High p_T Implications of $b \to s\ell\ell$ Anomalies

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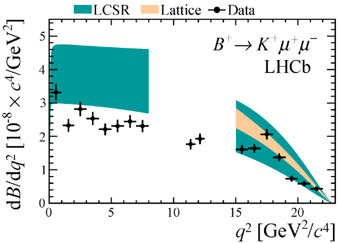
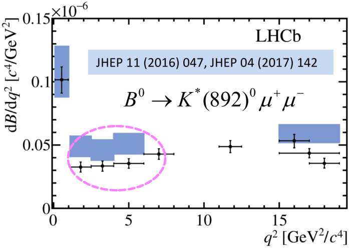
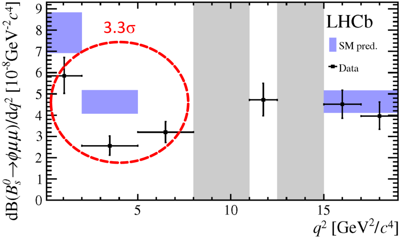
The Anomalies: Branching Ratios

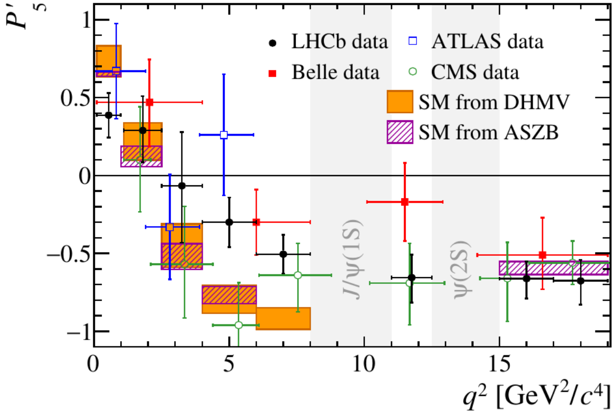






several $b \to s\mu\mu$ branching ratios are consistently 2σ - 3σ below the SM predictions

The Anomalies: Angular Distributions



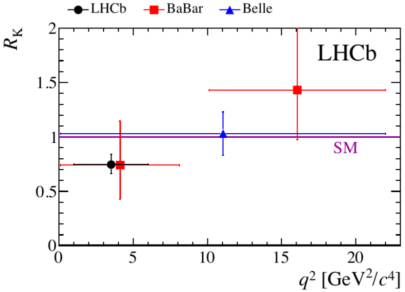
$\sim 3\sigma$ discrepancy in P_5' between SM predictions

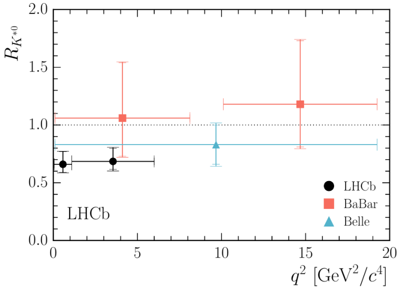
(ASZB = WA, Straub 1411.3161 + Bharucha, Straub, Zwicky 1503.05534)

(DHMV = Descotes-Genon, Hofer, Matias, Virto 1510.04239)

and measurements (LHCb collaboration 1512.04442)

The Anomalies: Lepton Universality Ratios





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

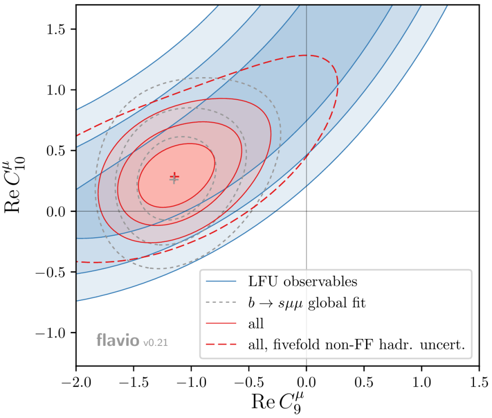
$$R_K^{[1,6]} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

$$R_{K^*}^{[0.045,1.1]} = 0.66^{+0.11}_{-0.07} \pm 0.03$$

$$R_{K^*}^{[1.1,6]} = 0.69^{+0.11}_{-0.07} \pm 0.05$$

3 observables deviating by $\sim 2\sigma - 2.5\sigma$ from the SM predictions

Model Independent New Physics Interpretation



WA, Stangl, Straub 1704.05435

WA, Niehoff, Stangl, Straub 1703.09189

(+ many others ...)

Best description of all anomalies by:

new physics in final states with muons

$C_9^\mu (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)$

SM-like final states with electrons

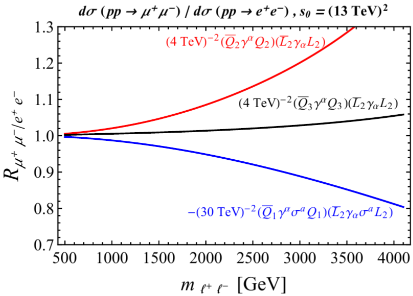
Implications for the New Physics Scale

unitarity bound	$\frac{4\pi}{\Lambda_{\rm NP}^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 120\text{ TeV} \times (C_9^{\rm NP})^{-1/2}$
generic tree	$\frac{1}{\Lambda_{\rm NP}^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 35\text{ TeV} \times (C_9^{\rm NP})^{-1/2}$
MFV tree	$\frac{1}{\Lambda_{\rm NP}^2}\, V_{tb}V_{ts}^*\, (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 7\text{ TeV} \times (C_9^{\rm NP})^{-1/2}$
generic loop	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 3\text{ TeV} \times (C_9^{\rm NP})^{-1/2}$
MFV loop	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2}\, V_{tb}V_{ts}^*\, (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 0.6\text{ TeV} \times (C_9^{\rm NP})^{-1/2}$

The New Physics might or might not be in reach of the HL/HE LHC ...

Searching for the Contact Interaction

even if the new degrees of freedom are not accessible at the LHC, high energy tails of di-lepton spectra are in principle sensitive

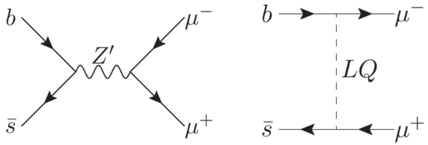


operator relevant for the $bs\ell\ell$ anomalies: $\frac{1}{\Lambda^2_{\rm NP}}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu P_L \mu)$

- currently probed up to scales of 2.5 TeV
- can be probed up to 4 TeV with 3/ab (extracted from Greljo, Marzocca 1704.09015)
- HE LHC will improve sensitivity (but will likely not reach the 35 TeV)

possible tree level explanations:

- Z' Bosons
- Lepto-Quarks

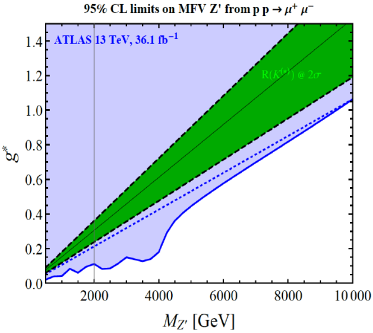


upper bounds on flavor violating couplings from B_s mixing imply
upper bounds on the particle masses

- $m_{Z'} \lesssim g_\mu \times 8\text{TeV}$
- $m_{\text{LQ}} \lesssim 20 - 40\text{TeV}$ (depending on the lepto-quark representation)

$\rightarrow$ a weakly coupled Z' is likely in reach of HE LHC assume that flavor diagonal and flavor violating couplings are related

$$g_L^{qq} = g_* \,, \qquad g_L^{bs} = V_{tb} V_{ts}^* g_*$$



Greljo, Marzocca 1704.09015

also WA, Straub 1411.3161

already ruled out
by di-muon resonance searches
+ searches for $qq\mu\mu$ contact interactions

$\rightarrow$ couplings to light quarks need to be suppressed

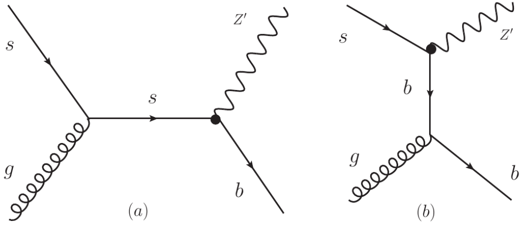
“Minimalistic” Z' Scenario

switch on only couplings that are needed for the $bs\mu\mu$ anomalies
(+ those that are dictated by SU(2))

$$g_L^{\mu\mu} Z'_\mu (\bar{\mu}\gamma^\mu P_L \mu) + g_L^{bs} Z'_\mu (\bar{s}\gamma^\mu P_L b) + \text{ h.c.}$$

(requires some sophisticated UV flavor story...)

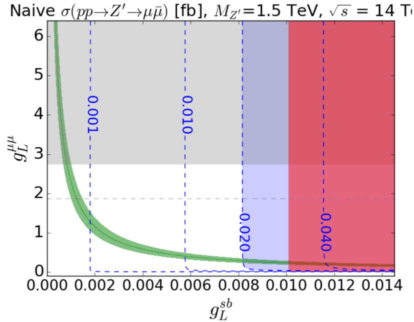
Irreducible Z' signature: $pp \to bZ' \to b\mu^+\mu^-$

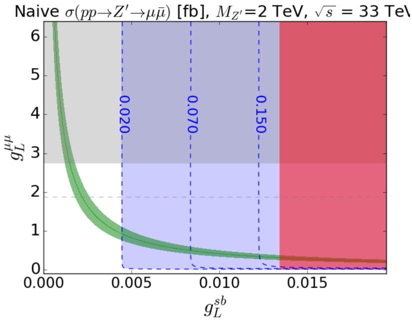


Sensitivities at HL/HE LHC

green: $R_{K^{(*)}}$ explanation, gray: low scale Landau pole

red: B_s mixing constraint, blue: LHC sensitivity

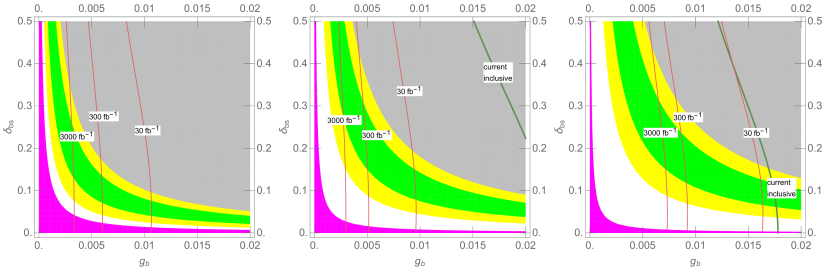




The "minimalistic" setup cannot be fully covered at the HL/HE LHC (3/ab) even for rather light Z' of O(TeV)

Allanach, Gripaios, You 1710.06363; also Chivukula et al. 1706.06575

(caveat: assume absence of "dark" decays) sensitivity increases in the presence of a sizable $Z' bb$ coupling



$m_{Z'} = 200$ GeV $\qquad$ $m_{Z'} = 350$ GeV $\qquad$ $m_{Z'} = 500$ GeV

Dalchenko, Dutta, Eusebi, Huang, Kamon, Rathjens 1707.07016

also Kohda, Modak, Soffer 1803.07492

(caveat: assume absence of “dark” decays)

“Minimalistic” Lepto-Quark Scenarios

three possible lepto-quark representations:

$S_3(\bar{3}, 3, 1/3) \qquad V_1(3, 1, 2/3) \qquad V_3(3, 3, -2/3)$

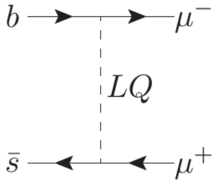
switch on only couplings that are needed for the $bs\mu\mu$ anomalies
(+ those that are dictated by SU(2))

S_3 example

$$\lambda_L^{b\mu}(\bar{b}^c P_L \mu) S_3^{4/3}$$

$$+\lambda_L^{s\mu}(\bar{s}^c P_L \mu) S_3^{4/3} + \text{ h.c.}$$

(UV flavor story?)

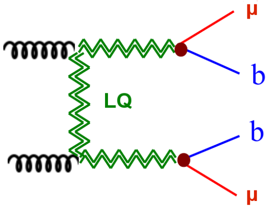


Irreducible lepto-quark signatures

Lepto-quarks are pair produced through QCD interactions

$$pp \to \text{LQ LQ} \to j(b)\mu^+ \; j(b)\mu^-$$

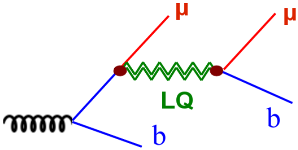
(pair production completely fixed by QCD for the scalar LQ, but could be model-dependent for vector LQ)



Lepto-quarks can be singly produced through their couplings to quarks/leptons

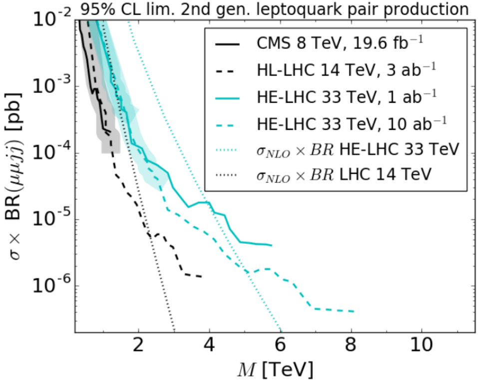
$$pp \to \text{LQ}\; \mu \to j(b)\mu^+\mu^-$$

(single production can be important for heavy LQ)



Sensitivities at the HL/HE LHC

pair production of lepto-quarks



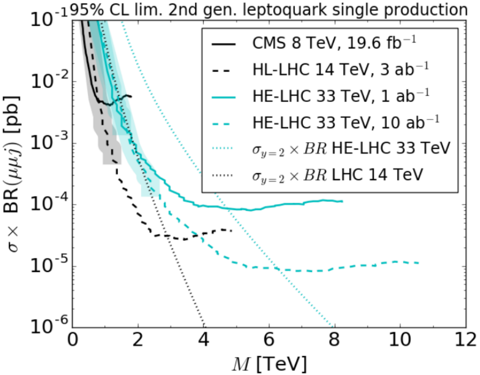
Allanach, Gripaios, You 1710.06363

caveat: dominant lepto-quark decay mode could be “exotic” LQ $\to \ell + 3j$

(Monteux, Rajaraman 1803.05962)

Sensitivities at the HL/HE LHC

single production can be relevant for heavy lepto-quarks



Allanach, Gripaios, You 1710.06363

also Hiller, Loose, Nisandzic 1801.09399

Summary

- $b \to s\ell\ell$ anomalies point to a four fermion contact interaction $(\bar{b}\gamma_\alpha P_L s)(\bar{\mu}\gamma^\alpha \mu)$ at a generic scale of $\sim$ 35 TeV
- Possible tree level explanations from Z' or lepto-quarks
- weakly coupled Z' are probably light(ish) ($\lesssim$ several TeV), but could in principle be hidden
- lepto-quarks are more difficult to hide, but could be very heavy ($\gtrsim$ 10 TeV)
- irreducible Z' signature:
  $pp \to bZ' \to b\mu^+\mu^-$
  (di-muon resonance in association with b-jet)
- Irreducible lepto-quark signatures:
  $pp \to$ LQ LQ $\to j(b)\mu^+ \; j(b)\mu^-$ (pair production)
  $pp \to$ LQ $\mu \to j(b)\mu^+\mu^-$ (single production)