + \left(1 + 4\,s_W^2 + 2\,v^2\,\frac{g_{Z'}^2}{m_{Z'}^2}\right)^2}{1 + \left(1 + 4\,s_W^2\right)^2}$$

Leptoquarks

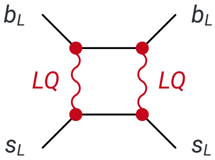


Leptoquarks: possible solutions for $b \to s\mu\mu$

Spin	G_{SM}	Name	Characteristic process	
0	$(\bar{3},1)_{1/3}$	S_1		Bauer, Neubert, arXiv:1511.01900
0	$(\bar{3},3)_{1/3}$	S_3		Hiller, Schmaltz, arXiv:1408.1627
0	$(3,2)_{7/6}$	R_2		Bečirević, Sumensari, arXiv:1704.05835
1	$(3,1)_{2/3}$	U_1		Barbieri et al., arXiv:1512.01560
1	$(3,3)_{2/3}$	U_3		Fajfer, Košnik, arXiv:1511.06024

Leptoquarks: B_s-$\bar{B}_s$ mixing loop-suppressed

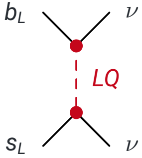
- Generic strong constraint on Z' models is loop-suppressed for leptoquark models



- Big advantage compared to Z'

Leptoquarks: $b \to s\bar{\nu}\nu$ at tree level

- S_1, S_3, U_3 generate $b \to s\nu\nu$ at tree level



$\to$ constraints from $B \to K^{(*)}\bar{\nu}\nu$

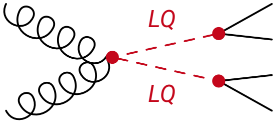
Buras, Girrbach-Noe, Niehoff, Straub, arXiv:1409.4557

- Way around:
  Can be suppressed by cancellation between S_1 and S_3 contributions

Crivellin, Müller, Ota, arXiv:1703.09226

Leptoquarks: direct constraints

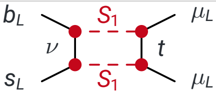
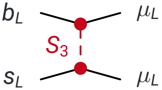
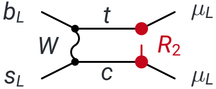
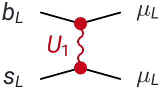
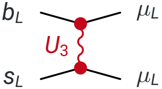
- QCD pair production
- Direct searches with $jj\ell\ell$ or $jj\nu\nu$ final states



Decays	Scalar LQ limits	Vector LQ limits	$\mathcal{L}_{\rm int}$ / Ref.
$jj\,\tau\bar{\tau}$	–	–	–
$b\bar{b}\,\tau\bar{\tau}$	1.0 (0.8) TeV	1.5 (1.3) TeV	36 fb^{-1} [39]
$t\bar{t}\,\tau\bar{\tau}$	1.4 (1.2) TeV	2.0 (1.8) TeV	140 fb^{-1} [40]
$jj\,\mu\bar{\mu}$	1.7 (1.4) TeV	2.3 (2.1) TeV	140 fb^{-1} [41]
$b\bar{b}\,\mu\bar{\mu}$	1.7 (1.5) TeV	2.3 (2.1) TeV	140 fb^{-1} [41]
$t\bar{t}\,\mu\bar{\mu}$	1.5 (1.3) TeV	2.0 (1.8) TeV	140 fb^{-1} [42]
$jj\,\nu\bar{\nu}$	1.0 (0.6) TeV	1.8 (1.5) TeV	36 fb^{-1} [43]
$b\bar{b}\,\nu\bar{\nu}$	1.1 (0.8) TeV	1.8 (1.5) TeV	36 fb^{-1} [43]
$t\bar{t}\,\nu\bar{\nu}$	1.2 (0.9) TeV	1.8 (1.6) TeV	140 fb^{-1} [44]

Angelescu, Bečirević, Faroughy, Jaffredo, Sumensari, arXiv:2103.12504

Leptoquarks: still viable solutions for $b \to s\mu\mu$

Spin	G_{SM}	Name	Characteristic process	$R_{K^{(*)}}$	
0	$(\bar{3},1)_{1/3}$	S_1		X	requires too large couplings
0	$(\bar{3},3)_{1/3}$	S_3		✓	
0	$(3,2)_{7/6}$	R_2		X	tension with LHC limits
1	$(3,1)_{2/3}$	U_1		✓	
1	$(3,3)_{2/3}$	U_3		✓	

cf. Angelescu, Bečirević, Faroughy, Jaffredo, Sumensari, arXiv:2103.12504

An explicit model

An explicit model

Model setup:

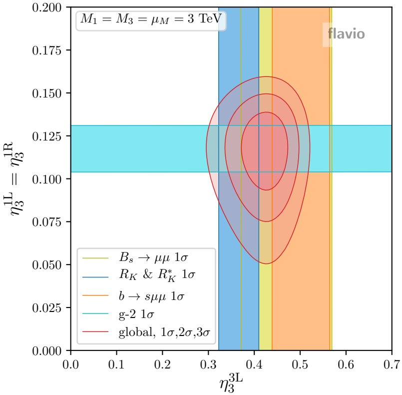
- Effect in $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$ can be generated at tree level by scalar leptoquark $S_3 \sim (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$
  Hiller, Schmaltz, arXiv:1408.1627
- Generic S_3 couples to all lepton generations $\Rightarrow$ **Lepton Flavour Violation** (LFV)
- Generic S_3 has di-quark couplings $\Rightarrow$ **proton decay**
- **Strong experimental constraints** on LFV and proton decay

Idea:

- Charge S_3 and muon under **new U(1) gauge symmetry** such that
  - S_3 cannot couple to two quarks $\Rightarrow$ prevents proton decay
  - Muon is only lepton that couples to S_3 $\Rightarrow$ prevents LFV

  Hambye, Heeck, arXiv:1712.04871
  Davighi, Kirk, Nardecchia, arXiv:2007.15016
- Second leptoquark $S_1 \sim (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$ charged under **same U(1)** gauge symmetry receives same protection (only coupling to muons, no LFV, no proton decay)
  $\Rightarrow$ "**Muoquark**" models **explaining** $\mathbf{R_{K^{(*)}}}$ and $(\mathbf{g}-\mathbf{2})_\mu$
  Greljo, PS, Thomsen, arXiv:2103.13991

A model for muon anomalies



$$\eta_i^{3L} = (V_{td},\, V_{ts},\, 1)\, \eta_3^{3L}$$
$$\eta_i^{1L} = (V_{td},\, V_{ts},\, 1)\, \eta_3^{1L}$$
$$\eta_i^{1R} = (0,\, 0,\, 1)\, \eta_3^{1R}$$

- Model for muon anomalies:
  $$\mathcal{L} \supset \eta_i^{3L}\, \overline{q}_L^{c\,i} \ell_L^2\, S_3 + \eta_i^{1L} \overline{q}_L^{c\,i} \ell_L^2\, S_1 + \eta_i^{1R} \overline{u}_R^{c\,i} \mu_R S_1$$
- One-loop matching to SMEFT
  Gherardi, Marzocca, Venturin, arXiv:2003.12525
- Interface to **smelli** - the **SME**FT **Like****LI**hood Python package
  Aebischer, Kumar, PS, Straub, arXiv:1810.07698
- Likelihood in space of model parameters
- Excellent fit to data with best fit point at $(\eta_3^{3L}, \eta_3^{1L} = \eta_3^{1R}) \simeq (0.43, 0.12)$ and $\Delta\chi^2 \simeq 62$ compared to SM point $(0, 0)$
- Compatible with all measurements included in smelli (>400 observables)

Conclusions

Conclusions

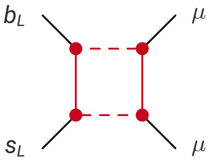
- Updated measurements of R_K and $B_s \to \mu\mu$
- New physics in the single muonic Wilson coefficients $\boldsymbol{C_9^{bs\mu\mu}}$, $\boldsymbol{C_{10}^{bs\mu\mu}}$, and $\boldsymbol{C_9^{bs\mu\mu}} = -\boldsymbol{C_{10}^{bs\mu\mu}}$ gives clearly better fit to data than SM ($\text{pull}_{\text{1D}} \gtrsim 5\sigma$).
- Slight tension between $R_{K^{(*)}}$ and $b \to s\mu\mu$ in $C_9^{bs\mu\mu}$-$C_{10}^{bs\mu\mu}$ scenario can be reduced by **lepton flavor universal $\boldsymbol{C_9^{\text{univ.}}}$**.
- $b \to s\ell\ell$ anomalies can be explained in particular by
  - $\boldsymbol{Z'}$ neutral vector boson
  - $\boldsymbol{U_1}$ vector leptoquark
  - $\boldsymbol{S_3}$ scalar leptoquark
- S_3 model can be protected from proton decay and LFV by new $U(1)$ gauge symmetry that makes the S_3 a **muoquark** (coupling only to 2nd gen. leptons).
- Same mechanism can be used for S_1 muoquark explaining $(g-2)_\mu$.

Backup slides

Loop models

- New scalars and vector-like fermions

Gripaios, Nardecchia, Renner, arXiv:1509.05020
Arnan, Crivellin, Hofer, Mescia, arXiv:1608.07832



$\rightarrow \Delta M_s$ always enhanced except with Majorana fermions

Blanke, Buras, arXiv:hep-ph/0610037
Arnan, Crivellin, Hofer, Mescia, arXiv:1608.07832

- Fundamental partial compositeness:
  New scalars and vector-like fermions charged under new strong interaction

D'Amico et al., arXiv:1704.05438
Sannino, PS, Straub, Thomsen, arXiv:1712.07646