The State of New Physics in Rare B Decays

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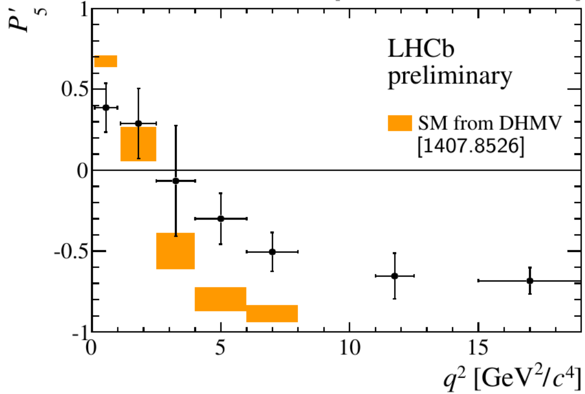
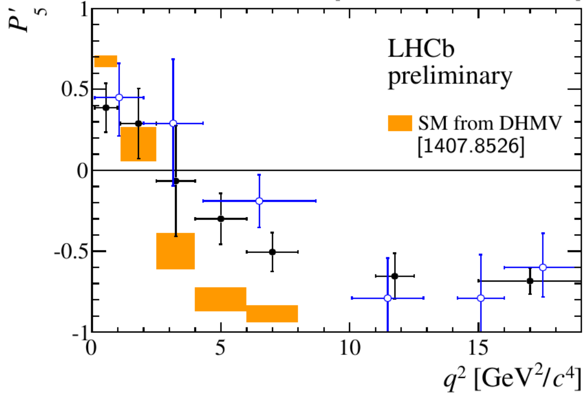


$$P'_5 = \frac{S_5}{\sqrt{F_L(1 - F_L)}}$$

2.9σ in [4,6] GeV^2 bin (+2.9σ in [6,8] GeV^2 bin)

[LHCb-CONF-2015-002]



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2.9σ in [4,6] GeV^2 bin (+2.9σ in [6,8] GeV^2 bin)

Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[2, 4.3]$	0.81 ± 0.02	0.26 ± 0.19	ATLAS	$+2.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[4, 6]$	0.74 ± 0.04	0.61 ± 0.06	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	$[4, 6]$	-0.33 ± 0.03	-0.15 ± 0.08	LHCb	-2.2
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[1.1, 6]$	-0.44 ± 0.08	-0.05 ± 0.11	LHCb	-2.9
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[4, 6]$	-0.77 ± 0.06	-0.30 ± 0.16	LHCb	-2.8
$B^- \to K^{*-}\mu^+\mu^-$	$10^7\ \frac{d\text{BR}}{dq^2}$	$[4, 6]$	0.54 ± 0.08	0.26 ± 0.10	LHCb	$+2.1$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8\ \frac{d\text{BR}}{dq^2}$	$[0.1, 2]$	2.71 ± 0.50	1.26 ± 0.56	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8\ \frac{d\text{BR}}{dq^2}$	$[16, 23]$	0.93 ± 0.12	0.37 ± 0.22	CDF	$+2.2$
$B_s \to \phi\mu^+\mu^-$	$10^7\ \frac{d\text{BR}}{dq^2}$	$[1, 6]$	0.48 ± 0.06	0.23 ± 0.05	LHCb	$+3.1$

\+ indication for lepton flavor non-universality

$$R_K = \frac{\text{BR}(B \to K\mu^+\mu^-)_{[1,6]}}{\text{BR}(B \to Ke^+e^-)_{[1,6]}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

What Could It Be?

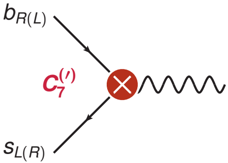
	branching ratios	angular observables	LFU ratios
parametric uncertainties?	✓	✗	✗
hadronic effects?	✓	✓	✗
New Physics?	✓	✓	✓

See also talks by Andi Crivellin, Roman Zwicky, Sebastian Jäger, Gudrun Hiller, Marco Nardecchia, Avelino Vicente, Andrzej Buras

New Physics in $b \to s$ Decays

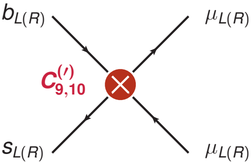
$$\mathcal{H}_{\text{eff}}^{b\to s} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

magnetic dipole operators



$\propto 1/q^2$

semileptonic operators



$\propto 1$

	C_7, C_7'	C_9, C_9'	C_{10}, C_{10}'
$B \to (X_s, K^*)\,\gamma$	★		
$B \to (X_s, K, K^*)\,\mu^+\mu^-$	★	★	★
$B_s \to \phi\,\mu^+\mu^-$	★	★	★
$B_s \to \mu^+\mu^-$			★

neglecting tensor operators
(secretly dimension 8)

neglecting scalar operators
(strongly constrained by
$B_s \to \mu^+\mu^-$)

(in linear EFT)

Global Fits of $b \to s$ Data

many processes and many observables are modified simultaneously

$\Rightarrow$ global fits are required

WA, Straub, Paradisi '11; Bobeth, Hiller, van Dyk, Wacker '11; WA, Straub '12, '13, '14;
Beaujean, Bobeth, van Dyk, Wacker; '12; Descotes-Genon, Matias, Virto '13, '14;
Beaujean, Bobeth, van Dyk '13; Hurth, Mahmoudi '13; Ghosh, Nardecchia, Renner '14;
Hurth, Mahmoudi, Neshatpour '14; Jäger, Martin Camalich '14; ...

We construct a χ^2 out of 91 measurements of 79 different observables
taking into account all theory correlations
in particular from form factors (Bharucha, Straub, Zwicky '15)

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

Global Fit: Individual Wilson Coefficients

$b \to s\mu^+\mu^-$ data

Coeff.	best fit	1σ	2σ	$\sqrt{\chi^2_{\text{b.f.}} - \chi^2_{\text{SM}}}$	p [%]
C_7^{NP}	-0.04	$[-0.07, -0.01]$	$[-0.10, 0.02]$	1.42	2.4
C_7'	0.01	$[-0.04, 0.07]$	$[-0.10, 0.12]$	0.24	1.8
C_9^{NP}	-1.07	$[-1.32, -0.81]$	$[-1.54, -0.53]$	3.70	11.3
C_9'	0.21	$[-0.04, 0.46]$	$[-0.29, 0.70]$	0.84	2.0
C_{10}^{NP}	0.50	$[0.24, 0.78]$	$[-0.01, 1.08]$	1.97	3.2
C_{10}'	-0.16	$[-0.34, 0.02]$	$[-0.52, 0.21]$	0.87	2.0
$C_9^{\text{NP}} = C_{10}^{\text{NP}}$	-0.22	$[-0.44, 0.03]$	$[-0.64, 0.33]$	0.89	2.0
$C_9^{\text{NP}} = -C_{10}^{\text{NP}}$	-0.53	$[-0.71, -0.35]$	$[-0.91, -0.18]$	3.13	7.1
$C_9' = C_{10}'$	-0.10	$[-0.36, 0.17]$	$[-0.64, 0.43]$	0.36	1.8
$C_9' = -C_{10}'$	0.11	$[-0.01, 0.22]$	$[-0.12, 0.33]$	0.93	2.0

$\chi^2_{\text{SM}} = 116.9$ for 88 measurements ($p = 2.14\%$)

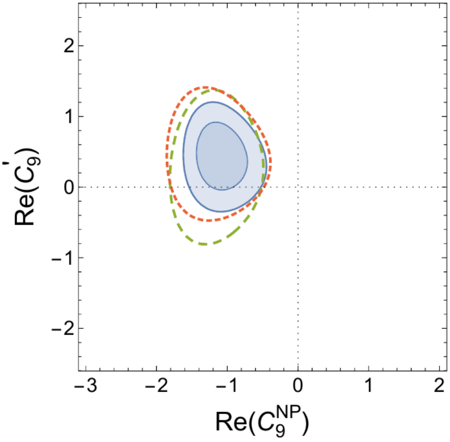
Global Fit: Individual Wilson Coefficients

$b \to s\mu^+\mu^-$ data $\quad + \quad$ $b \to se^+e^-$ data

Coeff.	best fit	1σ	2σ	$\sqrt{\chi^2_{\text{b.f.}} - \chi^2_{\text{SM}}}$	p [%]
C_7^{NP}	-0.04	$[-0.07, -0.02]$	$[-0.10, 0.01]$	1.52	1.1
C_7'	0.00	$[-0.05, 0.06]$	$[-0.11, 0.11]$	0.05	0.8
C_9^{NP}	-1.12	$[-1.34, -0.88]$	$[-1.55, -0.63]$	4.33	10.6
C_9'	-0.04	$[-0.26, 0.18]$	$[-0.49, 0.40]$	0.18	0.8
C_{10}^{NP}	0.65	$[0.40, 0.91]$	$[0.17, 1.19]$	2.75	2.5
C_{10}'	-0.01	$[-0.19, 0.16]$	$[-0.36, 0.33]$	0.09	0.8
$C_9^{\text{NP}} = C_{10}^{\text{NP}}$	-0.20	$[-0.41, 0.05]$	$[-0.60, 0.33]$	0.82	0.8
$C_9^{\text{NP}} = -C_{10}^{\text{NP}}$	-0.57	$[-0.73, -0.41]$	$[-0.90, -0.27]$	3.88	6.8
$C_9' = C_{10}'$	-0.08	$[-0.33, 0.17]$	$[-0.58, 0.41]$	0.32	0.8
$C_9' = -C_{10}'$	-0.00	$[-0.11, 0.10]$	$[-0.22, 0.20]$	0.03	0.8

$\chi^2_{\text{SM}} = 125.8$ for 91 measurements ($p = 0.92\%$)

Global Fit: C_9 - C'_9 Plane



WA, Straub 1411.3161 / 1503.06199

$$O_9^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu)$$

muonic vector current

- best fit result

$$C_9^{NP} = -1.1 \pm 0.3$$
$$C'_9 = +0.5 \pm 0.4$$

- pull: 4.0
- p-value: 12.5%

(only $b \to s\mu^+\mu^-$ data)

Distinguishing New Physics from Hadronic Effects

	LFU violation
hadronic effects?	✗
New Physics?	✓

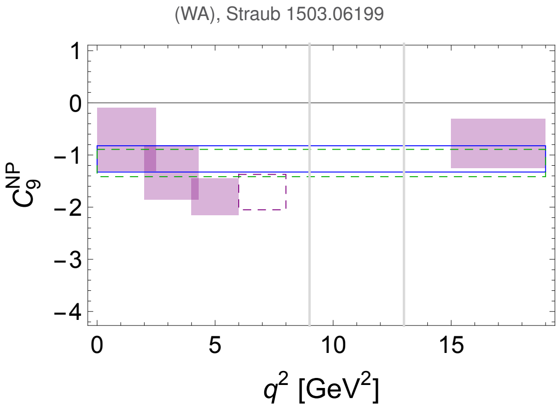
Distinguishing New Physics from Hadronic Effects

	LFU violation	CP violation
hadronic effects?	✗	✗
New Physics?	✓	✓

Distinguishing New Physics from Hadronic Effects

	LFU violation	CP violation	non-trivial q^2 dependence
hadronic effects?	✗	✗	✓
New Physics?	✓	✓	✗

q^2 Dependence of the Effect



compatible with a q^2 independent short distance contribution from new physics

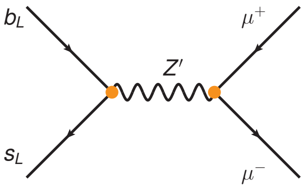
preferred value for C_9 seems to increase closer to the J/ψ
$\rightarrow$ indication for a charm loop effect?

Implications for the New Physics Scale

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	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2}\ V_{tb}V_{ts}^*\ (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 0.6\ \text{TeV} \times (C_9^{\rm NP})^{-1/2}$

(assumes New Physics has O(1) coupling to muons)

Models with Flavor Changing Z' Bosons



Z' models:

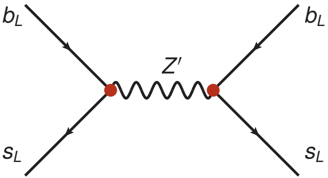
(WA, Straub '13/'14; Gauld, Goertz, Haisch '13; Buras et al. '13/'14; WA, Gori, Pospelov, Yavin '14; Glashow, Guadagnoli, Lane '14; Crivellin, D'Ambrosio, Heeck '14/'15; Niehoff, Stangl, Straub '15; Aristizabal Sierra, Staub, Vicente '15; Boucenna, Valle, Vicente '15; ...)

alternative option: lepto-quarks

(Hiller, Schmaltz '14; Gripaios, Nardecchia, Renner '14; Buras et al. '14; Becirevic, Fajfer, Kosnik '15; ...)

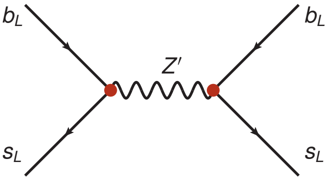
$$C_9^{\rm NP} = \frac{\Delta_L^{bs}\Delta_V^{\mu\mu}}{V_{tb}V_{ts}^*}\,\frac{v^2}{M_{Z'}^2}\,\frac{4\pi^2}{e^2} \simeq \frac{\Delta_L^{bs}\Delta_V^{\mu\mu}}{V_{tb}V_{ts}^*}\,\frac{(5~\text{TeV})^2}{M_{Z'}^2}$$

Constraints from B_s Mixing



- flavor changing Z' contributes also to B_s mixing at tree level

$$\frac{M_{12}}{M_{12}^{\text{SM}}} - 1 = \frac{v^2}{M_{Z'}^2}(\Delta_L^{bs})^2 \left(\frac{g_2^2}{16\pi^2}(V_{tb}V_{ts}^*)^2 S_0 \right)^{-1}$$



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- constraint on the Z' mass and the flavor changing coupling (allowing for 10% NP in B_s mixing)

$$\frac{M_{Z'}}{|\Delta_L^{bs}|} \gtrsim 244 \text{ TeV} \simeq \frac{10 \text{ TeV}}{|V_{tb}V_{ts}^*|}$$

Constraints from LEP

- assume the couplings of the Z' are lepton flavor universal
- LEP bounds on four lepton contact interactions

$$\mathcal{L} = \frac{4\pi}{\Lambda_\pm^2}(\bar{e}\gamma_\mu e)(\bar{\ell}\gamma^\mu \ell)$$

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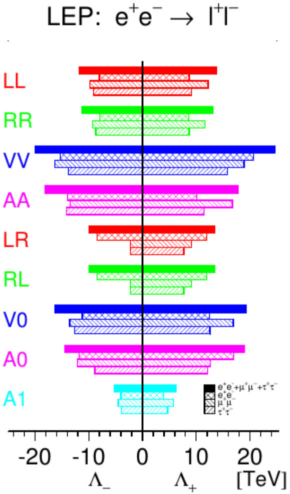
- LEP bounds on four lepton contact interactions

$$\mathcal{L} = \frac{4\pi}{\Lambda_\pm^2}(\bar{e}\gamma_\mu e)(\bar{\ell}\gamma^\mu \ell)$$

- constraint on the Z' mass and the vector coupling to leptons

$$\frac{M_{Z'}}{|\Delta_V^{\ell\ell}|} \gtrsim 3.5 \text{ TeV}$$



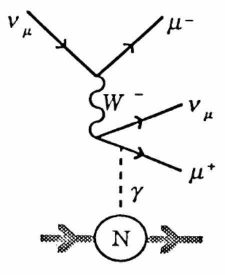
LEP Electroweak Working Group

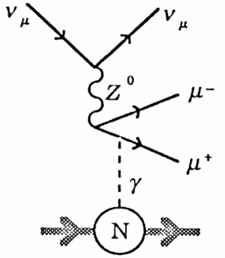
1302.3415

Constraints from Neutrino Tridents

- LEP bounds are avoided if the Z' does not couple to electrons
- "irreducible" constraint from neutrino tridents
- the Z' contributes to the trident cross section
  (WA, Gori, Pospelov, Yavin, 1403.1269 and 1406.2332)

$$\frac{\sigma}{\sigma_{\rm SM}} = \frac{1}{1+(1+4s_W^2)^2}\left[1+\left(1+4s_W^2+\frac{v^2(\Delta_V^{\mu\mu})^2}{2M_{Z'}^2}\right)^2\right]$$





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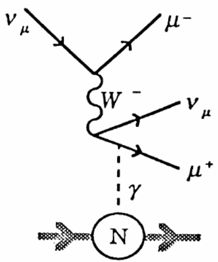
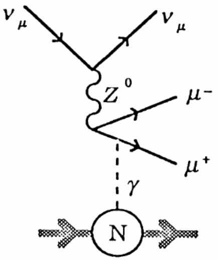
experimental measurement

$$\sigma/\sigma_{\text{SM}} = 0.82 \pm 0.28$$ (CCFR, PRL66 (1991) 3117)

$$\frac{M_{Z'}}{|\Delta_V^{\mu\mu}|} \gtrsim 0.27 \text{ TeV}$$

can be improved at Minos+, LBNF ?





Maximally Allowed Effect in C_9

$$|C_9^{\text{NP}}| = \frac{|\Delta_L^{bs}|}{M_{Z'}} \frac{|\Delta_V^{\mu\mu}|}{M_{Z'}} \frac{v^2}{|V_{tb}V_{ts}^*|} \frac{4\pi^2}{e^2} \lesssim \Bigg\{$$

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quark coupling constrained by

B_s mixing

muon coupling constrained by

1) LEP bounds on 4 lepton contact interactions
(in the case of lepton flavor universality)

Maximally Allowed Effect in C_9

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quark coupling
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1) LEP bounds on 4 lepton contact interactions
(in the case of lepton flavor universality)

2) neutrino trident production
(in the case of muon-specific couplings)

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(compare to the best fit value $C_9^{\rm NP} \simeq -1.1$)

quark coupling constrained by

B_s mixing

muon coupling constrained by

1) LEP bounds on 4 lepton contact interactions
(in the case of lepton flavor universality)

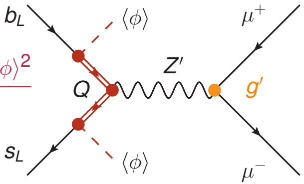
2) neutrino trident production
(in the case of muon-specific couplings)

muon number - tau number
is anomaly free
gauging it leads to the wanted
vector couplings with muons

$$\mathcal{L} \supset g'(\bar{\mu}\gamma^\mu\mu - \bar{\tau}\gamma^\mu\tau)Z'_\mu$$

couple the Z' to quarks only
indirectly, by mixing with
heavy vector-like fermions
charged under $U(1)'$

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



WA, Gori, Pospelov, Yavin 1403.1269

A Simple Model Based on Gauged $L_\mu - L_\tau$

muon number - tau number
is anomaly free
gauging it leads to the wanted
vector couplings with muons

$$\mathcal{L} \supset g'(\bar\mu\gamma^\mu\mu - \bar\tau\gamma^\mu\tau)Z'_\mu$$

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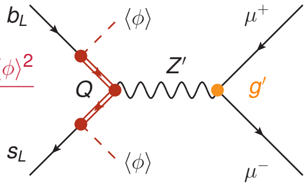
$$\frac{g' Y_{Qb} Y_{Qs}^* \langle\phi\rangle^2}{2m_Q^2}$$



contributions to $B \to K^* \mu^+\mu^-$ are
independent of the $U(1)'$ gauge
coupling and the Z' mass

$$C_9 \simeq \frac{Y_{Qb} Y_{Qs}^*}{2m_Q^2} \quad , \quad C_9' \simeq -\frac{Y_{Db} Y_{Ds}^*}{2m_D^2}$$

WA, Gori, Pospelov, Yavin 1403.1269

$(g-2)$ of the muon

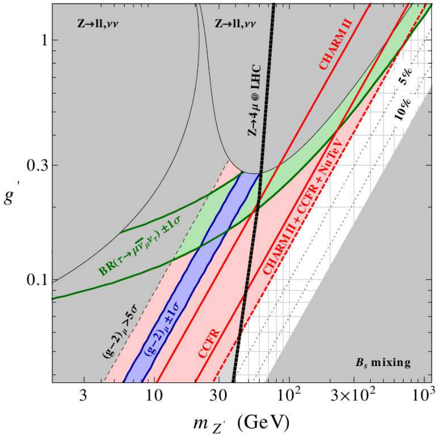
tau decays

Z couplings to leptons

$Z \to 4\mu$ @ LHC

B_s mixing

neutrino trident production



WA, Gori, Pospelov, Yavin 1403.1269

Probing the Z'

$(g-2)$ of the muon

tau decays

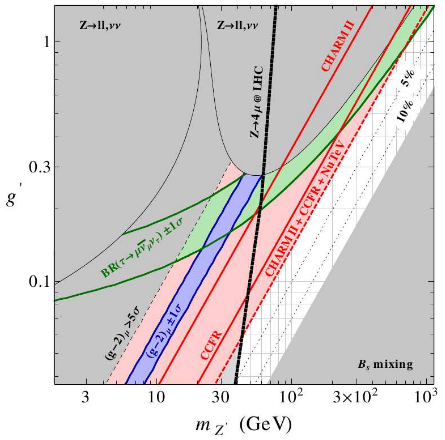
Z couplings to leptons

$Z \to 4\mu$ @ LHC

B_s mixing

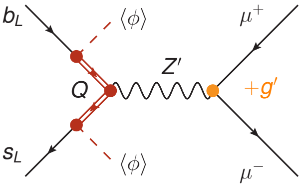
neutrino trident production

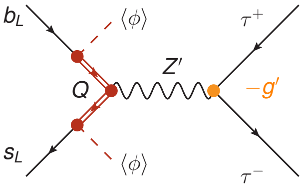
B_s mixing leads to an upper bound on the $U(1)'$ breaking vev
neutrino tridents lead to a lower bound



WA, Gori, Pospelov, Yavin 1403.1269

$L_\mu - L_\tau$ and Lepton Flavor Universality





- the Z' model based on gauged $L_\mu - L_\tau$ predicts:

  1) opposite effects in the $\mu^+\mu^-$ and $\tau^+\tau^-$ final state
  2) no effect in the e^+e^- final state

→ prediction for LFU observables, e.g. ratios of branching ratios:

$$R_K = \frac{\text{BR}(B \to K\mu^+\mu^-)_{[1,6]}}{\text{BR}(B \to Ke^+e^-)_{[1,6]}} \simeq 0.82 \pm 0.11 \qquad (R_K^{\text{SM}} \simeq 1)$$

$L_\mu - L_\tau$ and Lepton Flavor Universality

- the Z' model based on gauged $L_\mu - L_\tau$ predicts:

  1) opposite effects in the $\mu^+\mu^-$ and $\tau^+\tau^-$ final state
  2) no effect in the e^+e^- final state

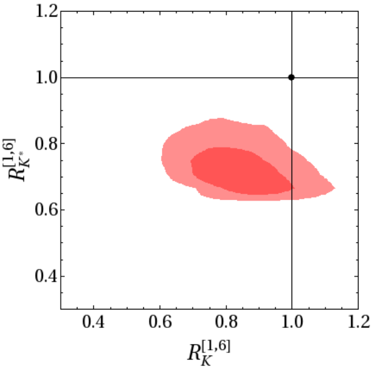
$\rightarrow$ prediction for LFU observables, e.g. ratios of branching ratios:

$$R_K = \frac{\text{BR}(B \to K\mu^+\mu^-)_{[1,6]}}{\text{BR}(B \to Ke^+e^-)_{[1,6]}} \simeq 0.82 \pm 0.11 \qquad (R_K^{\text{SM}} \simeq 1)$$

model passed the first test (LHCb Collaboration arXiv:1406.6482)

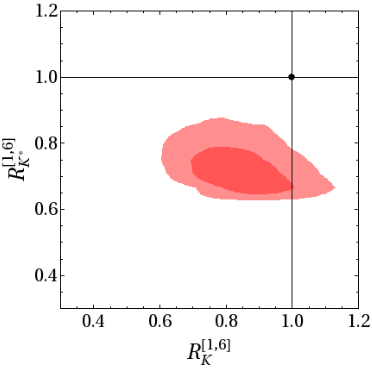
$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$$

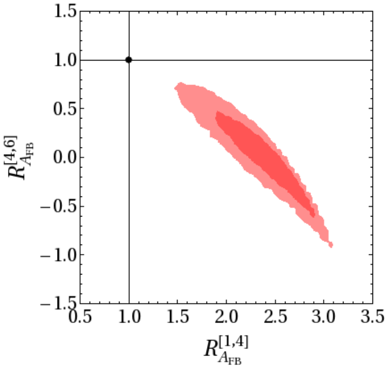
More Predictions for LFU Ratios



$$R_{K^*}^{[q_1^2,q_2^2]} = \frac{\text{BR}(B \to K^* \mu^+ \mu^-)_{[q_1^2,q_2^2]}}{\text{BR}(B \to K^* e^+ e^-)_{[q_1^2,q_2^2]}}$$

More Predictions for LFU Ratios





$$R_{K^*}^{[q_1^2,q_2^2]} = \frac{\text{BR}(B \to K^* \mu^+ \mu^-)_{[q_1^2,q_2^2]}}{\text{BR}(B \to K^* e^+ e^-)_{[q_1^2,q_2^2]}}$$

$$R_{A_{FB}}^{[q_1^2,q_2^2]} = \frac{A_{FB}(B \to K^* \mu^+ \mu^-)_{[q_1^2,q_2^2]}}{A_{FB}(B \to K^* e^+ e^-)_{[q_1^2,q_2^2]}}$$

- current $b \to s\mu^+\mu^-$ data shows anomalies both in branching ratios and angular observables
- can be consistently addressed by New Physics in the operator $(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$ at scales as high as 35 TeV
- models with a flavor changing Z' at (or below!) the TeV scale are natural candidates to explain the anomalies
- explicit example: Z' of gauged $L_\mu - L_\tau$ with effective flavor changing couplings to quarks