GDR-InF annual workshop, Arles, 06 November 2018

Zoology of New Physics Models for the Flavour Anomalies

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Disclaimer

- Focus on **particles** that could explain the flavour anomalies, **not explicit models**
  $\rightarrow$ sorry for not mentioning/citing your model!
- Focus on anomalies in **charged current** and **neutral current *B* decays**
  ($g_\mu - 2$, dark matter, etc. might be related, but very model-dependent)
- This is a **discussion session**!
  $\rightarrow$ Feel free to interrupt me anytime and comment also on explicit models and related topics!

Outline

Outline

Neutral current anomalies

- Several anomalies in neutral current B decays
  - **$b \to s\,\mu^+\mu^-$ anomaly**
    - Angular observable P_5' in $B \to K^*\mu^+\mu^-$. LHCb, arXiv:1512.04442
    - 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**
    - LFU ratio $R_K^{[1,6]}$ LHCb, arXiv:1406.6482
    - LFU ratio $R_{K^*}^{[0.045,1.1]}$, $R_{K^*}^{[1.1,6]}$ LHCb, arXiv:1705.05802
- Can be explained by **new physics in $b \to s\,\ell^+\ell^-$ transition** described by

$$\mathcal{H}_{\text{eff}}^{\text{NP},b\to s\ell\ell} = \mathcal{N}^{b\to s\ell\ell} \sum_{i,\ell} (C_i^\ell O_i^\ell + C_i'^{\,\ell} O_i'^{\,\ell}) + \text{h.c.}\,, \qquad \mathcal{N}^{b\to s\ell\ell} \approx \frac{1}{(34\,\text{TeV})^2}$$

- Global fits suggest

$$\boldsymbol{C_9^\mu - C_{10}^\mu \approx -1.3, \qquad 0 \gtrsim \frac{C_{10}^\mu}{C_9^\mu} \gtrsim -1}$$

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

Neutral current anomalies

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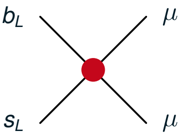
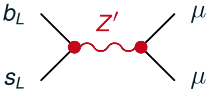
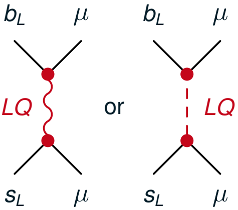


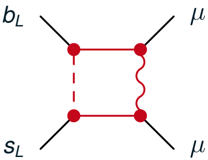
$$\sim \frac{C_9^\mu - C_{10}^\mu}{(34\,\text{TeV})^2}$$



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

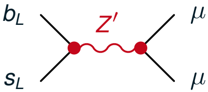


$$\sim \frac{g_{b\mu}\, g_{s\mu}}{m_{LQ}^2}$$

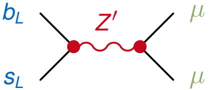


$$\sim \frac{g_b\, g_s\, g_{\mu,1}\, g_{\mu,2}}{16\,\pi^2\, m_{\text{NP}}^2}$$

Z'



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



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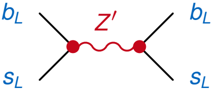


$$\sim \frac{g_{bs}\, g_{\mu\mu}}{m_{Z'}^2} \sim \frac{1}{(30\,\text{TeV})^2}$$

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

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

$$\Downarrow$$

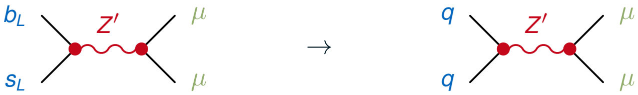
$$\frac{g_{\mu\mu}}{m_{Z'}} \gtrsim \frac{1}{3.7\,\text{TeV}}$$

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' from gauged horizontal symmetry $\rightarrow$ constraints from K-$\bar{K}$ mixing and LFV
- ...

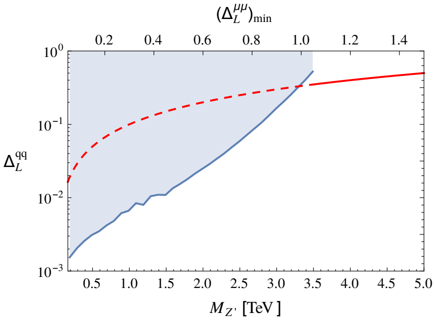
see also talk by Méril Reboud

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

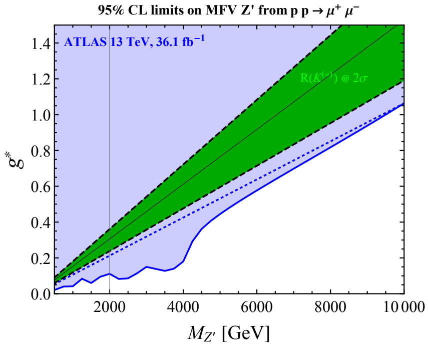


- Direct searches for a Z' resonance
- Searches for quark-lepton contact interactions

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



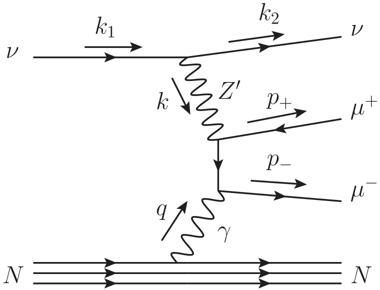
Altmannshofer, Straub, arXiv:1411.3161



Greljo, Marzocca, arXiv:1704.09015

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

light Z': Constraints from neutrino trident production

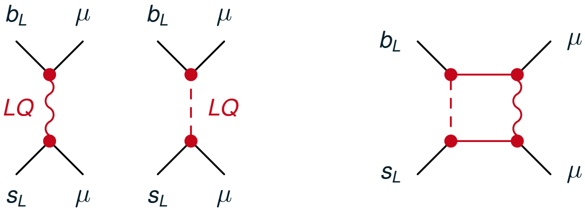


Altmannshofer, Gori, Pospelov, Yavin, arXiv:1406.2332

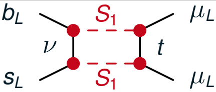
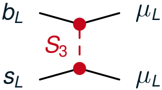
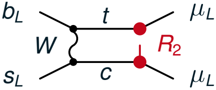
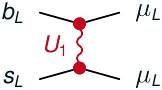
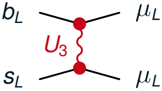
- $\mu^+\mu^-$ production induced by neutrino in Coulomb field of heavy nucleus
- Cross section with Z' contribution

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

Leptoquarks and loops

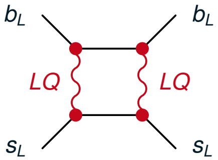


Leptoquarks: possible solutions for $b \to s\mu\mu$

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

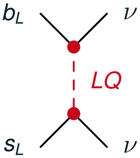
- Strongest constraint on Z' models is loop-suppressed for leptoquark models



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

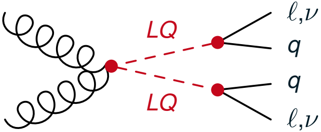
Buras, Girrbach-Noe, Niehoff, Straub, arXiv:1409.4557

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

Crivellin, Müller, Ota, arXiv:1703.09226

Leptoquarks: direct constraints

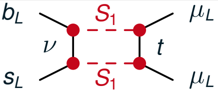
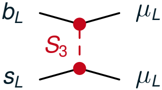
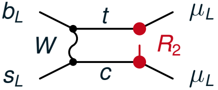
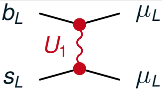
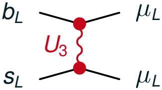
- QCD pair production
- Direct searches with $jj\ell\ell$ or $jj\nu\nu$ final states



Decays	LQs	Scalar LQ limits	Vector LQ limits	$\mathcal{L}_{\text{int}}$ / Ref.
$jj\,\tau\bar{\tau}$	S_1, R_2, S_3, U_1, U_3	–	–	–
$b\bar{b}\,\tau\bar{\tau}$	R_2, S_3, U_1, U_3	850 (550) GeV	1550 (1290) GeV	12.9 fb^{-1} [49]
$t\bar{t}\,\tau\bar{\tau}$	S_1, R_2, S_3, U_3	900 (560) GeV	1440 (1220) GeV	35.9 fb^{-1} [50]
$jj\,\mu\bar{\mu}$	S_1, R_2, S_3, U_1, U_3	1530 (1275) GeV	2110 (1860) GeV	35.9 fb^{-1} [51]
$b\bar{b}\,\mu\bar{\mu}$	R_2, U_1, U_3	1400 (1160) GeV	1900 (1700) GeV	36.1 fb^{-1} [52]
$t\bar{t}\,\mu\bar{\mu}$	S_1, R_2, S_3, U_3	1420 (950) GeV	1780 (1560) GeV	36.1 fb^{-1} [53, 54]
$jj\,\nu\bar{\nu}$	R_2, S_3, U_1, U_3	980 (640) GeV	1790 (1500) GeV	35.9 fb^{-1} [55]
$b\bar{b}\,\nu\bar{\nu}$	S_1, R_2, S_3, U_3	1100 (800) GeV	1810 (1540) GeV	35.9 fb^{-1} [55]
$t\bar{t}\,\nu\bar{\nu}$	R_2, S_3, U_1, U_3	1020 (820) GeV	1780 (1530) GeV	35.9 fb^{-1} [55]

Angelescu, Bečirević, Faroughy, Sumensari, arXiv:1808.08179

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

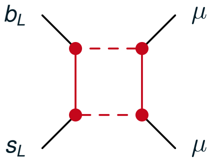
Spin	$G_{\rm SM}$	Name	Characteristic process	$R_{K^{(*)}}$	
0	$(\bar{3}, 1)_{1/3}$	S_1		✓ X	requires very large couplings
0	$(\bar{3}, 3)_{1/3}$	S_3		✓	
0	$(3, 2)_{7/6}$	R_2		X	tension with LHC limits
1	$(3, 1)_{2/3}$	U_1		✓	
1	$(3, 3)_{2/3}$	U_3		✓	

cf. Angelescu, Bečirević, Faroughy, Sumensari, arXiv:1808.08179

Other 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

see other talk by PS

Outline

Charged current anomalies

- Hints for LFU violation
  - LFU ration R_D
  - LFU ration R_{D^*}

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

- Can be explained by **new physics in $\boldsymbol{b \to c\,\ell\nu}$ transition** described by

$$\mathcal{H}_{\text{eff}}^{\text{NP},b\to c\ell\nu} = \mathcal{N}^{b\to c\ell\nu} \sum_{k\in\{V,S,T\}} C_k^{(\prime)\ell} O_k^{(\prime)\ell} + \text{h.c.}, \qquad \mathcal{N}^{b\to c\ell\nu} \approx \frac{1}{(0.85\,\text{TeV})^2}$$

- Global fits suggest
  - $\boldsymbol{C_V^\tau \approx 0.1}, \quad O_V^\tau = (\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$
  - $\boldsymbol{C_T^\tau \approx -0.04, \quad 0.16 \lesssim C_{S_L}^\mu \lesssim 0.6}$,
    e.g. $\boldsymbol{C_{S_L}^\mu = -4\, C_T^\tau \approx 0.16}$,
    $O_{S_L}^\tau = (\bar{c}P_L b)(\bar{\tau}P_L\nu_\tau)\,, \quad O_T^\tau = (\bar{c}\sigma^{\mu\nu}P_L b)(\bar{\tau}\sigma_{\mu\nu}P_L\nu_\tau)$
  - Other combinations (e.g. imaginary coefficients) are possible

Charged current anomalies

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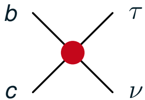
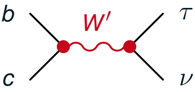
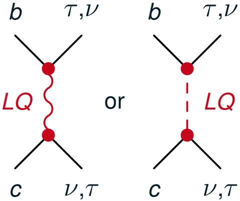
  e.g. $C_{S_L}^\mu = -4\, C_T^\tau \approx 0.16,$
  $O_{S_L}^\tau = (\bar{c} P_L b)(\bar{\tau} P_L \nu_\tau)\,, \quad O_T^\tau = (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau)$



$$\sim \frac{0.1}{(0.85\,\text{TeV})^2}$$

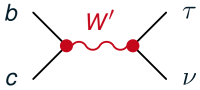


$$\sim \frac{g_{bc}\, g_{\tau\nu}}{m_{W'}^2}$$



$$\sim \frac{g_{b,\tau/\nu}\, g_{c,\nu/\tau}}{m_{LQ}^2}$$

W'



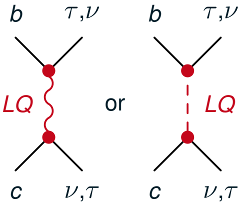
W'

cf. Buttazzo, Greljo, Isidori, Marzocca, arXiv:1706.07808

- $C_V^\tau \approx 0.1$ can be reproduced with combination of color-less triplet $(1,3)_0$ and singlet $(1,1)_0$
- Implications for triplet vector resonance from large value of C_V^τ
  - low mass
  - large coupling to $b_L b_L$ and $\tau_L \tau_L$

  $\rightarrow$ **very strong bounds from high-p_T di-tau searches**
- Only way to avoid bounds would be large width of resonances

Leptoquarks



Leptoquarks: viable solutions for $R_{D^{(*)}}$

Spin	G_{SM}	Name	$R_{D^{(*)}}$	
0	$(\bar{3}, 1)_{1/3}$	S_1	✓	
0	$(\bar{3}, 3)_{1/3}$	S_3	✗	wrong sign of contribution to $R_{D^{(*)}}$
0	$(3, 2)_{7/6}$	R_2	✓	
1	$(3, 1)_{2/3}$	U_1	✓	
1	$(3, 3)_{2/3}$	U_3	✗	wrong sign of contribution to $R_{D^{(*)}}$

cf. Angelescu, Bečirević, Faroughy, Sumensari, arXiv:1808.08179

Outline

Combined explanations

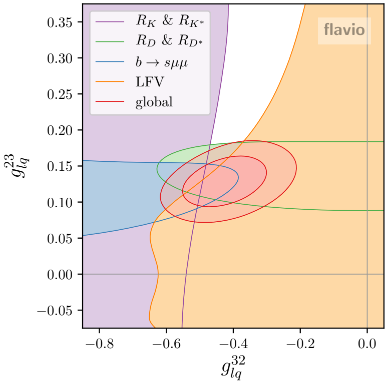
- Single mediator solution

Spin	G_{SM}	Name	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
0	$(\bar{3}, 1)_{1/3}$	S_1	✓ ✗	✓	✓ ✗
0	$(\bar{3}, 3)_{1/3}$	S_3	✓	✗	✗
0	$(3, 2)_{7/6}$	R_2	✗	✓	✗
1	$(3, 1)_{2/3}$	U_1	✓	✓	✓
1	$(3, 3)_{2/3}$	U_3	✓	✗	✗

cf. Angelescu, Bečirević, Faroughy, Sumensari, arXiv:1808.08179

- More complicated constructions possible
  - Combination of S_1 and S_3 e.g. Crivellin, Müller, Ota, arXiv:1703.09226; Marzocca, arXiv:1803.10972
  - ...

Vector leptoquark U_1 solution to B anomalies



Aebischer, Kumar, PS, Straub, arXiv:1810.07698

- Only truly viable single mediator solution
- Does not generate $B \to K\nu\nu$ at tree level
  Buras, Girrbach-Noe, Niehoff, Straub, arXiv:1409.4557
- Couplings:

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

  - $b \to s\mu\mu$ requires $g_{lq}^{22} g_{lq}^{23*}$
  - $b \to c\tau\nu$ requires $g_{lq}^{32} g_{lq}^{33*}$
  - $\tau \to \phi\mu$ constrains $g_{lq}^{32} g_{lq}^{22*}$

$$m_{U_1} = 1\ \text{TeV} \quad g_{lq}^{33} = 1 \quad g_{lq}^{22} = 0.04^2 \approx V_{cb}^2$$

U_1 leptoquark models

- Heavy vector boson needs UV completion
  - U_1 as resonance of new strong interaction
    Barbieri, Isidori, Pattori, Senia, arXiv:1512.01560
    Buttazzo, Greljo, Isidori, Marzocca, arXiv:1604.03940
    Barbieri, Murphy, Senia, arXiv:1611.04930
  - U_1 as gauge boson of extended gauge sector
    Diaz, Schmaltz, Zhong, arXiv:1706.05033
    Di Luzio, Greljo, Nardecchia, arXiv:1708.08450
    M. Bordone, Cornella, Fuentes-Martin, Isidori, arXiv:1712.01368
    Greljo, Stefanek, arXiv:1802.04274
- In these models, U_1 is part of $SU(4)$ multiplet (adjoint representation)
- This implies other heavy vector bosons
  - Heavy gluon-like resonance
  - Additional Z'
- Additional vector boson yield strong constraints from direct searches

Prediction from combined explanations

- Not easy to explain both $R_{K^{(*)}}$ and $R_{D^{(*)}}$ while satisfying all constraints
- Prediction:
  - Central values of $R_{D^{(*)}}$ measurements will move closer to SM value

    or

  - More sophisticated models are required to explain $R_{D^{(*)}}$

    or

  - We will soon see other **new physics** effects in **indirect and direct** searches.

Backup slides