B Physics Anomalies and a 100 TeV Collider

Wolfgang Altmannshofer
waltmannshofer@perimeterinstitute.ca

PERIMETER INSTITUTE

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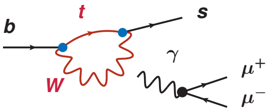
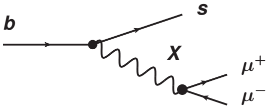
A New Physics Scale from Rare B Decays



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

SM amplitude is
loop suppressed and
CKM suppressed



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

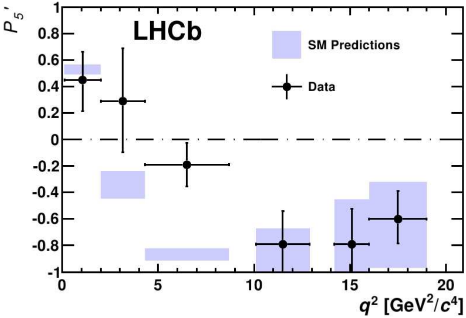
Generic NP
not necessarily
suppressed

- O(1) non-standard effects in rare B decays correspond to new physics in reach of a 100 TeV collider

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

“The $B \to K^* \mu^+ \mu^-$ Anomaly”

LHCb Collaboration, Phys. Rev. Lett. **111**, 191801 (2013)



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 ’13)

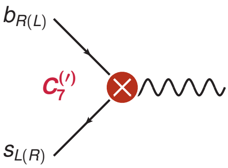
- statistical fluctuation?
  (update at Moriond?)
- underestimated SM uncertainties?
  (see Khodjamirian et al. ’10;
  Jäger, Martin Camalich ’12, ’14;
  Lyon, Zwicky ’14;
  Descotes-Genon et al. ’14;
  WA, Straub ’14; ...)
- New Physics?

  can anomaly be explained model independently?

  can anomaly be explained in concrete NP models?

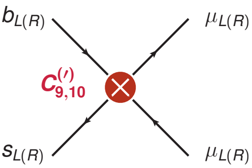
$$\mathcal{H}_{\text{eff}}^{b\to s} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

magnetic dipole operators



$\propto 1/q^2$

semileptonic operators



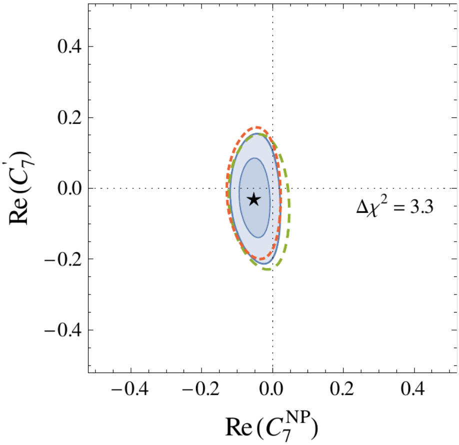
$\propto 1$

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

neglecting tensor operators (secretly dimension 8)

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

Global Fit: C_7 - C_7' Plane

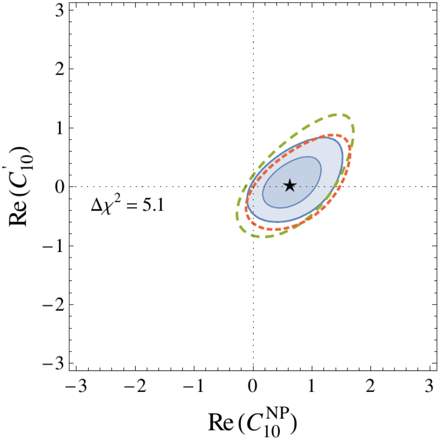


WA, Straub 1411.3161

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

flavor violating dipole

- NP contributions to C_7 and C_7' are strongly constrained by the $b \to s\gamma$ transition
- only insignificant improvement of the fit



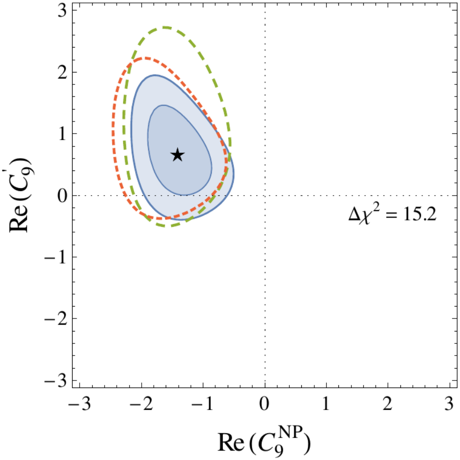
WA, Straub 1411.3161

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

muonic axial-vector current

- strong constraints from BR($B \to K\mu^+\mu^-$) and BR($B_s \to \mu^+\mu^-$)
- only very mild improvement of the fit

Global Fit: C_9 - C_9' Plane



WA, Straub 1411.3161

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

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

$$C_9^{\mathrm{NP}} = -1.4 \pm 0.4$$
$$C_9' = +0.7 \pm 0.6$$

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

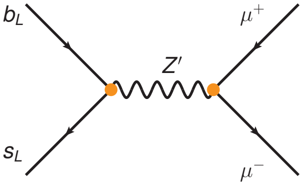
(assumes New Physics has O(1) coupling to muons)

Z' Explanations of the Anomalies

Models with Flavor Changing Z'

parametrization of generic Z' couplings (Buras et al. '12/'13)

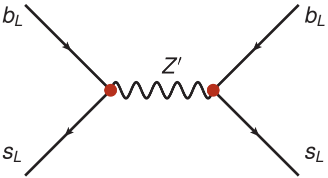
$$\mathcal{L} \supset \bar{f}_i \gamma^\mu \left[\Delta_L^{f_i f_j} P_L + \Delta_R^{f_i f_j} P_R \right] f_j Z'_\mu$$



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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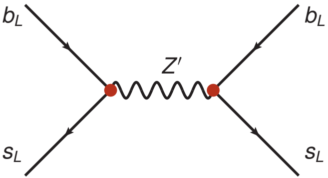

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- constraint on the Z' mass and the flavor changing coupling (allowing for 10% NP in B_s mixing)

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

Constraints from LEP

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

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

Constraints from LEP

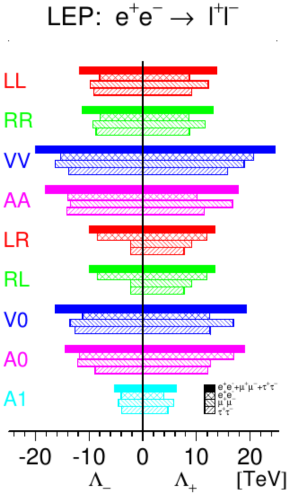
- assume the couplings of the Z' are lepton flavor universal
- LEP bounds on four lepton contact interactions

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

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

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

(can be improved at a CepC/FCC-ee/TLEP)



LEP Electroweak Working Group
1302.3415

Maximally Allowed Effect in C_9

combining constraints from B_s mixing and lepton contact interactions gives a strong upper bound on the Z' contribution to C_9 in the case of lepton flavor universality

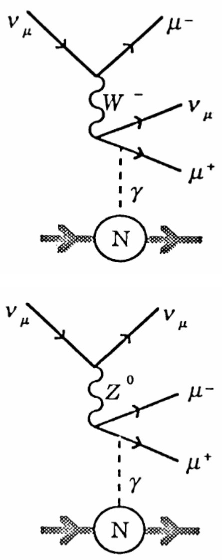
$$|C_9^{\rm NP}| = \frac{|\Delta_L^{bs}|}{M_{Z'}} \frac{|\Delta_V^{\ell\ell}|}{M_{Z'}} \frac{v^2}{V_{tb}V_{ts}^*} \frac{4\pi^2}{e^2} \lesssim 0.72$$

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

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)

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



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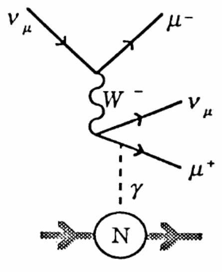
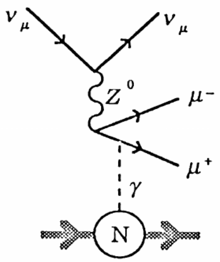
experimental measurement

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

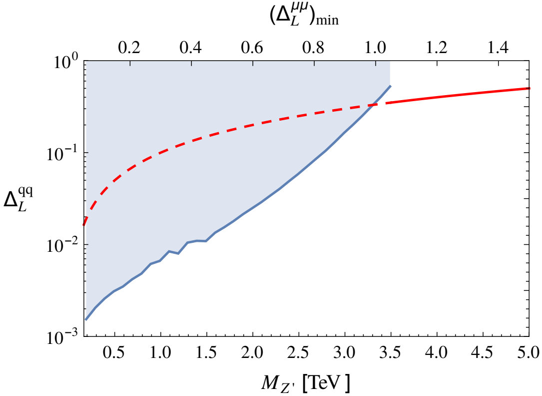
$$\frac{M_{Z'}}{|\Delta_V^{\mu\mu}|} \gtrsim 0.27 \text{ TeV} \quad \Rightarrow \quad |C_9^{\rm NP}| \lesssim 9.3$$





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 arXiv:1411.3161

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

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

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

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

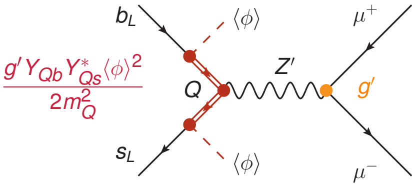
Z' gets its mass from the vev of a additional scalar Φ, charged under $U(1)' = L_\mu - L_\tau$

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

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

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



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

they are set by the heavy quark masses and the mixing Yukawas

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

$(g-2)$ of the muon

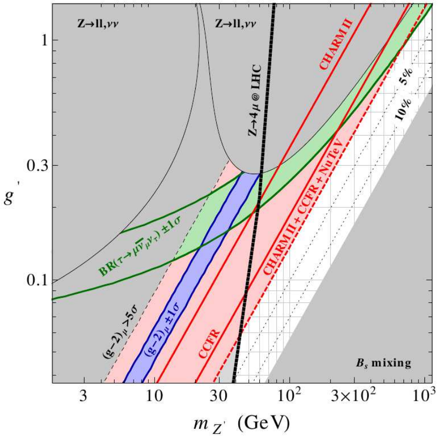
tau decays

Z couplings to leptons

$Z \to 4\mu$ @ LHC

B_s mixing

neutrino trident production



WA, Gori, Pospelov, Yavin 1403.1269

$(g-2)$ of the muon

tau decays

Z couplings to leptons

$Z \to 4\mu$ @ LHC

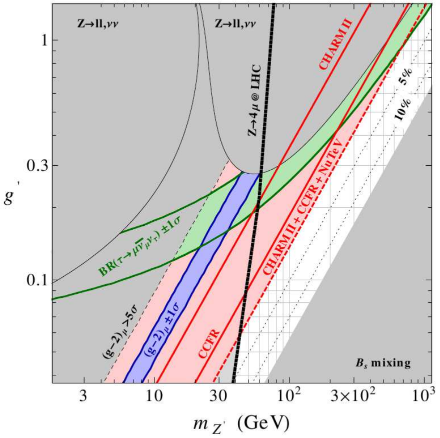
B_s mixing

neutrino trident production

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

540GeV $\lesssim \langle\phi\rangle \lesssim$ 1.8TeV

bound from Z couplings to leptons
can improve at CepC/FCC-ee/TLEP



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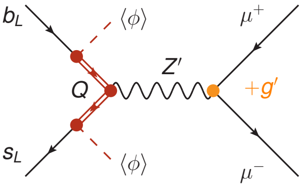
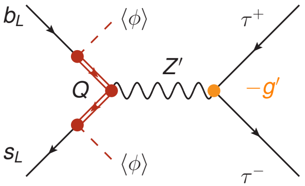




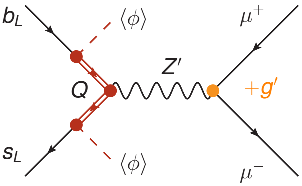
- the Z' model based on gauged $L_\mu - L_\tau$ predicts:

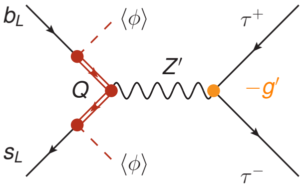
  1) opposite effects in the $\mu^+\mu^-$ and $\tau^+\tau^-$ final state
  2) no effect in the e^+e^- final state

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

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

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





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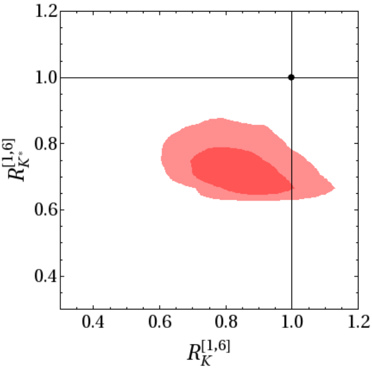
model passed the first test (LHCb Collaboration arXiv:1406.6482)

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

More Predictions for LFU Ratios

(work in progress with Itay Yavin)



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

More Predictions for LFU Ratios

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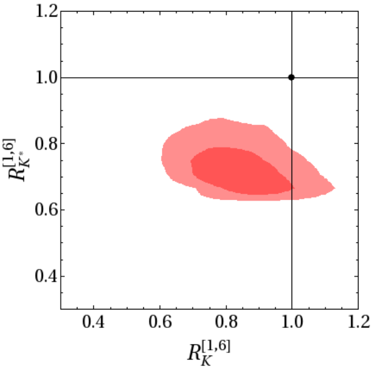
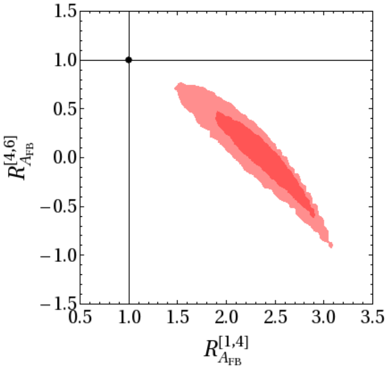




$$R_{K^*}^{[q_1^2,q_2^2]} = \frac{\mathrm{BR}(B \to K^* \mu^+\mu^-)_{[q_1^2,q_2^2]}}{\mathrm{BR}(B \to K^* e^+ e^-)_{[q_1^2,q_2^2]}} \qquad R_{A_{FB}}^{[q_1^2,q_2^2]} = \frac{A_{FB}(B \to K^* \mu^+\mu^-)_{[q_1^2,q_2^2]}}{A_{FB}(B \to K^* e^+ e^-)_{[q_1^2,q_2^2]}}$$

$$C_9 \simeq \frac{Y_{Qb} Y_{Qs}^*}{2m_Q^2}$$

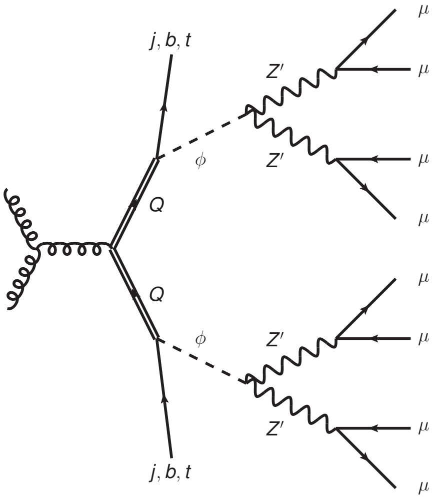
for CKM-like mixing, i.e.

$$Y_{Qb} Y_{Qs}^* \sim V_{tb} V_{ts}^* \sim 0.04$$

mass of the vector-like quarks is

$$m_Q \sim 4 \text{ TeV}$$

pair production at a 100 TeV collider can lead to spectacular 8 muon final states

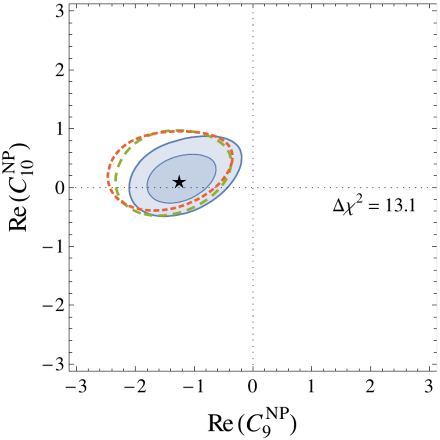


Summary

- current $b \to s\mu^+\mu^-$ data shows 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
- CepC/FCC-ee/TLEP:
  probe the Z' through precision $Z\ell\ell$ coupling measurements
  test the $L_\mu - L_\tau$ structure by measuring $b \to s\tau\tau$ transitions
- SppC/FCC-hh:
  direct production of the vector-like quarks

Back Up

Global Fit: C_9 - C_{10} Plane



WA, Straub 1411.3161

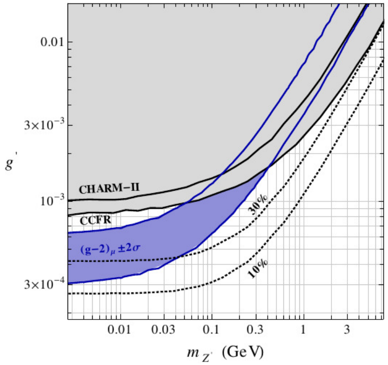
$$O_{9/10} \propto (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu / \gamma_\mu\gamma_5 \mu)$$

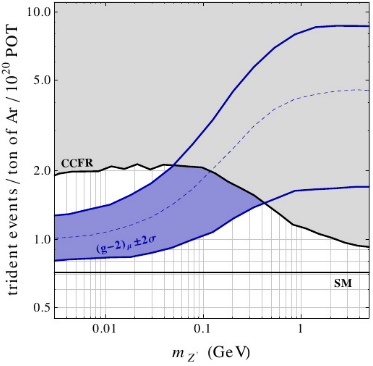
LH quark current

- best fit result

$$C_9^{\rm NP} = -1.3 \pm 0.4$$
$$C_{10}^{\rm NP} = +0.1 \pm 0.2$$

Probing the $L_\mu - L_\tau$ Gauge Boson at LBNE





WA, Gori, Pospelov, Yavin 1406.2332