New Physics in Radiative $b \to s$ Transitions

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PERIMETER INSTITUTE

Recontres de Moriond EW 2014
March 15 - 22, 2014

WA, David Straub
Eur.Phys.J.C **73**, 2646 (2013) [arXiv:1308.1501 [hep-ph]]

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arXiv:1403.1269 [hep-ph]

New Physics in $B \to K^* \mu^+ \mu^-$?

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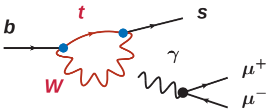
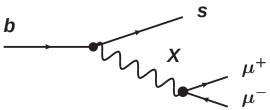


$$\sim \frac{g^4}{16\pi^2}\frac{1}{M_W^2}V_{ts}^* V_{tb}$$

SM amplitude is
loop suppressed and
CKM suppressed



$$\sim \frac{1}{\Lambda_{\rm NP}^2}$$

Generic NP
not necessarily suppressed

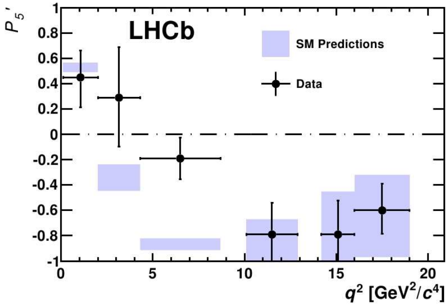
- rare B decays can probe high scales

$$\Lambda_{\rm NP} \sim \frac{M_W}{g^2}\sqrt{\frac{16\pi^2}{|V_{ts}^* V_{tb}|}} \sim 10~\text{TeV}$$

potentially sensitive to NP beyond the direct reach of the LHC

The $B \to K^*\mu^+\mu^-$ "Anomaly"

latest $B \to K^*\mu^+\mu^-$ results
from LHCb (with 1fb^{-1}) 1308.1707

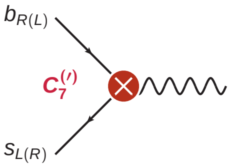


3.7σ discrepancy
in the $4.3 < q^2 < 8.68$ GeV^2 bin
with respect to a SM prediction
(Descotes-Genon, Hurth, Matias, Virto 1303.5794)

- statistical fluctuation?
  (update with full 7+8 TeV data hopefully soon)
- underestimated SM uncertainties?
  (see Jäger, Martin Camalich 1212.2263)
- New Physics?
  can anomaly be explained model independently?
  can anomaly be explained in concrete NP models?

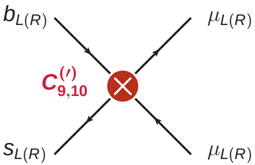
$$\mathcal{H}_{\text{eff}}^{b\to s} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{e^2}{16\pi^2}\sum_i \left(C_i\mathcal{O}_i + C_i'\mathcal{O}_i'\right)$$

magnetic dipole operators



$\propto 1/q^2$

semileptonic operators



$\propto 1$

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

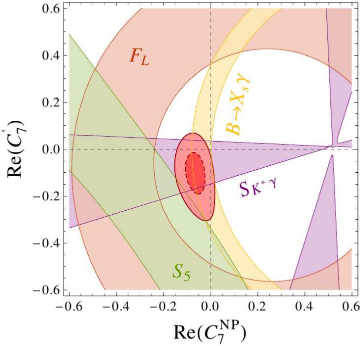
neglecting tensor operators

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

C_7 - C_7' Plane

$$O_7^{(\prime)} \propto (\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}$$

magnetic dipoles



WA, Straub 1308.1501

- large negative $C_7^{\text{NP}} \simeq -0.4$ could explain the anomaly in P_5' ($\sim S_5$)
- new physics in C_7 and C_7' strongly constrained by data on $B \to X_s\gamma$ and $B \to K^*\gamma$
- best fit values

$$C_7^{\text{NP}} = -0.06 \pm 0.04$$

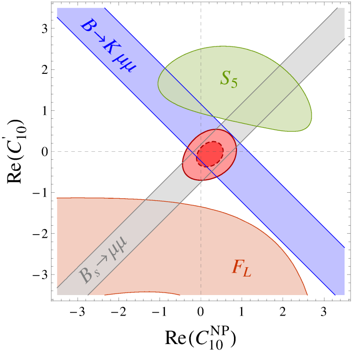
$$C_7' = -0.1 \pm 0.1$$

improve the tension only slightly

(see also: Descotes-Genon, Matias, Virto 1307.5683 and Beaujean, Bobeth, van Dyk 1310.2478 Hurth, Mahmoudi 1312.5267)

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

muonic axial-vector current



WA, Straub 1308.1501

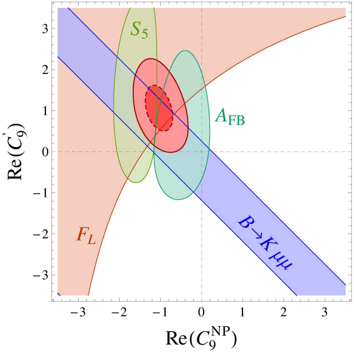
- NP contribution to $C'_{10} \simeq +1.5$ could explain the anomaly in P'_5 ($\sim S_5$)
- would worsen a small tension in F_L
- strong constraints from $B_s \to \mu^+\mu^-$ and $B \to K\mu^+\mu^-$

$\to$ no improvement compared to SM

(see also: Descotes-Genon, Matias, Virto 1307.5683 and Beaujean, Bobeth, van Dyk 1310.2478
Hurth, Mahmoudi 1312.5267)

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

muonic vector current



WA, Straub 1308.1501

- NP contribution to $C_9^{NP} \simeq -1.5$ would give the best fit to P_5' ($\sim S_5$) (compare $C_9^{SM} \simeq 4.1$)
- the tension in F_L pulls in the same direction
- A_{FB} gives important constraint
- $C_9' \simeq -C_9^{NP}$ helps to avoid constraints from $B \to K \mu^+\mu^-$
- best fit result

$$C_9^{NP} = -1.0 \pm 0.3$$

$$C_9' = +1.0 \pm 0.5$$

(see also: Descotes-Genon, Matias, Virto 1307.5683 and Beaujean, Bobeth, van Dyk 1310.2478
Hurth, Mahmoudi 1312.5267)

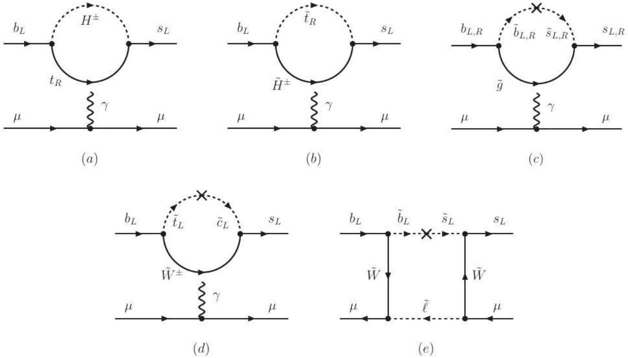
Implications for the New Physics Scale

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

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

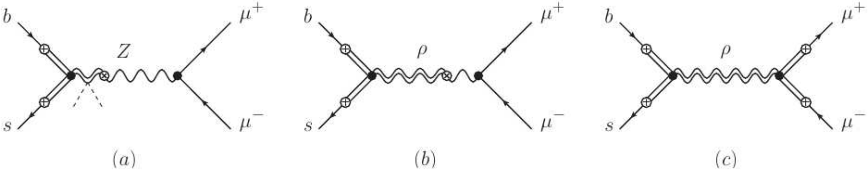
Implications for Models of New Physics

contributions to C_9 and C_9' at the loop level
(Z penguins, photon penguins, boxes)



contributions are only sizable for very light squarks and gauginos
at the level of few hundred GeV

$|C_9^{(\prime)}| \simeq 1$ in the MSSM is excluded by bounds from direct searches contributions to C_9 and C_9' already at tree level



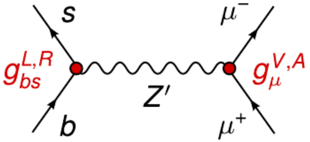
contributions are suppressed by either
the small vector coupling of the SM Z to muons
or by the small amount of compositness of the muons

$|C_9^{(\prime)}| \simeq 1$ cannot be achieved in models with partial compositness

Models with Flavor Changing Z'

parametrization of generic Z' couplings

$$\mathcal{L} \supset \frac{g_2}{2c_W}\left[\bar{s}\gamma^\mu(g_{bs}^L P_L + g_{bs}^R P_R)b + \bar{\mu}\gamma^\mu(g_\mu^V + \gamma_5 g_\mu^A)\mu\right]Z'_\mu$$



$$\frac{e^2}{16\pi^2}(V_{ts}^* V_{tb})\left\{C_9^{\rm NP}, C'_9, C_{10}^{\rm NP}, C'_{10}\right\} = \frac{m_Z^2}{2m_{Z'}^2}\left\{g_{bs}^L g_\mu^V, g_{bs}^R g_\mu^V, g_{bs}^L g_\mu^A, g_{bs}^R g_\mu^A\right\}$$

(see also: Descotes-Genon, Matias, Virto 1307.5683; Buras, Girrbach 1309.2466;

Gauld, Goertz, Haisch 1308.1959; 1310.1082)

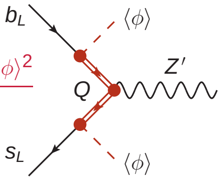
muon number - tau number
is anomaly free
gauging it leads to the wanted
vector couplings with muons

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

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

e.g. Fox, Liu, Tucker-Smith, Weiner 1104.4127

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



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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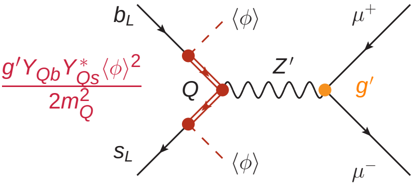
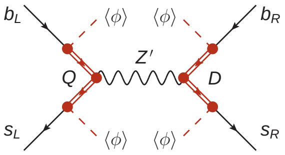


contributions to $B \to K^* \mu^+ \mu^-$ are
independent of the $U(1)'$ gauge
coupling and the Z' mass

$$C_9 \simeq \frac{Y_{Qb} Y^*_{Qs}}{2m_Q^2} \quad , \quad C'_9 \simeq -\frac{Y_{Db} Y^*_{Ds}}{2m_D^2}$$

(note: opposite effect in the $\tau^+\tau^-$ final state, no effect in e^+e^-)

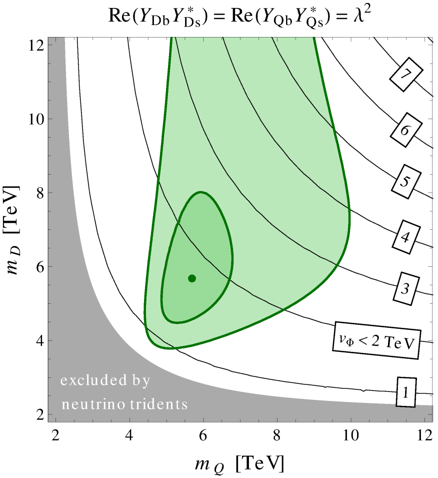
the Z' also leads to
tree level contribution to B_s mixing



$$M_{12}^s \propto (Y_{Qb} Y_{Qs}^*)(Y_{Db} Y_{Ds}^*) \frac{\langle\phi\rangle^2}{m_Q^2 m_D^2} + \ldots$$

upper bound on the $U(1)'$ breaking vev,
if the Z' explains the $B \to K^* \mu^+ \mu^-$ anomaly

$\langle\phi\rangle \lesssim 1.8\text{TeV}$



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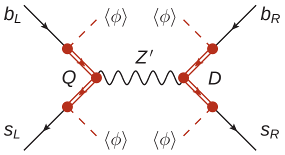
Bounds from Neutral Meson Mixing

the Z' also leads to
tree level contribution to B_s mixing



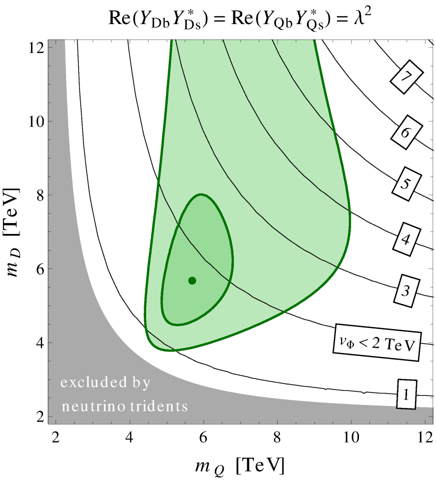
$$M_{12}^s \propto (Y_{Qb} Y_{Qs}^*)(Y_{Db} Y_{Ds}^*) \frac{\langle\phi\rangle^2}{m_Q^2 m_D^2} + \ldots$$

upper bound on the $U(1)'$ breaking vev,
if the Z' explains the $B \to K^* \mu^+ \mu^-$ anomaly

$\langle\phi\rangle \lesssim 1.8$TeV

Kaon mixing strongly constrains the couplings
to first generation quarks

$\to$ tiny production cross section at LHC



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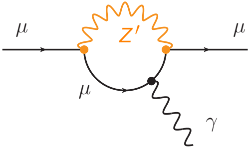
anomalous magnetic moment
of the muon



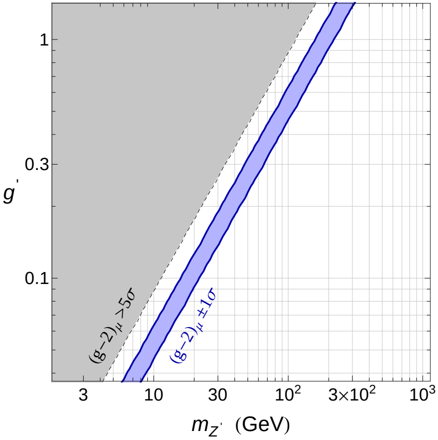
$$\Delta a_\mu \simeq \frac{1}{12\pi^2} \frac{m_\mu^2}{\langle \phi \rangle^2}$$

the $(g-2)_\mu$ anomaly:

$$\Delta a_\mu = (2.9 \pm 0.9) \times 10^{-9}$$

preferred value for the $U(1)'$ breaking vev

$$\langle \phi \rangle \simeq 180\text{GeV}$$



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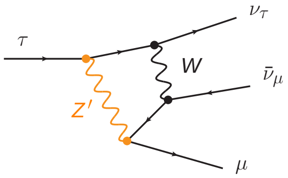
tau decays

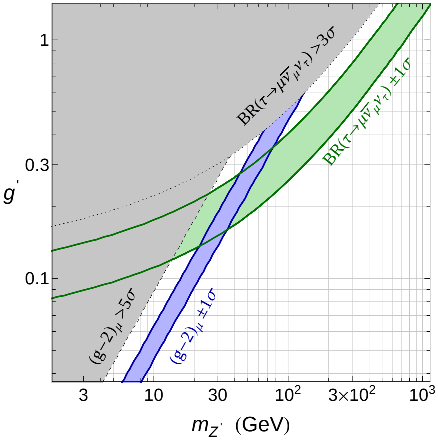


$$\frac{\text{BR}(\tau \to \mu\nu_\tau\bar{\nu}_\mu)}{\text{BR}(\tau \to \mu\nu_\tau\bar{\nu}_\mu)_{\text{SM}}} \simeq 1 + \Delta$$

$$\Delta = \frac{3(g')^2}{4\pi^2} \frac{\log(m_W^2/m_{Z'}^2)}{1 - m_{Z'}^2/m_W^2}$$

combining SM prediction (Pich 1310.7922)
with exp. results (PDG + Belle 1310.8503)

$$\Delta = (7.0 \pm 3.0) \times 10^{-3}$$



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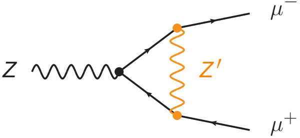
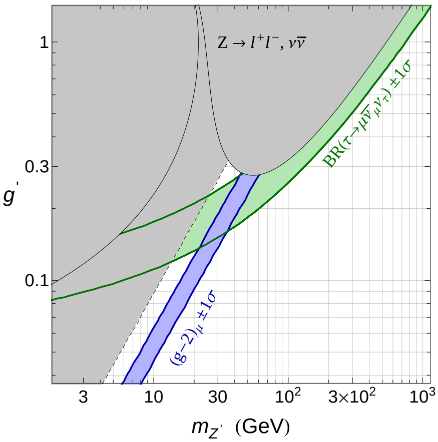
Probing the Z'

Z couplings to leptons

loops involving the Z'
lead to corrections of the
couplings of the SM Z to
muons, taus and neutrinos



$\rightarrow$ strong constraints
from LEP measurements



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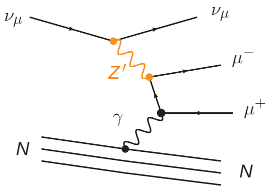
neutrino trident production



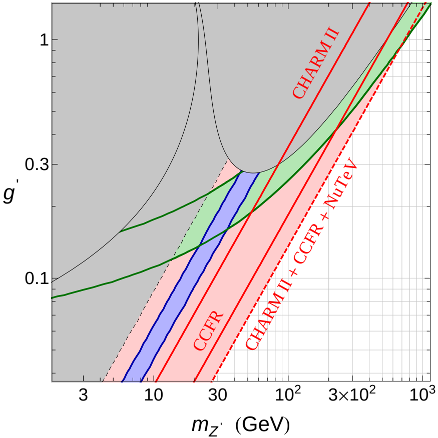
$$\frac{\sigma}{\sigma_{\rm SM}} \simeq \frac{1 + \left(1 + 4s_W^2 + 2v^2/\langle\phi\rangle^2\right)^2}{1 + \left(1 + 4s_W^2\right)^2}$$

measurements at CHARM II, CCFR, NuTeV

$$\sigma/\sigma_{\rm SM} = 0.83 \pm 0.18$$

$\rightarrow$ lower bound on the $U(1)'$ breaking vev

$$\langle\phi\rangle \gtrsim 750\text{GeV}$$



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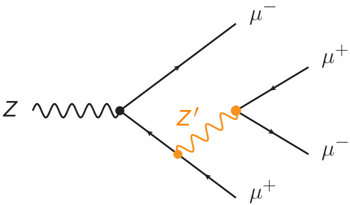
Probing the Z'

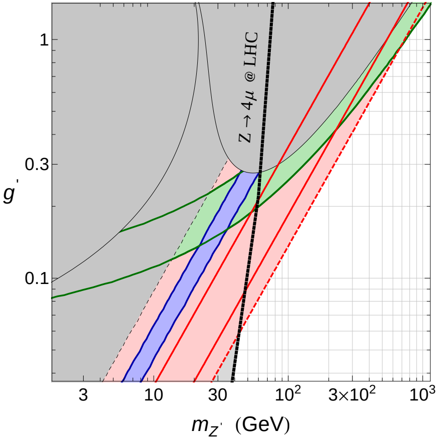
$Z \to 4\mu$ @ LHC



branching ratio measured at 10% level by
ATLAS (CONF-2013-055)
and CMS (1210.3844)

$$\text{BR}(Z \to 4\mu) = (4.2 \pm 0.4) \times 10^{-6}$$

possible to improve at LHC run II



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Probing the Z'

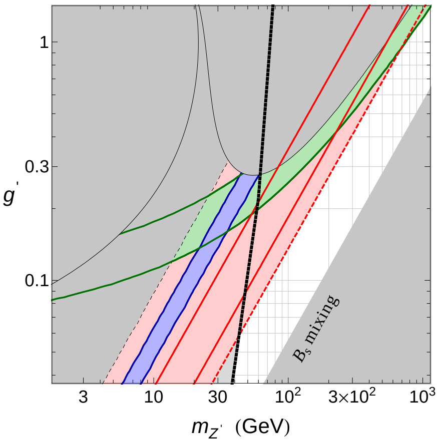
B_s mixing leads to an upper bound
on the $U(1)'$ breaking vev,
if the Z' is to explain
the $B \to K^* \mu^+ \mu^-$ anomaly

neutrino tridents lead to a lower bound
on the $U(1)'$ breaking vev

$750\text{GeV} \lesssim \langle \phi \rangle \lesssim 1.8\text{TeV}$

viable parameter space where the
$B \to K^* \mu^+ \mu^-$ anomaly can be explained
can be narrowed down considerably

how to probe the
remaining parameter space?



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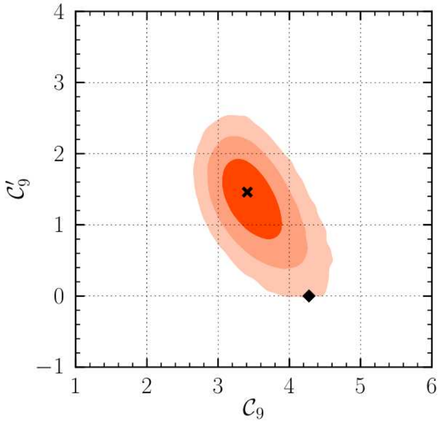
Summary

- rare B decays are highly sensitive to New Physics
- among them, $B \to K^*(\to K\pi)\mu^+\mu^-$ is a unique laboratory to probe sources of flavor violation beyond the SM
- angular decay distribution gives access to up to 24 observables
- most observables show reasonable agreement with SM predictions
- LHCb measurement of P_5' shows a discrepancy in the low q^2 region
- might be due to (unexpectedly) large power corrections or New Physics
- a consistent New Physics explanation points to the operators $(\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu\mu)$ and $(\bar{s}\gamma_\mu P_R b)(\bar{\mu}\gamma^\mu\mu)$ with a generic scale of $\sim$ 35 TeV
- models with a flavor changing Z' at (or below!) the TeV scale are natural candidates to explain the discrepancy
- explicit example: Z' of gauged $L_\mu - L_\tau$ with effective couplings to quarks

Back Up

More $C_9 - C_9'$ Planes (I)



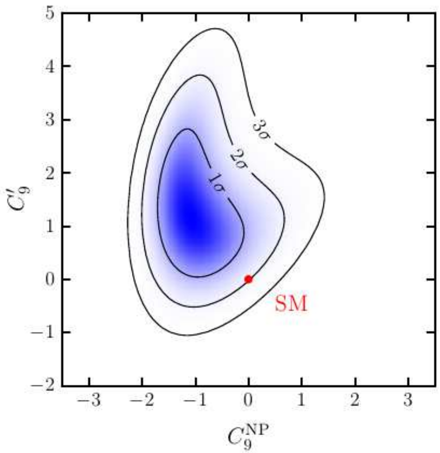
Beaujean, Bobeth, van Dyk

1310.2478

best fit point

$$C_9^{NP} = -0.8^{+0.3}_{-0.3}$$

$$C_9' = +1.4^{+0.3}_{-0.4}$$



Horgan, Liu, Meinel, Wingate

1310.3887

best fit point

$C_9^{NP} = -1.1 \pm 0.5$

$C'_9 = +1.1 \pm 0.9$

driven by $B \to K^* \mu^+\mu^-$ and $B_s \to \phi\mu^+\mu^-$ BRs at high q^2

P'_5 at low q^2 not included in the fit!

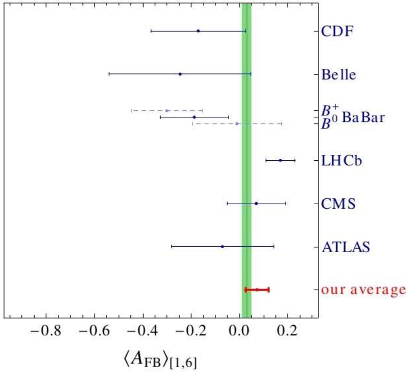
More $B \to K^*\mu^+\mu^-$ Fits

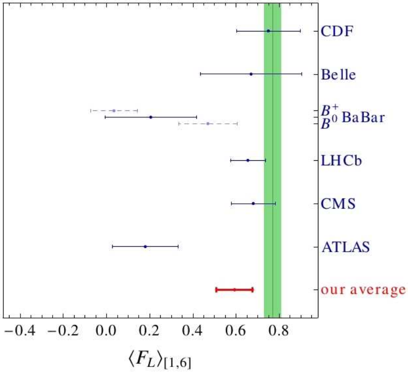
Scenario	$C_7^{\rm NP}$	C_7'	$C_9^{\rm NP}$	C_9'	$C_{10}^{\rm NP}$	C_{10}'	$\Delta\chi^2(\rm SM)$
(7)	$-0.07_{\pm 0.04}$						3.4
(9)			$-0.8_{\pm 0.3}$				**4.3**
(77′)	$-0.06_{\pm 0.04}$	$-0.1_{\pm 0.1}$					4.7
(97)	$-0.05_{\pm 0.04}$		$-0.6_{\pm 0.3}$				6.0
(97′)		$-0.1_{\pm 0.1}$	$-0.7_{\pm 0.3}$				5.5
(99′)			$-1.0_{\pm 0.3}$	$+1.0_{\pm 0.5}$			**8.3**
(910′)			$-1.0_{\pm 0.3}$			$-0.4_{\pm 0.2}$	7.0
Real	-0.03	-0.11	-0.9	$+0.7$	-0.1	-0.2	**10.8**
Complex	$+0.03$ $+0.09i$	-0.23 $-0.23i$	-1.9 $+1.2i$	$+1.2$ $+3.3i$	$+1.6$ $-0.1i$	$+1.0$ $+1.6i$	**14.1**

WA, Straub 1308.1501

the C_9 - C_9' scenario works best

$B \to K^*\mu^+\mu^-$ Data Averages





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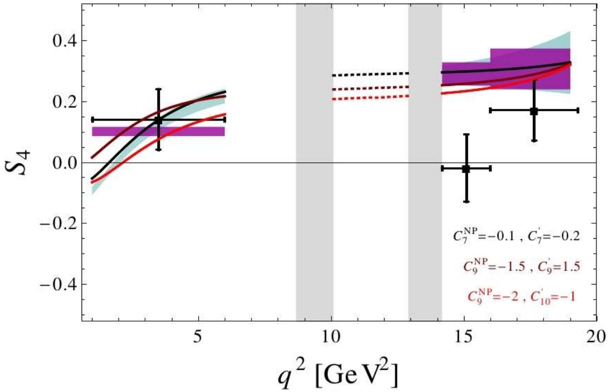
Tension in S_4 at high q^2



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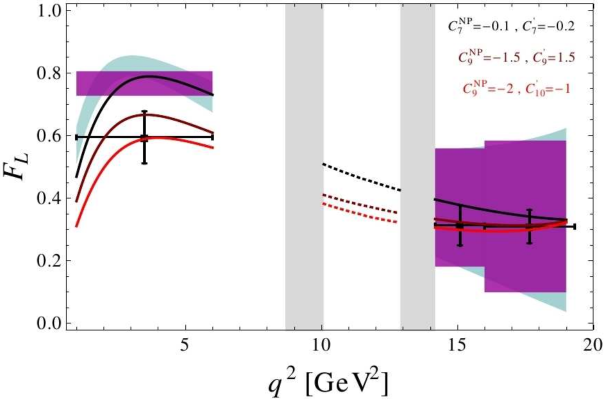
Tension in F_L at low q^2 ?



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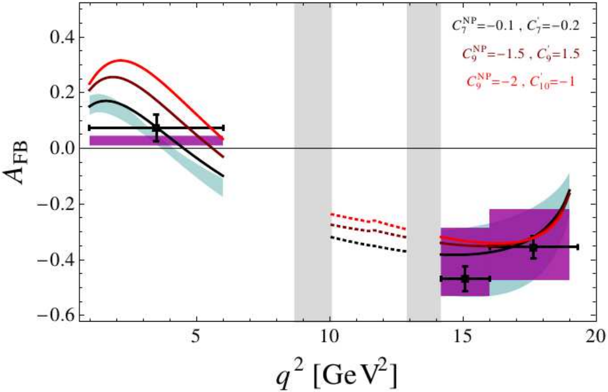
Tension in A_{FB} at low q^2 ?



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