LFUV at MuC

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Motivation

- The LHCb anomalies in $b \to s\mu^{+}\mu^{-}$ decays remind us that — New Physics might take an exotic form an option we should embrace given the present status of the field.
- Several *anomalous* observables: BRs, angular distributions, LFUV ratios. see LHCb Implications next week
- Coherent explanation by a short-distance $bsμμ$ contact interaction — $\mathcal{O}(10^{-5})G_F$ — the violation of perturbative unitarity $~\lesssim 100 \,\mathrm{TeV}$
- New mass threshold in the vicinity of colliders?
- Today: Azatov, Garosi, AG, Marzocca, Salko,Trifinopoulos; [2205.13552](https://arxiv.org/abs/2205.13552)

Complementary high- p_T searches at future colliders: FCC-hh versus MuC

The scope

Competitors

New Physics benchmarks: F SICS-DEITCHIH III III IS.

1. Semileptonic 4F interactions and two second-generation leptons, and two second-

2. Gauged $U(1)$ extensions and $U(2)$

leptoquarks (color-triplet scalars or vectors).

The Muon Beam

- Collinear radiation: Spreads the muon energy to lower values and generates different initial states \Longrightarrow Parton Distribution Functions
- We cross-check and numerically solve the DGLAP equations from (Han et al, 2007.14300, 2103.09844) with appropriate initial conditions at the LL accuracy
- Selected PDFs at $Q = 3 \text{ TeV}$:

4

The Muon Beam

Parton luminosities

$$
\mathcal{L}_{ij}(\tau) = \int_{\tau}^{1} \frac{dx}{x} f_i(x, m) f_j\left(\frac{\tau}{x}, m\right) \qquad m^2 = (p_i + p_j)^2
$$

$$
\tau = m^2 / s_0
$$

$$
m^2 = (p_i + p_j)^2
$$

$$
\tau = m^2/s_0
$$

Azatov, Garosi, AG, Marzocca, Salko,Trifinopoulos; [2205.13552](https://arxiv.org/abs/2205.13552)

The signatures at MuC

 $m_X < \sqrt{ }$

 $m_X > \sqrt{s_0}$

- Kinematical features at *mμμ* ∼ *mX* e.g. a resonance peak
- Corrections to the bins $m_{\mu\mu} \approx \sqrt{s_0}$ "fifth force searches"

- Monotonously decreasing ϵ and collidate and considering the full unbroken standard the full unbroken ϵ luminosities in proton colliders and right chiralities, as well as the two transverse results.

• Corrections to the bins $m_{\mu\mu} \approx \sqrt{s_0}$ "EFT searches"

Results

Contact interactions

Figure 7. Sensitivity reach (95%CL) for the $(\bar{s}_L \gamma_\alpha b_L)(\bar{\mu}_L \gamma^\alpha \mu_L)$ contact interaction as function of the upper cut on the final-state invariant mass, compared to the value required to fit $bs\mu\mu$ anomalies (dashed orange line).

Contact interactions

Figure 8. Sensitivity reach (95%CL) for the $(\bar{b}_L \gamma_\alpha b_L)(\bar{\mu}_L \gamma^\alpha \mu_L)$ contact interaction as function of the upper cut on the final-state invariant mass. Solid (dashed) lines represent the limit for positive (negative) values of $C_{bb\mu\mu}$. The orange dotted and dashed lines shows reference values in relation to the $bs\mu\mu$ anomalies fit, with or without a $1/V_{ts}$ enhancement of the b operator compared to the bs one, respectively. 11

Assuming only the rotations for left-handed fermions and ✓*sb* ⌧ 1, the leading *Z*⁰

Figure 9. Discovery reach at 5σ for the $B_3 - L_\mu$ model with $\epsilon_{sb} = 0$, for different final states at each collider (as indicated by the labels). The region excluded at 95% CL by LHC [111] is above the black line while in the dark gray region the Z' has a large width, signaling a loss of perturbativity.

$$
bs\mu\mu: \ \epsilon_{sb}=-1.7\times10^{-3}\left(\frac{M_{Z'}}{g_{Z'}\text{TeV}}\right)^2
$$

 $0.5 - 1$

 $5 \overline{10}$

 $\overline{5}$ C

Z' models: $L_\mu - L_\tau$ generation, respectively. The relevant *SU*(2)*^L* invariant *Z*⁰ interactions are

corresponding left-handed quark down-quark down-quark down-quark mass basis of third and second-quark mass basi
Third and second-quark mass basis of third and second-quark mass basis of third and second-quark mass basis of

 $\frac{1}{2}$ + h.e $\mathcal{L}_{Z_L'}^{\mathrm{int}}$ $\frac{dU}{L_{\mu}-L_{\tau}} = -\; g_{Z'} Z^{\prime}_{\alpha}$ $\left[\bar{L}_L^2 \gamma^\alpha L_L^2 + \bar{\mu}_R \gamma^\alpha \mu_R - \bar{L}_L^3 \gamma^\alpha L_L^3 - \bar{\tau}_R \gamma^\alpha \tau_R + \right.$ $\mathcal{L}[\epsilon_b]$ - $Q_L^{\sigma} \gamma^{\alpha} Q_L^{\sigma} + |\epsilon_s|$ - $Q_L^{\sigma} \gamma^{\alpha} Q_L^{\sigma}$ $\overline{\Omega}^*$ $R\gamma^0$ $\alpha_{\mu R} - \bar{L}_L^3 \gamma^{\alpha} L_L^3$ - $-\bar{\tau}_P \gamma^\alpha \tau_P$ *L* $\frac{1}{2}$ + $\frac{1}{2}$ + + $|\epsilon_b|^2 \bar{Q}_L^3 \gamma^{\alpha} Q_L^3 + |\epsilon_s|^2 \bar{Q}_L^2 \gamma^{\alpha} Q_L^2 + (\epsilon_b \epsilon_s^* \bar{Q}_L^2 \gamma^{\alpha} Q_L^3 + \text{h.c.}) + ...]$

dark gray region the Z' has a large width, signaling a loss of perturbativity. **Figure 11**. Discovery reach at 5σ for the $L_{\mu} - L_{\tau}$ model with $\epsilon_s = \epsilon_b = 0$ in Eq. (5.6). In the

$$
bs\mu\mu: \epsilon_b \epsilon_s^* = -5.7 \times 10^{-4} \left(\frac{M_{Z'}}{g_{Z'} \text{TeV}}\right)^2
$$

$$
es_c \epsilon_b = -\epsilon_s
$$

$$
0.100
$$

$$
0.010
$$

$$
0.010
$$

$$
0.010
$$

$$
0.000
$$

Even after imposing *C^µ* ⁹ = 0*.*73, we are left with other free parameters besides *MZ*⁰ and *gZ*0. Our goal here is to study the case where *|*✏*s/*✏*b|* ⇠ *O*(1) which is qualitatively different from the model in Section 5.1. For concreteness, in our numerical analysis we assume ✏*^b* = ✏*^s* and Im ✏*^b* = 0. With this simplification, we are able to plot our results in the (*MZ*0*, gZ*0) plane. Analogously to Section 5.1, the *B^s* mixing, *C*¹ *Bs* = (*gZ*0✏⇤ *s*✏*b*)2*/M*² Eq. (5.8), imply the lower limit *^gZ*⁰ *>* ⁰*.*125*MZ*0*/*TeV. The *^D*⁰ *^D*⁰ mixing gives another constraint on the parameters: *C*¹ *^D*⁰ = (*gZ*0*V* ⇤ *usVcs|*✏*s|* ²)2*/M*² *^Z*⁰ *<* ²*.*⁵ ⇥ ¹⁰13GeV² [158, 159], corresponding to *gZ*⁰ *>* 0*.*25*MZ*0*/*TeV. Interestingly, *D*⁰ mixing provides stronger constraints than *Bs*-mixing in this model. Our main results are shown in Fig. 12. The present CMS *pp* ! *^µ*+*µ* data [111] exclude at 95% CL the region *inside* the thick black lines. For the future colliders listed in Table 1, the parameter space discoverable at 5 is the one *on the side* of the corresponding line where the label is shown. To help the reader better understand the sensitivity reach for each collider, below the main plot in Fig. 12 we report four smaller plots where the 5 discover sensitivity for each collider is isolated and shaded. Note that, in the case of *pp* ! *^µ*+*µ* at the (*MZ*0*, gZ*0) plane. Analogously to Section 5.1, the *B^s* mixing, *C*¹ = (*gZ*0✏⇤ Eq. (5.8), imply the lower limit *^gZ*⁰ *>* ⁰*.*125*MZ*0*/*TeV. The *^D*⁰ *^D*⁰ mixing gives another constraint on the parameters: *C*¹ *^D*⁰ = (*gZ*0*V* ⇤ *usVcs|*✏*s|* ²)2*/M*² corresponding to *gZ*⁰ *>* 0*.*25*MZ*0*/*TeV. Interestingly, *D*⁰ mixing provides stronger constraints than *Bs*-mixing in this model. Our main results are shown in Fig. 12. The present CMS *pp* ! *^µ*+*µ* data [111] exclude at 95% CL the region *inside* the thick black lines. For the future colliders listed in Table 1, the parameter space discoverable at 5 is the one *on the side* of the corresponding line where the label is shown. To help the reader better understand the sensitivity reach for each collider, below the main plot in Fig. 12 we report four smaller plots where the 5 discover sensitivity for each collider is isolated and shaded. Note that, in the case of *pp* ! *^µ*+*µ* at hadron colliders or *^µ*+*µ* ! *jj* at MuCs, the only accessible region is for intermediate values of *gZ*0. According to Eq. (5.8), for a given *Z*⁰ mass the couplings to quarks are inversely proportional to *gZ*0. Since too large *gZ*⁰ values imply too small couplings to quarks, and vice versa, there is always a suppression in ⇥ *B* for the two processes. The di-muon searches Azatov, Garosi, AG, Marzocca, Salko,Trifinopoulos; [2205.13552](https://arxiv.org/abs/2205.13552)

 $\overline{5}0$

 v_{α}

Scalar Leptoquark

the discoverable side of a curve.

NOT FOR DISTRIBUTION JHEP_106P_0622 v3 We start with the leptoquark *^S*³ ⇠ (¯3*,* ³*,* ¹*/*3) [22]. The interaction Lagrangian reads *^L*int *S*³ = *iµ Qi c ^L* ✏ *IL*² *LS^I* ³ + h.c. *,* (6.1) degenerate mass spectrum for the components, as expected from the *SU*(2)*^L* gauge symmetry. In the mass basis of SM fermions, the interaction Lagrangian (6.1) becomes ⁼ *iµS*(1*/*3) ³ (*V* ⇤ *jiuj c ^L µL*+*di c ^L* ⌫*µ*)+^p ²*iµ* ⇣ *V* ⇤ *jiS*(2*/*3) ³ *^uj c ^L* ⌫*^µ ^S*(4*/*3) ³ *di c ^L µ^L* ⌘ +h.c. *.* (6.3)

The 5σ discovery prospects at future colliders for the S_3 leptoquark assuming the Figure 13. \pm to mu $\frac{1}{4}$ and $\frac{1}{4}$

Scalar Leptoquark ⁹ ⁼ *C^µ* ¹⁰ = *r l* ahtor

bµsµ

p
Palau

$$
bs\mu\mu:~~\lambda_{b\mu}\lambda_{s\mu}=-8.4\times10^{-4}\left(\frac{M_{S_3}}{\text{TeV}}\right)^2
$$

C^µ

Let us consider the SM with a heavy vector leptoquark *U₂* Assuming only left-handed couplings, the interaction Lagrangian is

Vector Leptoquark ⁹ ⁼ *C^µ* ¹⁰ = *r l* abtor

bµsµ

p
Palau

$$
bs\mu\mu:~~\lambda_{b\mu}\lambda_{s\mu}=-8.4\times10^{-4}\left(\frac{M_{U_1}}{\text{TeV}}\right)^2
$$

C^µ

Resonant Leptoquark at FCC-hh

