Probing the B Anomalies at a Muon Collider

Wolfgang Altmannshofer
waltmann@ucsc.edu

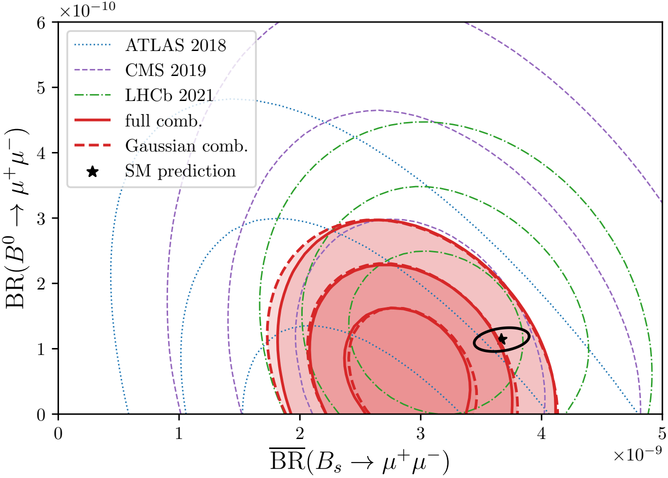
UC SANTA CRUZ

Muon Collider Physics and Detector Workshop
Virtual world, June 2 - 4, 2021

Overview of the Anomalies

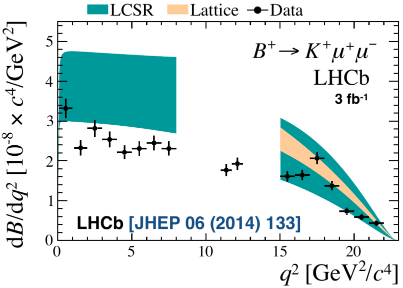
The $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$ Decays

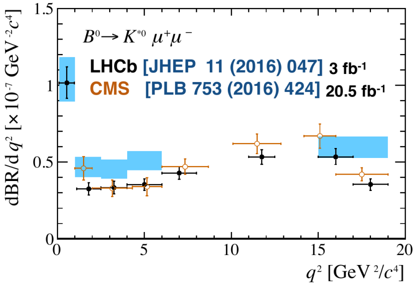
WA, Stangl 2103.13370; combination of LHCb-paper-2021-007, CMS 1910.12127, ATLAS 1812.03017

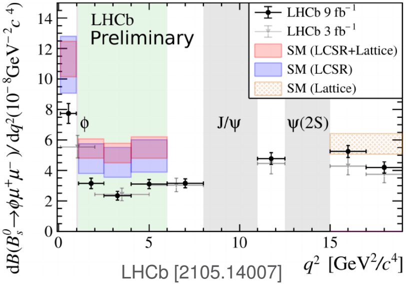


$\sim 2\sigma$ tension between SM and experiment

Semileptonic Branching Ratios





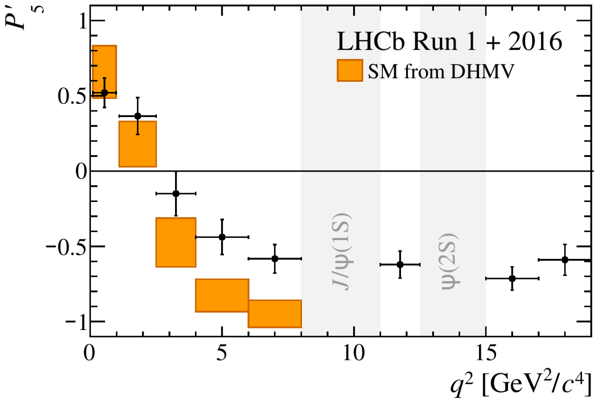


LHCb [2105.14007]

Experimental results for
$BR(B \to K\mu\mu)$
$BR(B \to K^*\mu\mu)$
$BR(B_s \to \phi\mu\mu)$
are consistently low
across many q^2 bins

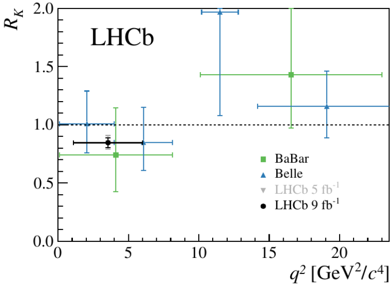
$P_5' \sim$ a moment of the $B \to K^* \mu^+ \mu^-$ angular distribution

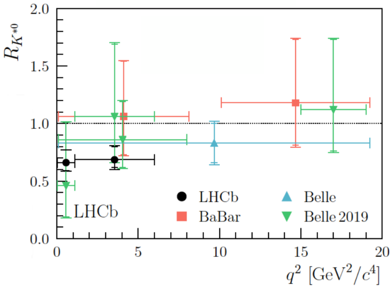
LHCb 2003.04831



Anomaly persists in the latest update of $B^0 \to K^{*0} \mu^+ \mu^-$ with 2016 data.
(Anomaly also seen in $B^\pm \to K^{*\pm} \mu^+ \mu^-$ LHCb 2012.13241)

Evidence for Lepton Flavor Universality Violation





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

$$R_K^{[1,6]} = 0.846^{+0.042\,+0.013}_{-0.039\,-0.012}$$

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

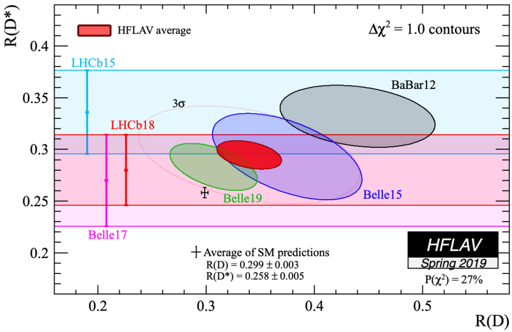
$$R_{K^*}^{[1.1,6]} = 0.69^{+0.11}_{-0.07} \pm 0.05$$

R_K update, LHCb 2103.11769
deviation by 3.1σ
from the SM prediction

also: $R_{pK}^{[0.1,6]} = 0.86^{+0.14}_{-0.11} \pm 0.05$

LFU in Charged Current Decays: R_D and R_{D^*}

world average from the heavy flavor averaging group



$$R_D = \frac{BR(B \to D\tau\nu)}{BR(B \to D\ell\nu)}$$

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

$\ell = \mu, e$ (BaBar/Belle)

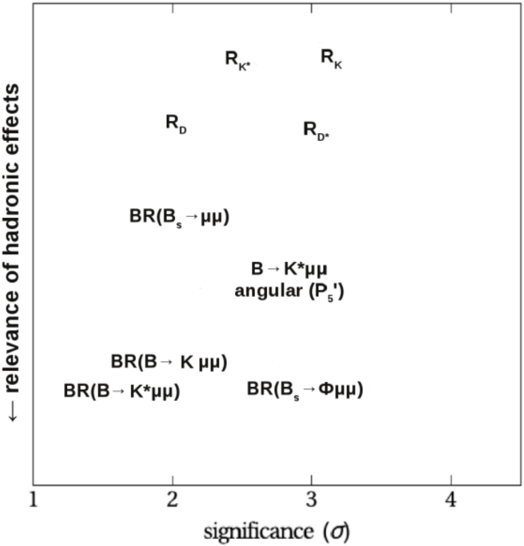
$\ell = \mu$ (LHCb)

$$R_D^{\rm exp} = 0.340 \pm 0.027 \pm 0.013 \ , \qquad R_{D^*}^{\rm exp} = 0.295 \pm 0.011 \pm 0.008$$

$$R_D^{\rm SM} = 0.299 \pm 0.003 \ , \qquad R_{D^*}^{\rm SM} = 0.258 \pm 0.005$$

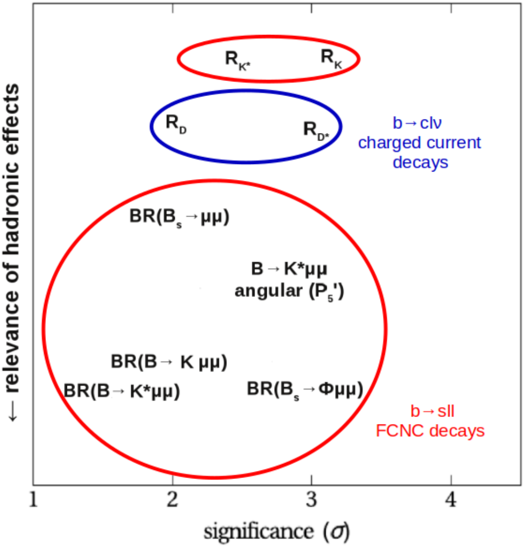
discrepancy with the SM by $\sim 3.1\sigma$

B Decay Anomalies 2021



(inspired by Zoltan Ligeti)

B Decay Anomalies 2021



(inspired by

Zoltan Ligeti)

What Could It Be?

	$B_s \to \mu\mu$ rate	semileptonic rates	angular observables	LFU ratios

What Could It Be?

	$B_s \to \mu\mu$ rate	semileptonic rates	angular observables	LFU ratios
experimental issues?	?	?	?	?

What Could It Be?

	$B_s \to \mu\mu$ rate	semileptonic rates	angular observables	LFU ratios
experimental issues?	?	?	?	?
statistical fluctuations?	✓	✓	✓	✓

What Could It Be?

	$B_s \to \mu\mu$ rate	semileptonic rates	angular observables	LFU ratios
experimental issues?	?	?	?	?
statistical fluctuations?	✓	✓	✓	✓
parametric uncertainties?	✓	✓	✗	✗

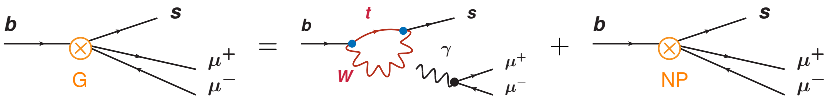
What Could It Be?

	$B_s \to \mu\mu$ rate	semileptonic rates	angular observables	LFU ratios
experimental issues?	?	?	?	?
statistical fluctuations?	✓	✓	✓	✓
parametric uncertainties?	✓	✓	✗	✗
underestimated hadronic effects?	✗	✓	✓	✗

What Could It Be?

	$B_s \to \mu\mu$ rate	semileptonic rates	angular observables	LFU ratios
experimental issues?	?	?	?	?
statistical fluctuations?	✓	✓	✓	✓
parametric uncertainties?	✓	✓	✗	✗
underestimated hadronic effects?	✗	✓	✓	✗
New Physics?	✓	✓	✓	✓

Implications for New Physics



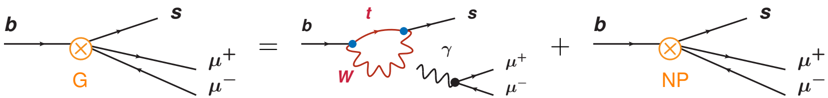
$$G \sim \frac{1}{16\pi^2} \frac{g^4}{m_W^2} \frac{m_t^2}{m_W^2} V_{tb} V_{ts}^* + \frac{C_{NP}}{\Lambda_{NP}^2}$$

measure precisely

calculate precisely the SM contribution

get information on NP coupling and scale

New Physics in Rare B Decays



$$G \sim \frac{1}{16\pi^2} \frac{g^4}{m_W^2} \frac{m_t^2}{m_W^2} V_{tb} V_{ts}^* + \frac{C_{NP}}{\Lambda_{NP}^2}$$

measure precisely

calculate precisely the SM contribution

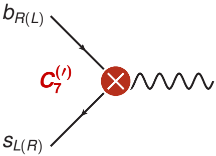
get information on NP coupling and scale

Anomalies in rare B decays could establish
a new scale in particle physics

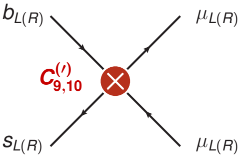
Model Independent New Physics Analysis

$$\mathcal{H}_{\text{eff}}^{b\to s} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

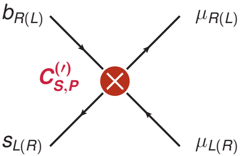
magnetic dipole operators



semileptonic operators



scalar operators



$C_7^{(\prime)}(\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}$, $C_9^{(\prime)}(\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\mu}\gamma^\mu\mu)$, $C_S^{(\prime)}(\bar{s}P_{R(L)}b)(\bar{\mu}P_{L(R)}\mu)$

$C_{10}^{(\prime)}(\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\mu}\gamma^\mu\gamma_5\mu)$

neglecting tensor operators and additional scalar operators

(secretly dimension 8: Alonso, Grinstein, Martin Camalich 1407.7044) many processes and many observables are modified simultaneously

$\Rightarrow$ global fits are required

most recent papers:

Geng, Grinstein, Jäger, Li, Martin Camalich, Shi 2103.12738

WA, Stangl 2103.13370

Cornella, Faroughy, Fuentes-Martin, Isidori, Neubert 2103.16558

Lancierini, Isidori, Owen, Serra 2104.05631

Alguero, Capdevila, Descotes-Genon, Matias, Novoa-Brunet 2104.08921

Hurth, Mahmoudi, Martinez Santos, Neshatpour 2104.10058

WA, Stangl 2103.13370

	LFU, $B_s \to \mu\mu$		all rare B decays	
Wilson coefficient	best fit	pull	best fit	pull
C_9^{bsee}	$+0.74^{+0.20}_{-0.19}$	4.1σ		
C_{10}^{bsee}	$-0.67^{+0.17}_{-0.18}$	4.2σ		
$C_9^{\prime bse}$	$+0.36^{+0.18}_{-0.17}$	2.1σ		
$C_{10}^{\prime bsee}$	$-0.31^{+0.16}_{-0.16}$	2.0σ		
$C_9^{bsee} = C_{10}^{bsee}$	$-1.39^{+0.26}_{-0.26}$	4.0σ		
$C_9^{bsee} = -C_{10}^{bsee}$	$+0.37^{+0.10}_{-0.10}$	4.2σ		

for comparison: $C_9^{\text{SM}} \simeq 4$, $C_{10}^{\text{SM}} \simeq -4$

New Physics in Electrons

WA, Stangl 2103.13370

	LFU, $B_s \to \mu\mu$		all rare B decays	
Wilson coefficient	best fit	pull	best fit	pull
C_9^{bsee}	$+0.74^{+0.20}_{-0.19}$	4.1σ	$+0.75^{+0.20}_{-0.19}$	4.1σ
C_{10}^{bsee}	$-0.67^{+0.17}_{-0.18}$	4.2σ	$-0.66^{+0.16}_{-0.17}$	4.3σ
$C_9^{\prime bse}$	$+0.36^{+0.18}_{-0.17}$	2.1σ	$+0.40^{+0.19}_{-0.18}$	2.3σ
$C_{10}^{\prime bsee}$	$-0.31^{+0.16}_{-0.16}$	2.0σ	$-0.30^{+0.15}_{-0.16}$	2.0σ
$C_9^{bsee} = C_{10}^{bsee}$	$-1.39^{+0.26}_{-0.26}$	4.0σ	$-1.28^{+0.24}_{-0.23}$	4.1σ
$C_9^{bsee} = -C_{10}^{bsee}$	$+0.37^{+0.10}_{-0.10}$	4.2σ	$+0.37^{+0.10}_{-0.10}$	4.3σ

for comparison: $C_9^{\text{SM}} \simeq 4$, $C_{10}^{\text{SM}} \simeq -4$

New Physics in Muons

WA, Stangl 2103.13370

	LFU, $B_s \to \mu\mu$		all rare B decays	
Wilson coefficient	best fit	pull	best fit	pull
$C_9^{bs\mu\mu}$	$-0.74^{+0.20}_{-0.21}$	4.1σ		
$C_{10}^{bs\mu\mu}$	$+0.60^{+0.14}_{-0.14}$	4.7σ		
$C_9^{\prime bs\mu\mu}$	$-0.32^{+0.16}_{-0.17}$	2.0σ		
$C_{10}^{\prime bs\mu\mu}$	$+0.06^{+0.12}_{-0.12}$	0.5σ		
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$+0.43^{+0.18}_{-0.18}$	2.4σ		
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.35^{+0.08}_{-0.08}$	4.6σ		

New Physics in Muons

WA, Stangl 2103.13370

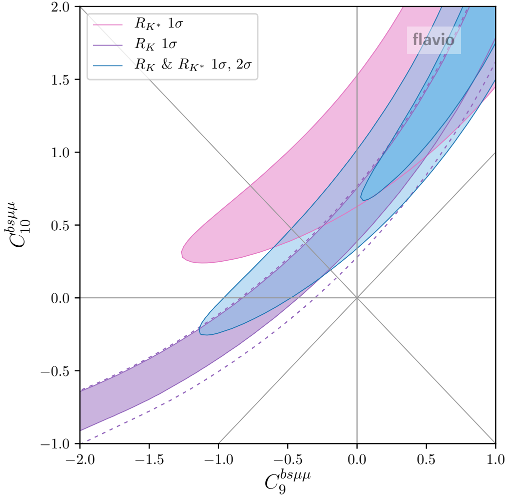
Wilson coefficient	LFU, $B_s \to \mu\mu$ best fit	LFU, $B_s \to \mu\mu$ pull	all rare B decays best fit	all rare B decays pull
$C_9^{bs\mu\mu}$	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.80^{+0.14}_{-0.14}$	5.7σ
$C_{10}^{bs\mu\mu}$	$+0.60^{+0.14}_{-0.14}$	4.7σ	$+0.55^{+0.12}_{-0.12}$	4.8σ
$C_9^{\prime bs\mu\mu}$	$-0.32^{+0.16}_{-0.17}$	2.0σ	$-0.14^{+0.13}_{-0.13}$	1.0σ
$C_{10}^{\prime bs\mu\mu}$	$+0.06^{+0.12}_{-0.12}$	0.5σ	$+0.04^{+0.10}_{-0.10}$	0.4σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$+0.43^{+0.18}_{-0.18}$	2.4σ	$-0.01^{+0.12}_{-0.12}$	0.1σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.35^{+0.08}_{-0.08}$	4.6σ	$-0.41^{+0.07}_{-0.07}$	5.9σ

high preference for non-standard muonic C_9 and/or C_{10}:

$\sqrt{\Delta\chi^2} \sim 6$ if you trust our theory errors, $\sqrt{\Delta\chi^2} \gtrsim 4$ if you don't

Global significance with look elsewhere effect $\sim 3.9\sigma$ (Lancierini et al. 2104.05631)

Fits of Pairs of Wilson Coefficients



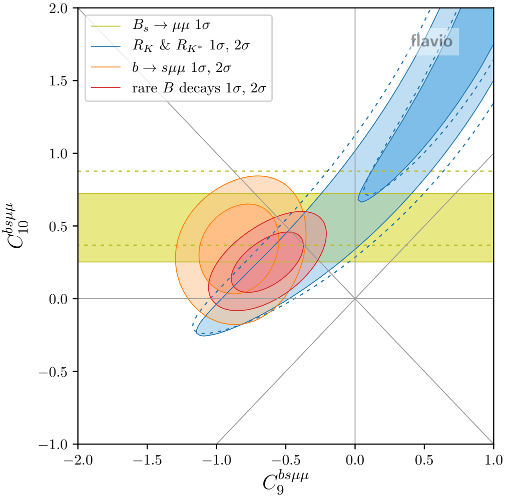
WA, Stangl 2103.13370

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

$$C_{10}^{bs\mu\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \gamma_5 \mu)$$

- LFU ratios prefer non-standard C_{10}, but large degeneracy

Fits of Pairs of Wilson Coefficients



WA, Stangl 2103.13370

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

$$C_{10}^{bs\mu\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \gamma_5 \mu)$$

- LFU ratios prefer non-standard C_{10}, but large degeneracy
- $B_s \to \mu^+\mu^-$ branching ratio shows slight preference for non-standard C_{10}
- $b \to s\mu\mu$ observables prefer non-standard C_9
- best fit point

$$C_9^{bs\mu\mu} \simeq -0.63$$

$$C_{10}^{bs\mu\mu} \simeq +0.25$$

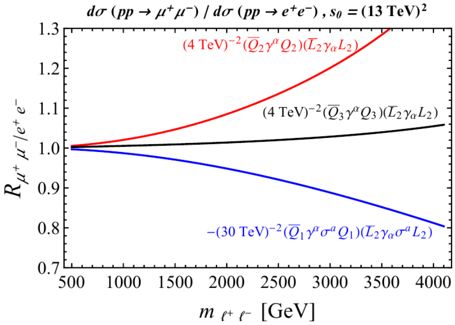
Implications for the New Physics Scale

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

(MFV = Minimal Flavor Violation)

Testing the Anomalies at a Muon Collider

Greljo, Marzocca 1704.09015



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

$pp \to \mu^+\mu^-$ vs. $pp \to e^+e^-$

$$C_9^{bs\mu\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha\mu) \qquad C_{10}^{bs\mu\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha\gamma_5\mu)$$

- operators are currently probed up to scales of 2.5 TeV
- can be probed up to $\sim$ 4 TeV with 3/ab
- order of magnitude is missing to probe the $b \to s\ell\ell$ anomalies

Model Independent Approach at a Muon Collider

[I am not aware of any study. Below a few naive thoughts.]

$$C_9^{bs\mu\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \mu) \qquad C_{10}^{bs\mu\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \gamma_5 \mu)$$

- At a muon collider look for $\mu^+\mu^- \to bs$
- Main background probably from $\mu^+\mu^- \to bb$ and $\mu^+\mu^- \to qq$ with misidentified jets. Mis-ID rate $\mathcal{O}(1\%)$?
- (Background from $WW \to bs$ negligible(?) GIM suppression m_t^4/s^2)

Model Independent Approach at a Muon Collider

[I am not aware of any study. Below a few naive thoughts.]

$$C_9^{bs\mu\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \mu) \qquad C_{10}^{bs\mu\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \gamma_5 \mu)$$

- At a muon collider look for $\mu^+\mu^- \to bs$
- Main background probably from $\mu^+\mu^- \to bb$ and $\mu^+\mu^- \to qq$ with misidentified jets. Mis-ID rate $\mathcal{O}(1\%)$?
- (Background from $WW \to bs$ negligible(?) GIM suppression m_t^4/s^2)
- Very naive estimate for signal over background

$$\frac{S}{B} \sim \frac{s^2}{g^4 \Lambda_{\text{NP}}^4} \frac{1}{\epsilon_{\text{mis-ID}}} \sim \left(\frac{\sqrt{s}}{10 \text{ TeV}} \right)^4$$

Model Independent Approach at a Muon Collider

[I am not aware of any study. Below a few naive thoughts.]

$$C_9^{bs\mu\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \mu) \qquad C_{10}^{bs\mu\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \gamma_5 \mu)$$

- At a muon collider look for $\mu^+\mu^- \to bs$
- Main background probably from $\mu^+\mu^- \to bb$ and $\mu^+\mu^- \to qq$ with misidentified jets. Mis-ID rate $\mathcal{O}(1\%)$?
- (Background from $WW \to bs$ negligible(?) GIM suppression m_t^4/s^2)
- Very naive estimate for signal over background

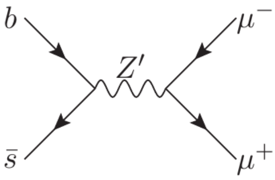
$$\frac{S}{B} \sim \frac{s^2}{g^4 \Lambda_{\rm NP}^4} \frac{1}{\epsilon_{\text{mis-ID}}} \sim \left(\frac{\sqrt{s}}{10 \text{ TeV}} \right)^4$$

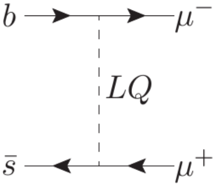
- Because of $SU(2)_L$ also expect operators with top quarks
  Search for single top production $\mu^+\mu^- \to tc$?
- Polarized beams to identify the chirality structure of operators?

Simplified Models

possible tree level explanations:

- *Z′* Bosons
- Lepto-Quarks

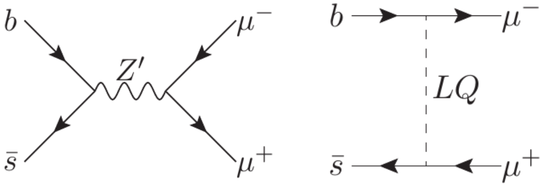




Simplified Models

possible tree level explanations:

- Z' Bosons
- Lepto-Quarks



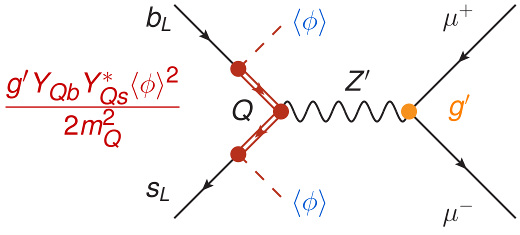
upper bounds on flavor violating couplings from B_s mixing imply upper bounds on the particle masses

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

My Favorite Z' Model

Z' based on gauging $L_\mu - L_\tau$ (He, Joshi, Lew, Volkas PRD 43, 22-24)
with effective flavor violating couplings to quarks

WA, Gori, Pospelov, Yavin 1403.1269; WA, Yavin 1508.07009

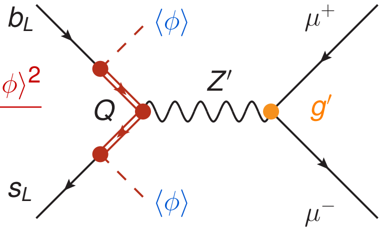


Q: heavy vectorlike fermions with mass $\sim 1 - 10$ TeV
ϕ: scalar that breaks $L_\mu - L_\tau$

Z' based on gauging $L_\mu - L_\tau$ (He, Joshi, Lew, Volkas PRD 43, 22-24)
with effective flavor violating couplings to quarks

WA, Gori, Pospelov, Yavin 1403.1269; WA, Yavin 1508.07009

$$\frac{g' Y_{Qb} Y^*_{Qs} \langle\phi\rangle^2}{2 m_Q^2}$$



predicted Lepton Universality Violation!

Q: heavy vectorlike fermions with mass $\sim 1 - 10$ TeV
ϕ: scalar that breaks $L_\mu - L_\tau$

Probing the Z' Parameter Space

Neutrino Tridents

B_s mixing

$(g-2)_\mu$

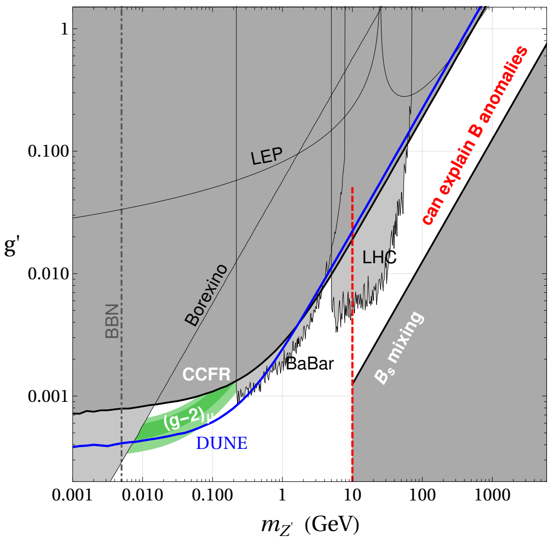
νe scattering

$Z \to \ell\ell$

$Z \to 4\mu$

$e^+e^- \to 4\mu$

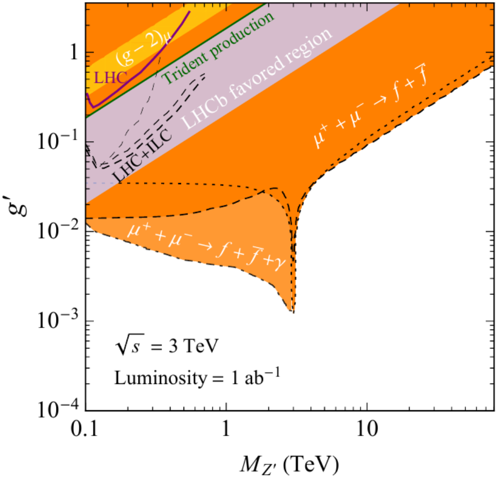
WA, Gori, Martin-Albo, Sousa, Wallbank 1902.06765



$L_\mu - L_\tau$ at a Muon Collider

- The Z' of gauged $L_\mu - L_\tau$ is hard to miss at a muon collider
- For heavy Z', look for 4μ contact interactions
- For light Z', look for $\mu\mu \to \gamma Z'$

Huang, Jana, Queiroz, Rodejohann 2101.04956



Leptoquarks at a Muon Collider

- pair production

$$\mu^+\mu^- \to LQ\ LQ$$

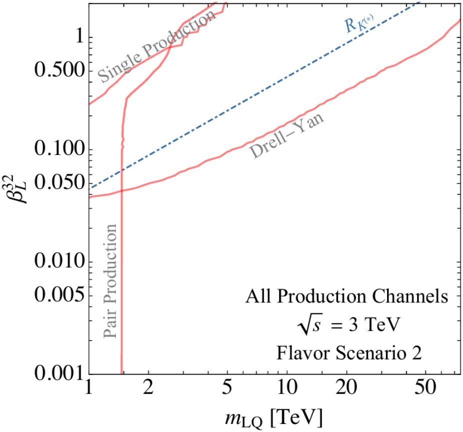
- single production

$$\mu V \to LQ + jet$$

- Drell-Yan with t-channel LQ

$$\mu^+\mu^- \to bb$$

$$\mu^+\mu^- \to ss$$



Asadi, Capdevilla, Cesarotti, Homiller 2104.05720

Leptoquarks at a Muon Collider

- pair production

$$\mu^+\mu^- \to LQ\,LQ$$

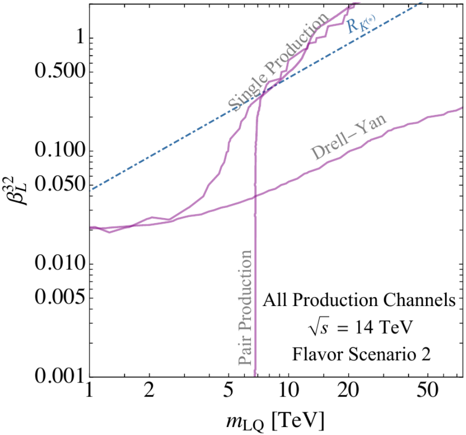
- single production

$$\mu V \to LQ + jet$$

- Drell-Yan with t-channel LQ

$$\mu^+\mu^- \to bb$$

$$\mu^+\mu^- \to ss$$



Asadi, Capdevilla, Cesarotti, Homiller 2104.05720

Leptoquarks at a Muon Collider

- pair production

$$\mu^+\mu^- \to LQ\,LQ$$

- single production

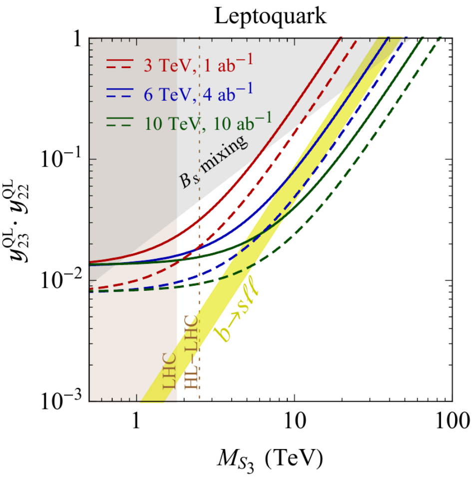
$$\mu V \to LQ + jet$$

- Drell-Yan with t-channel LQ

$$\mu^+\mu^- \to bb$$

$$\mu^+\mu^- \to ss$$

$$\mu^+\mu^- \to bs$$



Huang, Jana, Queiroz, Rodejohann 2103.01617

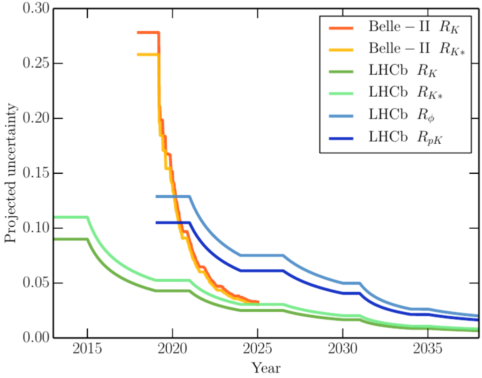
Summary

- Rare b decay data shows persistent discrepancies with SM predictions.
- If significance of LFU violation continues to grow with more statistics $\Rightarrow$ clear indication of new physics.
- The discrepancies point to $bs\mu\mu$ 4-fermion interactions with a new physics scale of $\sim$ 35 TeV.
- Model independent test at a muon collider: $\mu^+\mu^- \to bs$
- Z' models and lepto-quark models should be in reach of a muon collider with $\sqrt{s}$ of several TeV.

Back Up

Future Prospects for R_K and R_{K^*}

- LHCb and Belle II can push uncertainties down to few percent
- (can ATLAS and CMS say something?)
- with sufficient statistics, LFU of angular distrib. can be tested



Bifani et al. 1809.06229

- LHCb can cross check in other modes:

$$R_\phi \ , \quad R_{pK} \ , \quad \ldots$$