Effective Z' Bosons in Rare B Decays

Wolfgang Altmannshofer
waltmannshofer@perimeterinstitute.ca

ERC Workshop

"Effective Field Theories for Collider Physics,
Flavor Phenomena and Electroweak Symmetry Breaking"

Schloss Waldthausen
November 10 - 13, 2014

Outline

WA, David Straub

“State of new physics in $b \to s$ transitions” (1411.soon)

WA, Stefania Gori, Maxim Pospelov, Itay Yavin

“Dressing $L_\mu - L_\tau$ in color” (PRD 89 (2014) 095033; 1403.1269)

“Neutrino Trident Production: A Powerful Probe of New Physics with Neutrino Beams” (PRL 113 (2014) 091801; 1406.2332)

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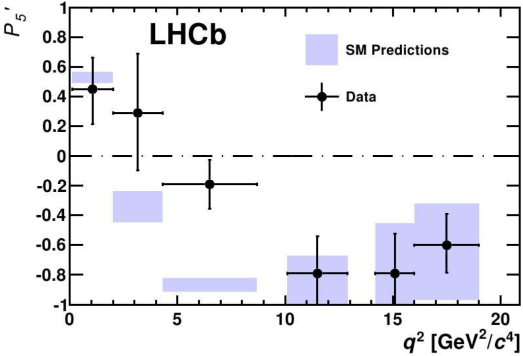
1. Anomalies in $b \to s$ Transitions
2. Z' Explanations of the Anomalies
3. Effective Z' Bosons and $L_\mu - L_\tau$
4. Summary

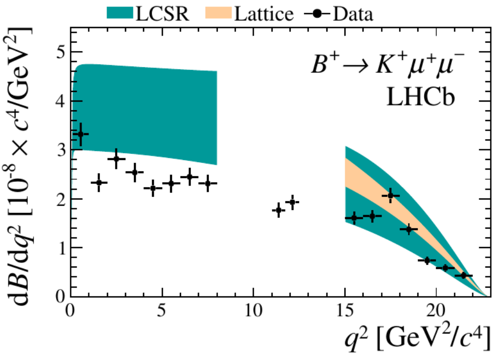
The $B \to K^* \mu^+ \mu^-$ Anomaly

LHCb Collaboration 1308.1707



tension in angular observables in the $B \to K^* \mu^+ \mu^-$ decay

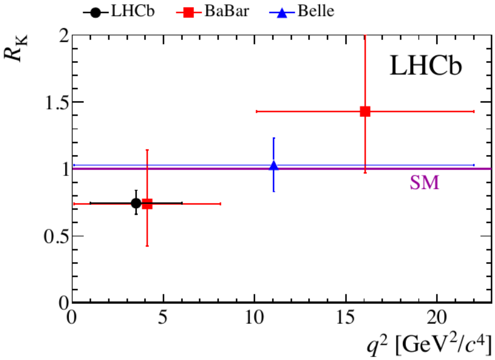
LHCb Collaboration 1305.2168, 1403.8044



$B \to K^* \mu^+\mu^-$, $B \to K \mu^+\mu^-$ and $B_s \to \phi\mu^+\mu^-$ branching ratio measurements seem systematically below SM predictions

Violation of Lepton Flavor Universality

LHCb Collaboration 1406.6482



$B \to K\mu^+\mu^-$ rate seems suppressed with respect to $B \to Ke^+e^-$

What could it be?

statistical fluctuation?

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underestimated SM uncertainties?
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New Physics?

can anomalies be explained model independently?
can anomalies be explained in concrete NP models?

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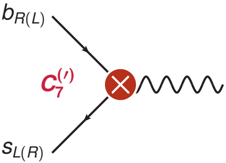
for much more details see tomorrow's talks by Jäger, Hurth, Straub

New Physics in $b \to s$ Decays

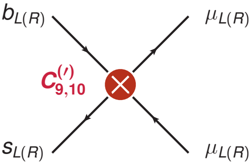
$$\mathcal{H}_{\text{eff}}^{b\to s} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

magnetic dipole operators



$\propto 1/q^2$

semileptonic operators



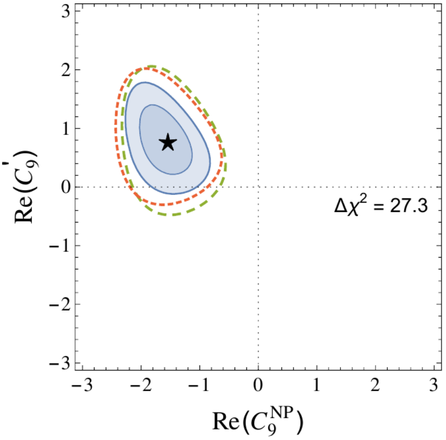
$\propto 1$

	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 $B_s \to \mu^+\mu^-$)

C_9 - C_9' Plane



WA, Straub *preliminary*

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

muonic vector current

- NP contributions to C_9 give best description of the data
- (NP with $C_9 = -C_{10}$ works almost equally well)
- best fit result

$$C_9^{NP} = -1.5 \pm 0.4$$
$$C_9' = +0.6 \pm 0.4$$

- slight preference for NP in RH currents; but nothing significant

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

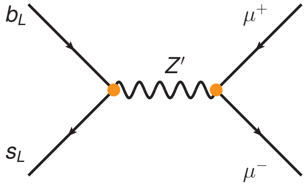
(assumes New Physics has O(1) coupling to muons)

Z' Explanations of the Anomalies

Models with Flavor Changing Z'

parametrization of generic Z' couplings (Buras, De Fazio, Girrbach 1211.1896)

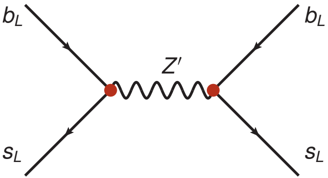
$$\mathcal{L} \supset \bar{f}_i \gamma^\mu \left[\Delta_L^{f_i f_j} P_L + \Delta_R^{f_i f_j} P_R \right] f_j Z'_\mu$$



want vectorial coupling to muons: $\Delta_L^{\mu\mu} = \Delta_R^{\mu\mu} = \frac{1}{2}\Delta_V^{\mu\mu}$

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

Constraints from B_s Mixing



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

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

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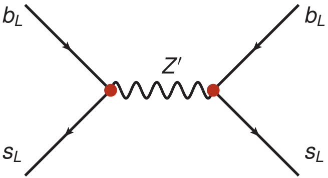

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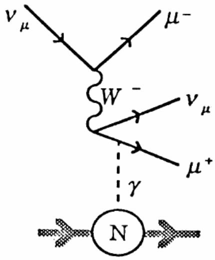
- constraint on the Z' mass and the flavor changing coupling (allowing for 10% NP in B_s mixing)

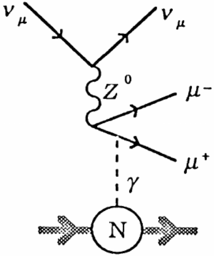
$$\frac{M_{Z'}}{|\Delta_L^{bs}|} \gtrsim 244 \text{ TeV} \simeq \frac{10 \text{ TeV}}{|V_{tb}V_{ts}^*|}$$

Constraints from Neutrino Tridents

- production of a muon anti-muon pair in the scattering of a muon-neutrino in the Coulomb field of a heavy nucleus
- 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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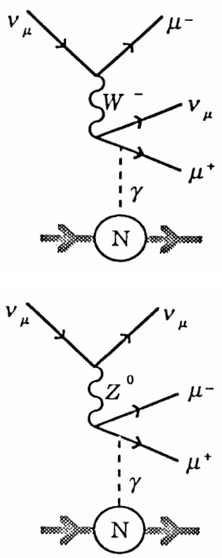
experimental measurement

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

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



Maximally Allowed Effect in C_9

combining constraints from B_s mixing and neutrino tridents gives an upper bound on the Z' contribution to C_9

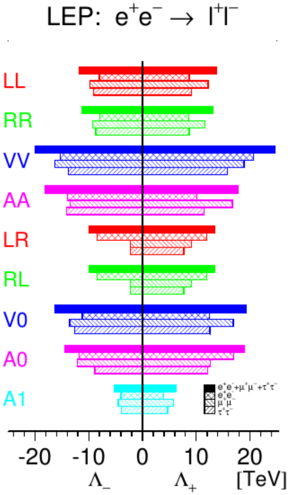
$$|C_9^{\rm NP}| = \frac{|\Delta_L^{bs}|}{M_{Z'}} \frac{|\Delta_V^{\mu\mu}|}{M_{Z'}} \; \frac{v^2}{V_{tb} V_{ts}^*} \; \frac{4\pi^2}{e^2} \lesssim 9.3$$

(compare to the best fit value $C_9^{\rm NP} \simeq 1.4$)

Constraints from LEP

- assume the couplings of the Z' are lepton flavor universal
- strong constraints from LEP results on four lepton contact interactions

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



LEP Electroweak Working Group

1302.3415

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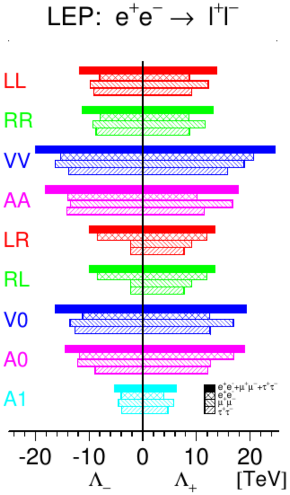
$$\mathcal{L} = \frac{4\pi}{\Lambda_\pm^2} (\bar{e}\gamma_\mu e)(\bar{\ell}\gamma^\mu \ell)$$

- much stronger upper bound on C_9 in the case of lepton flavor universality

$$\frac{M_{Z'}}{|\Delta_V^{\ell\ell}|} \gtrsim 3.5 \text{ TeV} \quad \Rightarrow \quad |C_9^{\rm NP}| \lesssim 0.72$$

(factor 2 below the best fit)

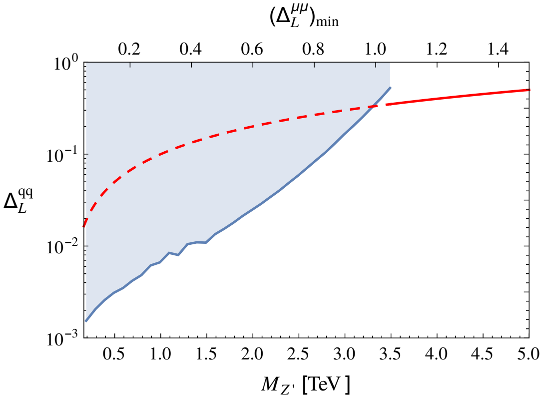


LEP Electroweak Working Group

1302.3415

Constraints from LHC

Z' couplings to first generation quarks are strongly constrained by LHC results from direct Z' searches and searches for quark-lepton contact interactions



WA, Straub *preliminary*

WANTED

Z' gauge boson with

sizable vector couplings to muons

small flavor changing $b \to s$ coupling

suppressed couplings to
electrons and 1st generation quarks

Effective Z' Bosons and $L_\mu - L_\tau$

Gauging $L_\mu - L_\tau$

muon number - tau number is anomaly free in the Standard Model

gauging it leads to the wanted vector couplings with muons

$$\mathcal{L} = -\frac{1}{4}(Z')^{\alpha\beta}(Z')_{\alpha\beta} + (D_\alpha\Phi)^*(D^\alpha\Phi) + V(\Phi)$$

$$+g'(\bar{\mu}\gamma^\alpha\mu - \bar{\tau}\gamma^\alpha\tau + \bar{\nu}_\mu\gamma^\alpha P_L\nu_\mu - \bar{\nu}_\tau\gamma^\alpha P_L\nu_\tau)Z'_\alpha$$

Z' gets its mass from the vev of a additional scalar Φ, charged under $U(1)' = L_\mu - L_\tau$

$$m_{Z'} = g'\langle\Phi\rangle$$

Effective Couplings to Quarks

a scalar current can be coupled to quark currents at dimension 6 level

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

$$\mathcal{L}_{\rm dim6} = (\Phi^* i \overleftrightarrow{D}_\alpha \Phi) \left[\frac{\lambda_{ij}^{(q)}}{\Lambda^2} (\bar{q}_L^i \gamma^\alpha q_L^j) + \frac{\lambda_{ij}^{(d)}}{\Lambda^2} (\bar{d}_R^i \gamma^\alpha d_R^j) + \frac{\lambda_{ij}^{(u)}}{\Lambda^2} (\bar{u}_R^i \gamma^\alpha u_R^j) \right]$$

gives couplings of the Z' to quarks once Φ is replaced by its vev

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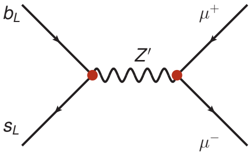
contributions to $b \to s\mu^+\mu^-$ are independent of
the $U(1)'$ gauge coupling and the Z' mass

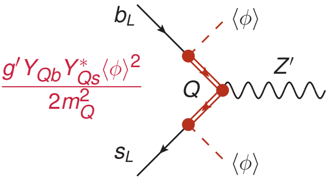


$$C_9 \simeq \frac{\lambda_{bs}^{(q)}}{\Lambda^2} \quad , \quad C_9' \simeq \frac{\lambda_{bs}^{(d)}}{\Lambda^2}$$

A Simple Model for the Quark Couplings

introduce heavy vector-like quarks that are charged under the $U(1)'$ and that mix with the SM quarks

$$\mathcal{L}_{\text{mix}} = \Phi \bar{Q} (Y_{Qb} b_L + Y_{Qs} s_L + Y_{Qd} d_L) + \ldots$$

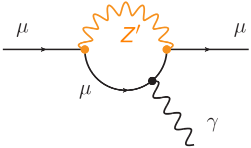


contributions to $b \to s \mu^+ \mu^-$ are set by the heavy quark masses and the mixing Yukawas

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

($L_\mu - L_\tau$ predicts no effects in e^+e^- mode; opposite effects in $\mu^+\mu^-$ and $\tau^+\tau^-$ modes)

Anomalous Magnetic Moment of the Muon



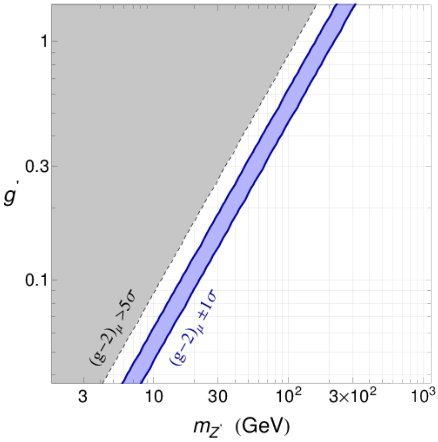
$$\Delta a_\mu \simeq \frac{1}{12\pi^2} \frac{m_\mu^2}{\langle \Phi \rangle^2}$$

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

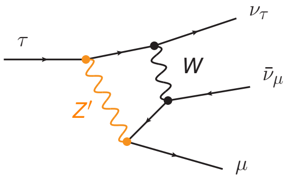
$$\Delta a_\mu = (2.9 \pm 0.9) \times 10^{-9}$$

preferred value for the scalar vev

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



WA, Gori, Pospelov, Yavin 1403.1269



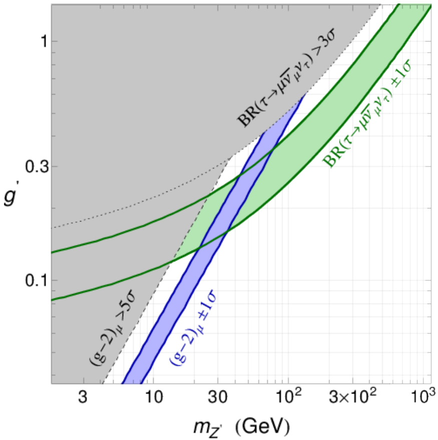
$$\frac{\text{BR}(\tau \to \mu\nu_\tau\bar{\nu}_\mu)}{\text{BR}(\tau \to \mu\nu_\tau\bar{\nu}_\mu)_{\text{SM}}} \simeq 1 + \Delta$$

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

SM prediction: Pich 1310.7922

exp. results: PDG + Belle 1310.8503

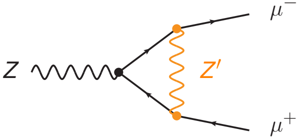
$$\Delta = (7.0 \pm 3.0) \times 10^{-3}$$



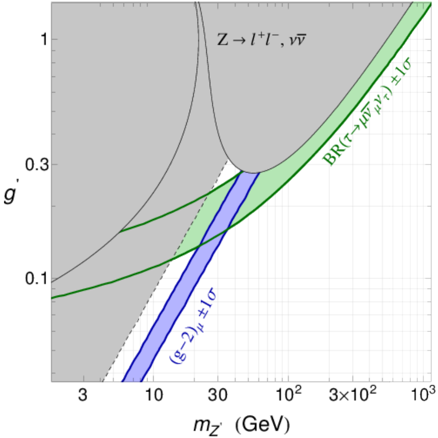
WA, Gori, Pospelov, Yavin 1403.1269

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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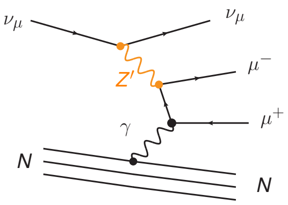
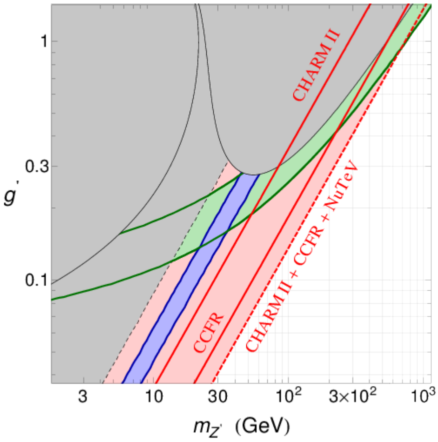
Neutrino Trident Production



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

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

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



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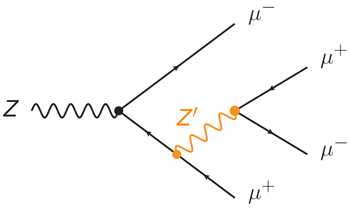
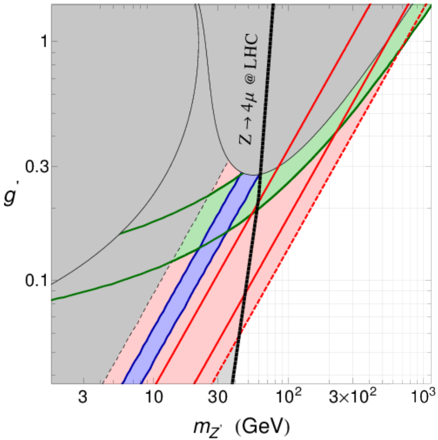


branching ratio measured at 10% level by

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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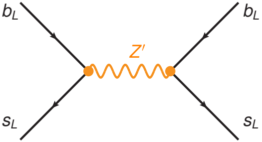
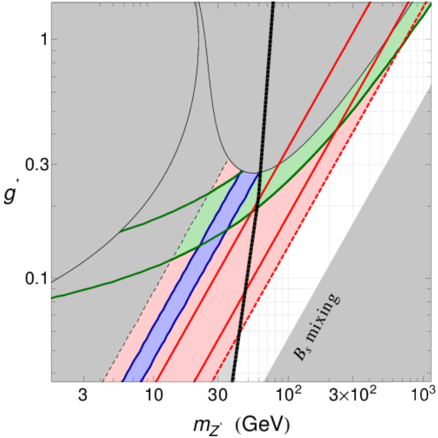


$$M_{12}^{\rm NP} \propto (Y_{Qb} Y_{Qs}^*)^2 \frac{\langle \Phi \rangle^2}{m_Q^4}$$

B_s mixing leads to an upper bound
on the $U(1)'$ breaking vev,
if the Z' is to explain
the $b \to s\mu^+\mu^-$ anomalies

$\langle \Phi \rangle \lesssim 1.8$TeV



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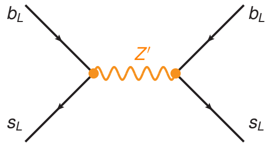
B_s Mixing



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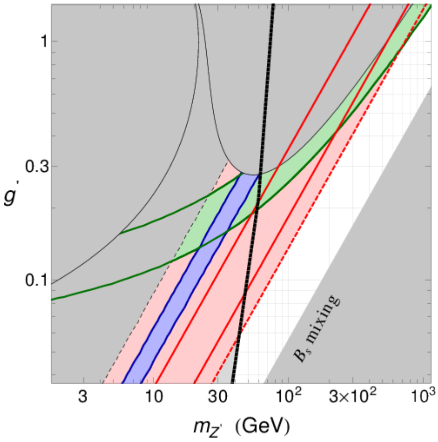
might be possible to probe (parts of) the
open parameter space with neutrino
tridents at LBNE

(WA, Gori, Pospelov, Yavin 1406.2332)

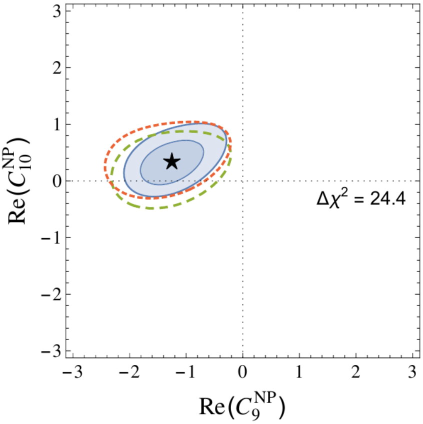


WA, Gori, Pospelov, Yavin 1403.1269

Summary

- current $b \to s\mu^+\mu^-$ data shows various discrepancies 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 discrepancies
- explicit example: Z' of gauged $L_\mu - L_\tau$ with effective flavor changing couplings to quarks

Back Up



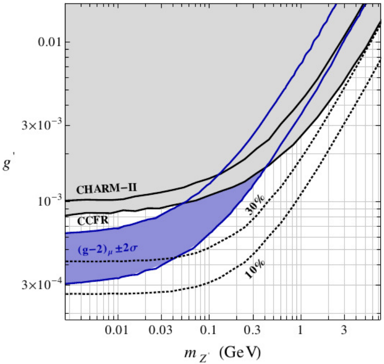
WA, Straub   *preliminary*

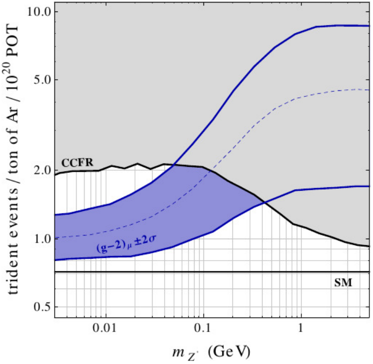
$$O_{9/10} \propto (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu/\gamma_\mu\gamma_5\mu)$$

LH quark current

- best fit result

$$C_9^{NP} = -1.3 \pm 0.3$$
$$C_{10}^{NP} = +0.3 \pm 0.2$$





WA, Gori, Pospelov, Yavin 1406.2332