Phenomenology of Gauged $L_\mu - L_\tau$

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CERN Theory Institute

From flavor anomalies to direct discoveries of new physics

CERN, October 29, 2018

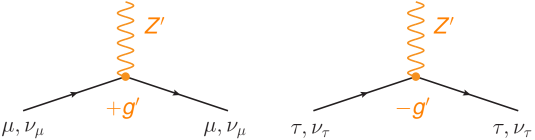
Minimal $L_\mu - L_\tau$ Model

The Minimal $L_\mu - L_\tau$ Model

(He, Joshi, Lew, Volkas, Phys.Rev. D43 (1991) 22-24)

$L_\mu - L_\tau$ is anomaly free with the SM matter content.

Gauging $L_\mu - L_\tau$ gives Z' with vectorial couplings to muons and taus and couplings to the corresponding LH neutrinos.



no lepton flavor violating couplings!

$$g' Z'_\alpha \left(\bar\mu \gamma^\alpha \mu - \bar\tau \gamma^\alpha \tau + \bar\nu_\mu \gamma^\alpha P_L \nu_\mu - \bar\nu_\tau \gamma^\alpha P_L \nu_\tau \right)$$

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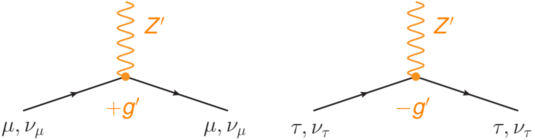

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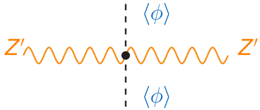
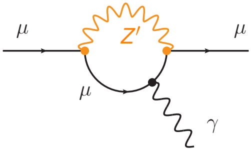
Z' can get mass from a scalar ϕ that spontaneously breaks $L_\mu - L_\tau$

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



Muon Anomalous Magnetic Moment

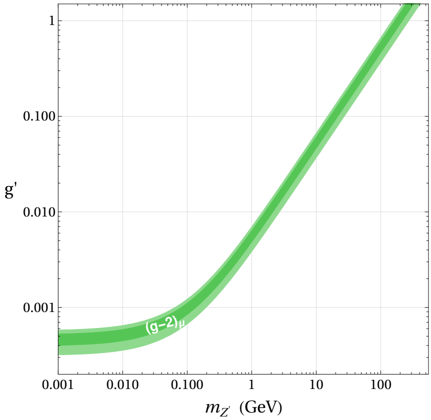
Z' contributes to $(g-2)_\mu$ at the 1-loop level



$$\Delta a_\mu \simeq \frac{(g')^2}{12\pi^2}\frac{m_\mu^2}{m_{Z'}^2} + \mathcal{O}\left(\frac{m_\mu^4}{m_{Z'}^4}\right)$$

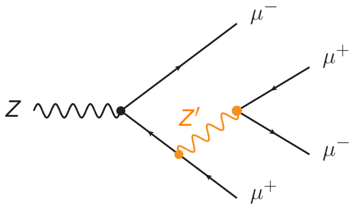
Can it explain the long standing discrepancy?

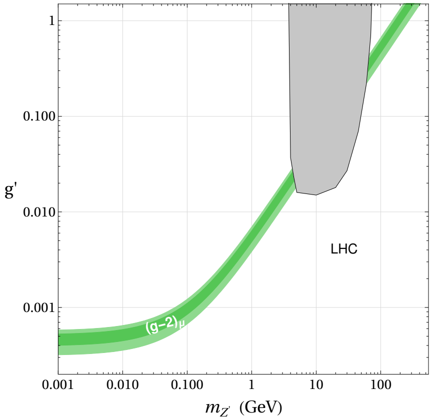
$$\Delta a_\mu \simeq (2.9 \pm 0.9) \times 10^{-9}$$



Can obtain bounds from measured
$Z \to 4\mu$ branching ratio

(WA, Gori, Pospelov, Yavin, 1406.2332)





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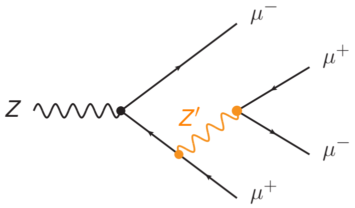
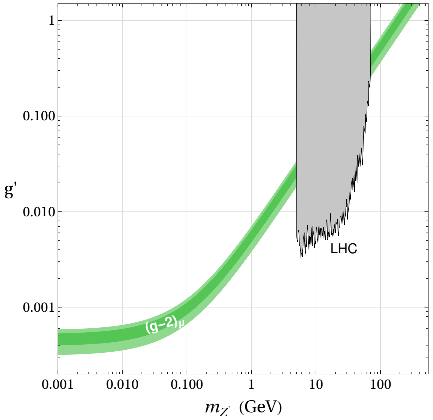


recent dedicated search for the $L_\mu - L_\tau$ gauge boson (CMS 1808.03684)

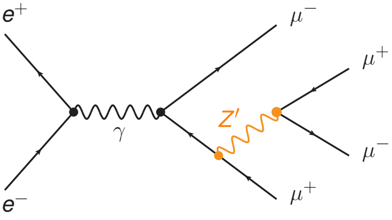
extension to lower masses possible?

(Elahi, Martin 1511.04107)



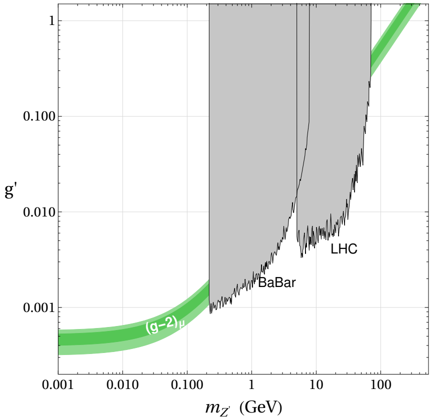
Direct Search at B-factories

$$e^+e^- \to 2\mu Z' \to 4\mu$$



BaBar 1606.03501

(Can be improved at Belle 2)



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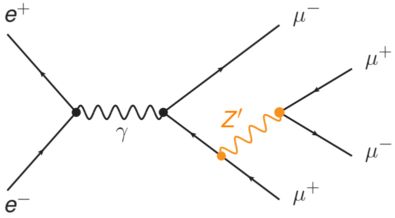

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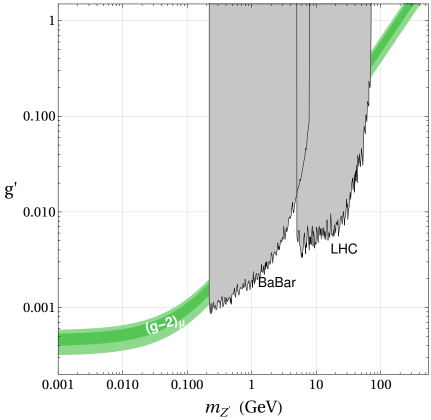
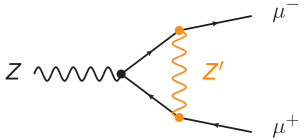


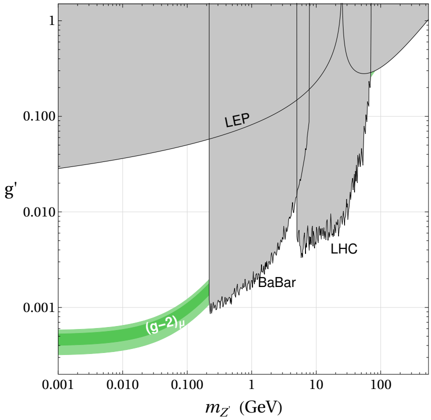
What about the region below the di-muon threshold?

$$e^+e^- \to \mu^+\mu^- + E_{\text{miss}} \ ?$$

Modified Z Couplings to Leptons

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



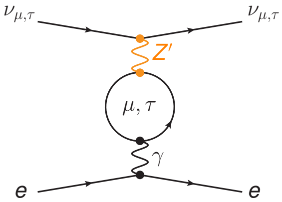


→ constraints from LEP measurements

WA, Gori, Pospelov, Yavin 1403.1269

Neutrino-Electron Scattering

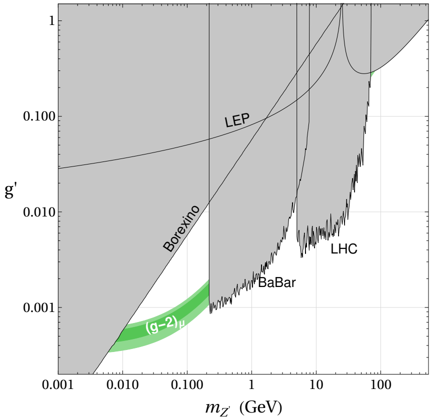
Borexino measures the scattering rate of solar neutrinos on electrons



tiny momentum transfer
$\Rightarrow$ Z' can mix with photon

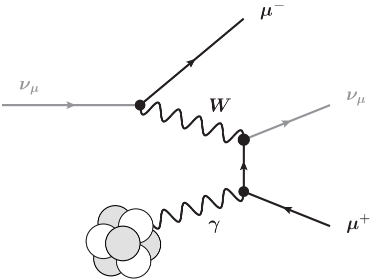
relevant constraint at low masses

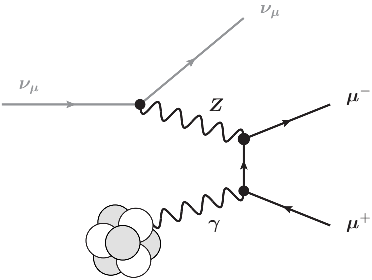
Kamada, Yu 1504.00711



Neutrino Tridents

- neutrino induced $\mu^+\mu^-$ production in the Coulomb field of a heavy nucleus: "neutrino trident production"





Neutrino Tridents

- neutrino induced $\mu^+\mu^-$ production in the Coulomb field of a heavy nucleus: "neutrino trident production"

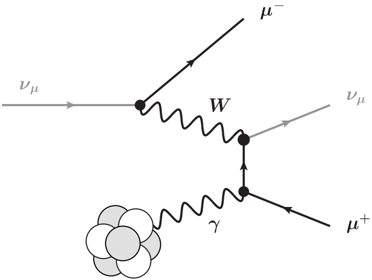
- Z' contribution to the cross section
  (WA, Gori, Pospelov, Yavin, 1406.2332)

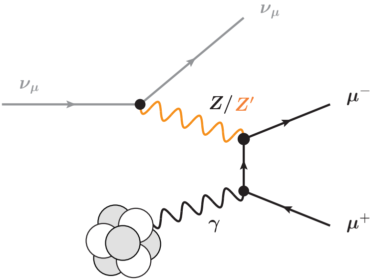
$$\frac{\sigma}{\sigma_{\rm SM}} \simeq \frac{1 + \left(1 + 4s_W^2 + \frac{2v^2 (g')^2}{M_{Z'}^2}\right)^2}{1 + (1+4s_W^2)^2}$$

experimental measurement by CCFR

$$\sigma/\sigma_{\rm SM} = 0.82 \pm 0.28$$

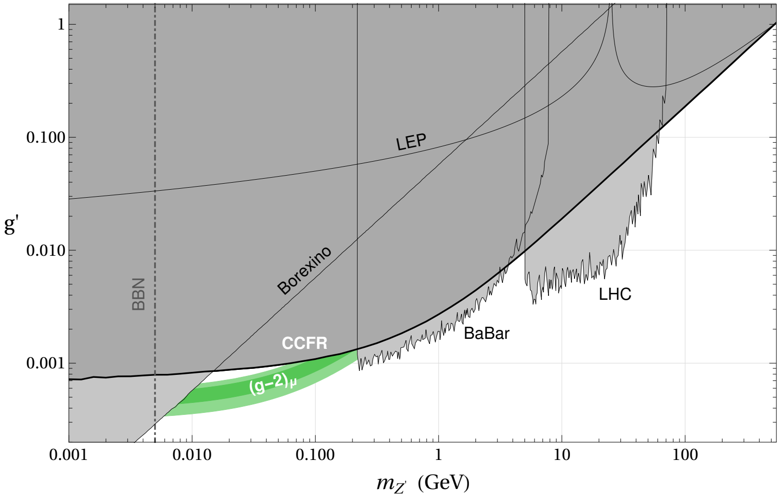
(CCFR, PRL66 (1991) 3117)





Summary of Current Constraints on $L_\mu - L_\tau$

WA, Gori, Pospelov, Yavin, 1406.2332 (updated)



Neutrino Tridents at DUNE

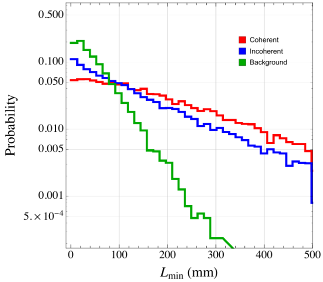
WA, Gori, Martin-Albo, Sousa, Wallbank (in preparation)

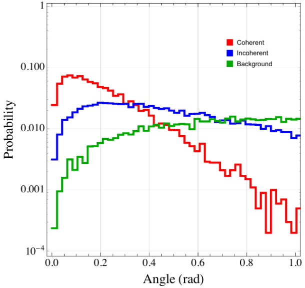
expect $\sim$ 150 trident events per year
in the DUNE near detector

main challenge:
huge background from $\nu_\mu N \to \mu^- N' \pi$

developed optimized event selection
based on simple kinematical cuts

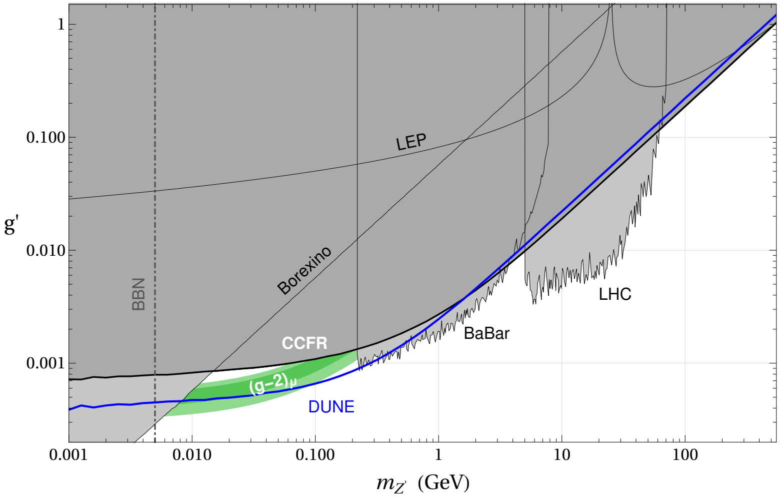
we find that DUNE should be able to
measure the trident cross section with
$\sim$ 20% accuracy



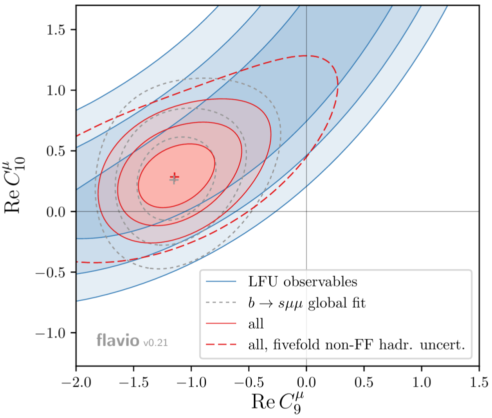


Expected DUNE Sensitivity

WA, Gori, Martin-Albo, Sousa, Wallbank (in preparation)



Addressing the $b \to s\ell\ell$ anomalies



WA, Stangl, Straub 1704.05435

WA, Niehoff, Stangl, Straub 1703.09189

(+ many others ...)

R_K and R_{K^*} are fully compatible with other anomalies that are seen in $b \to s\mu\mu$ transitions ("P_5' and friends")

Best description of all anomalies by:

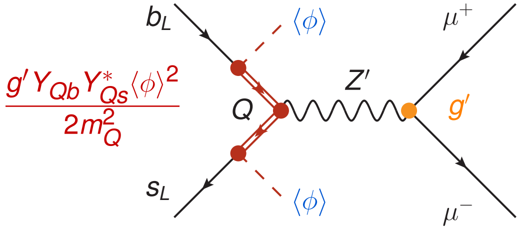
new physics in final states with muons

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

SM-like final states with electrons

add effective flavor violating quark couplings to the $L_\mu - L_\tau$ model

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

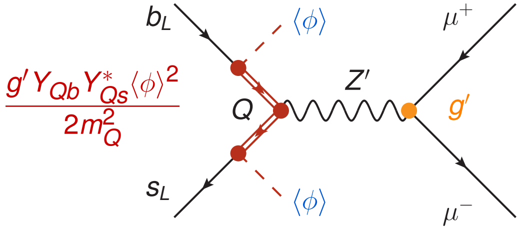


Q: heavy vector-like fermions with mass $\sim 1 - 10$ TeV
ϕ: the scalar that breaks $L_\mu - L_\tau$

Extended $L_\mu - L_\tau$ Model

add effective flavor violating quark couplings to the $L_\mu - L_\tau$ model

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



predicted Lepton Universality Violation!

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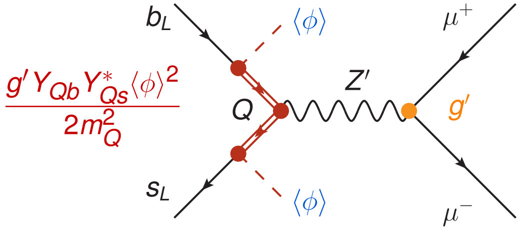


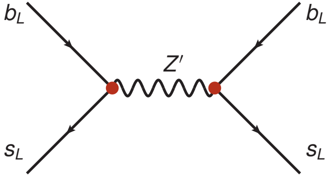
predicted Lepton Universality Violation!

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

(independent of the Z' mass and g' gauge coupling!)

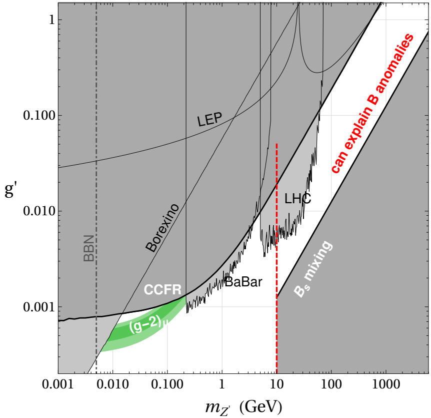
Q: heavy vector-like fermions with mass $\sim 1 - 10$ TeV
ϕ: the scalar that breaks $L_\mu - L_\tau$

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

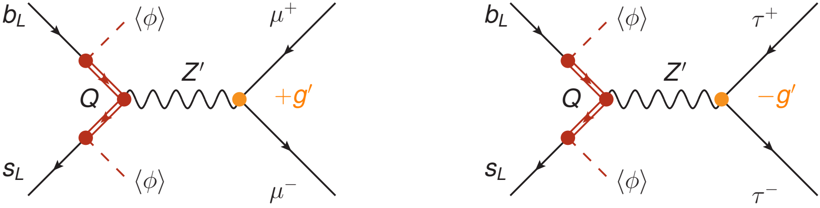


$$M_{12}^{\rm NP} \propto \frac{(g')^2 \langle \phi \rangle^4}{m_{Z'}^2 m_Q^4} = \frac{m_{Z'}^2}{(g')^2 m_Q^4}$$

gives upper bound on the Z' mass
(if we want to explain the anomalies)



$L_\mu - L_\tau$ 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

Precise Predictions for Plenty LFU Observables

ratios of branching ratios

$$R_K = \frac{\text{BR}(B \to K\mu\mu)}{\text{BR}(B \to Kee)}$$

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

$$R_\phi = \frac{\text{BR}(B_s \to \phi\mu\mu)}{\text{BR}(B_s \to \phi ee)}$$

...

$$R_i^{\text{SM}} \simeq 1$$

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...

$$R_i^{\text{SM}} \simeq 1$$

differences of angular observables

WA, Yavin 1508.07009

(also Capdevilla et al. 1605.03156; Serra et al. 1610.08761)

$$D_{P_5'} = P_5'(B \to K^*\mu\mu) - P_5'(B \to K^*ee)$$

$$D_{A_{\text{FB}}} = A_{\text{FB}}(B \to K^*\mu\mu) - A_{\text{FB}}(B \to K^*ee)$$

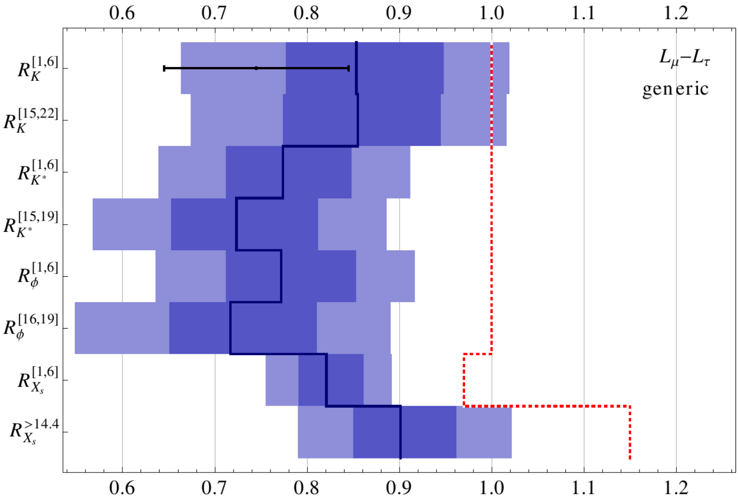
$$D_{F_L} = F_L(B \to K^*\mu\mu) - F_L(B \to K^*ee)$$

...

$$D_i^{\text{SM}} \simeq 0$$

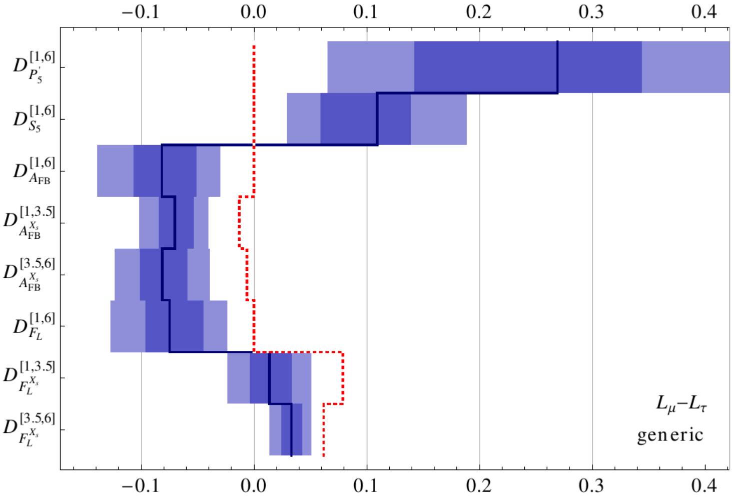
Predictions for LFU Ratios

WA, Yavin 1508.07009



Predictions for LFU Differences

WA, Yavin 1508.07009



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$\Rightarrow$ no lepton flavor violating couplings of the Z'
$\Rightarrow$ negligible rates of $B_s \to \tau\mu$, $B \to K^{(*)}\tau\mu$, etc
(in contrast to many other models)

More Predictions of $L_\mu - L_\tau$

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(c) $B \to K^{(*)}\nu_\mu\bar{\nu}_\mu$ suppressed, $B \to K^{(*)}\nu_\tau\bar{\nu}_\tau$ enhanced,
$B \to K^{(*)}\nu_e\bar{\nu}_e$ unaffected
neutrino flavor cannot be measured in experiment
$\Rightarrow$ $B \to K^{(*)}\nu\bar{\nu}$ is SM-like to a very good approximation
(in contrast to many other models)

Connection to
Dark Matter?

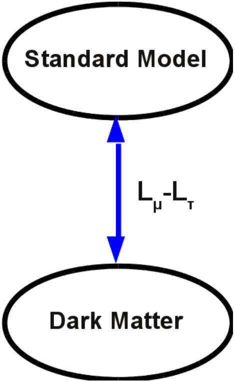
Adding Dark Matter to the $L_\mu - L_\tau$ Model

$L_\mu - L_\tau$ can be a
portal to dark matter

simple example: dark matter is a
Dirac fermion charged under $L_\mu - L_\tau$

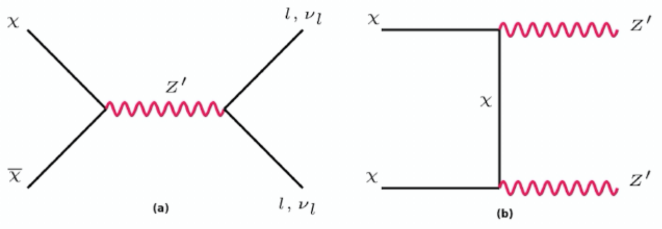
$$q_\chi g' \bar{\chi}\gamma^\mu \chi Z'_\mu$$

WA, Gori, Profumo, Queiroz 1609.04026



(for similar setups see Kile et al. 1411.1407; Kim et al. 1505.04620; Baek 1510.02168 ...)

Dark Matter Annihilation



relic density is set by annihilation into muons, taus, and neutrinos through a s-channel Z' and/or annihilation into Z' bosons

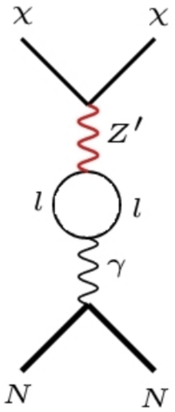
Dark Matter Direct Detection

Dark Matter nucleus scattering at 1-loop

(corresponds to finite loop induced kinetic mixing of Z' and photon at very low energies)

$$\sigma_{\rm SI} = \frac{m_\chi^2 m_N^2}{(m_\chi + m_N)^2} \frac{(g')^4 q_\chi^2}{m_{Z'}^4} \frac{\alpha_{\rm em}^2 Z^2}{9\pi^2} \log^2\left(\frac{m_\tau^2}{m_\mu^2}\right)$$

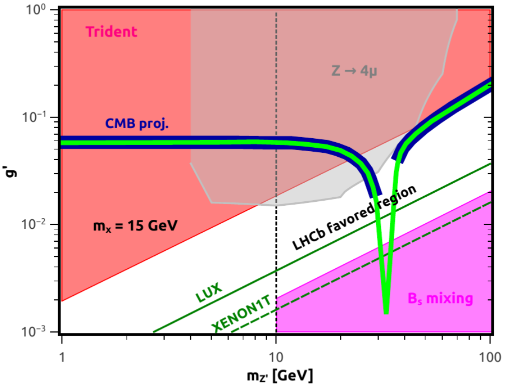
can be sizable, despite the loop suppression



Dark Matter and B Anomalies

because of constraints from direct detection, right relic density can only be obtained close to the resonance $m_{Z'} \simeq 2m_\chi$

expected sensitivity of Xenon1T should cover the entire parameter space that allows to explain the B physics anomalies



WA, Gori, Profumo, Queiroz 1609.04026

current direct detection limit pretty close to the XENON1T projection (sorry, no time to update)

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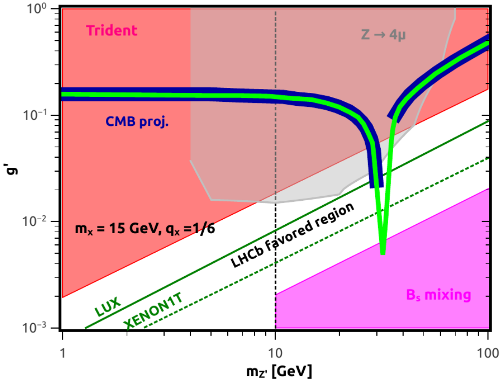
parameter space can open up with smaller dark matter charges



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(4) No lepton flavor violating *b* decays ($B \to K^{(*)}\tau\mu$, etc)
at an experimentally accessible level.

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will be confirmed with more data.

(2) The $B_s \to \mu^+\mu^-$ decay is SM-like.

(3) The $B \to K^{(*)}\nu\bar{\nu}$ decays are SM-like.

(4) No lepton flavor violating *b* decays ($B \to K^{(*)}\tau\mu$, etc)
at an experimentally accessible level.

(5) $B \to K^{(*)}\tau^+\tau^-$ rates are enhanced by 25%
(build FCC-ee to confirm :-)).