New Physics in $b \to s\mu\mu$: FCC-hh or a Muon Collider?

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[Azatov, Garosi, Greljo, Marzocca, Salko, ST]
2205.13552

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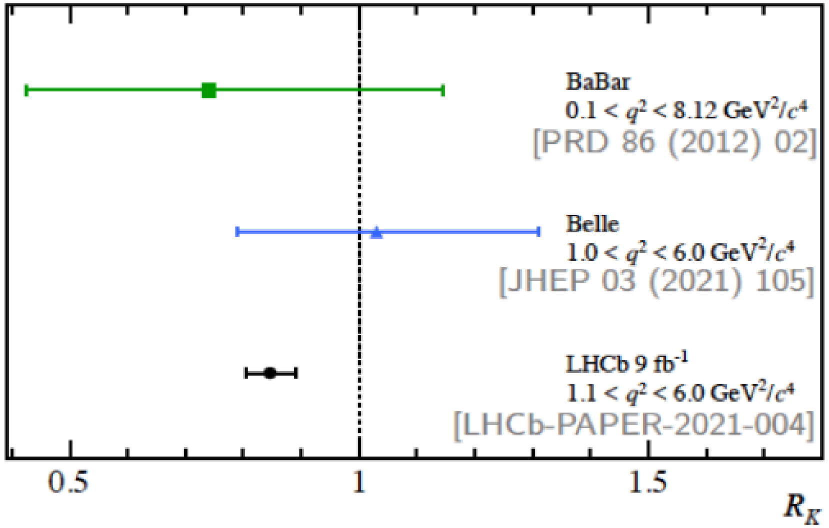
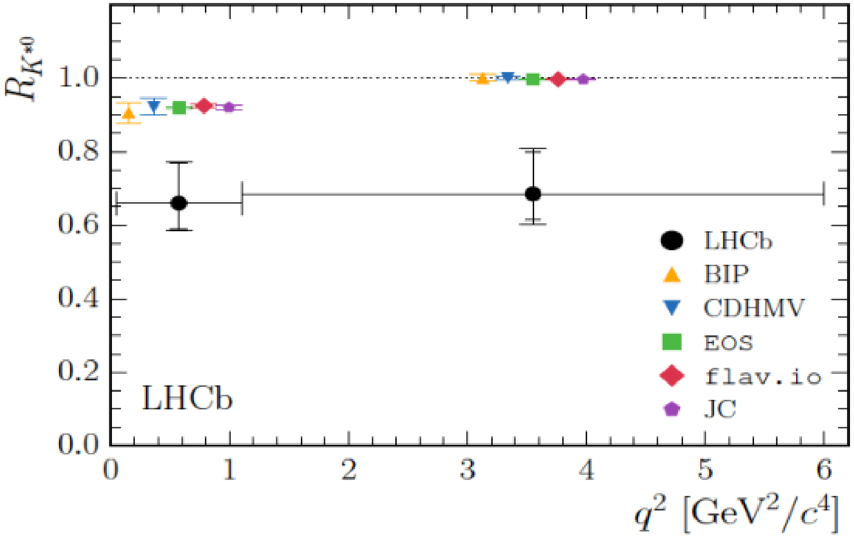
Probes of high-energy scales: rare B decays

- Rare FCNCs are processes where we traditionally anticipate hints of NP.
- Recently, deficit of the charged-current transition in μ vs. e has been observed

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\bar{\mu})}{\mathcal{B}(B \to K^{(*)}e\bar{e})}$$

+ $B_s \to \mu^+\mu^-$, angular distributions of $B \to K^* \mu^+\mu^-$, various BRs





New Physics in $b \to s\mu\mu$?

- R_K survived the latest update by the LHCb even after employing the full dataset of Run I and II <u>independently</u> at 3.1σ!

[LHCb] 2103.11769

- Fits obtained by varying one or two relevant NP WCs at a time yield pulls at a staggering 5σ level!

[Altmannshofer et al] 2103.13370

A recent analysis evaluated the global significant using a conservative & unbiased method and found a **global 4.1σ** (still remarkable!)

[Lancierini et al] 2104.05631

- Yet, there are some unsettling rumors about an upcoming re-analysis.

New LFUV interactions within reach

- The anomalies implies violation of Lepton Flavor Universality (LFUV), which is an accidental symmetry of the SM and they can be coherently explained by a short-distance NP contribution in the underlying $b \to s\mu\mu$ transition.

Contact interactions | Z' vector bosons | Leptoquarks

- If confirmed, they provide empirical evidence for a new mass threshold within the reach of planned colliders!

Collider	C.o.m. Energy	Luminosity	Label
LHC Run-2	13 TeV	140 fb^{-1}	LHC
HL-LHC	14 TeV	6 ab^{-1}	HL-LHC
FCC-hh	100 TeV	30 ab^{-1}	FCC-hh
Muon Collider	3 TeV	1 ab^{-1}	MuC3
Muon Collider	10 TeV	10 ab^{-1}	MuC10
Muon Collider	14 TeV	20 ab^{-1}	MuC14

MUON Collider
FCC

Signatures at a muon collider

- Muon colliders combine the advantages of both proton-proton and electron-positron colliders: high energy reach, where all the collider energy is accessible in $\mu^+\mu^-$ collisions, with high precision measurements, thanks to low QCD background and clean initial state.

- Collinear radiation emitted by splitting of the initial state must be taken into account. → complete EW PDFs of muons!

  [Garosi, Marzocca, ST] TBA

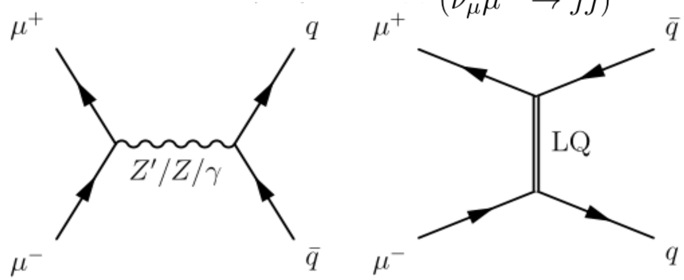
- We assume the same performances between MuC and FCC-hh for the hadronic calorimeter and muon system.

  [FCC-hh: The Hadron Collider] EPJC 79 (2019) 474.

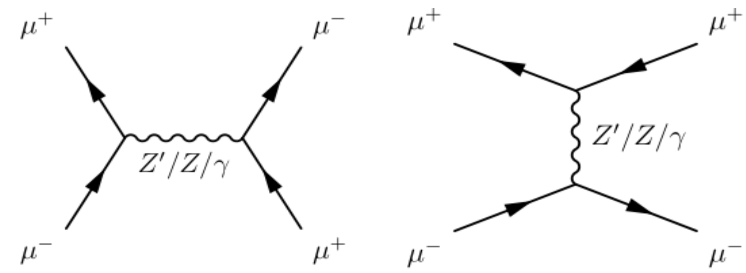
Signatures at a muon collider (channels)

i) Inverted Drell-Yan: $\mu\bar{\mu} \to jj$

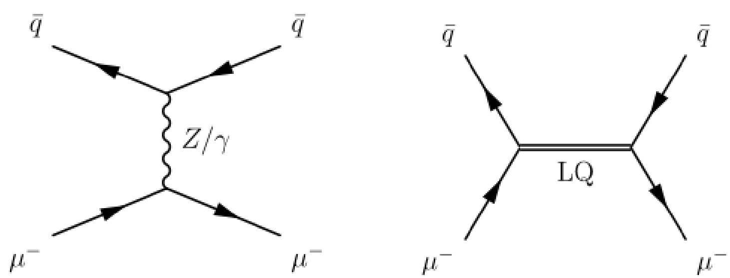
$(\nu_\mu \mu^+ \to jj)$



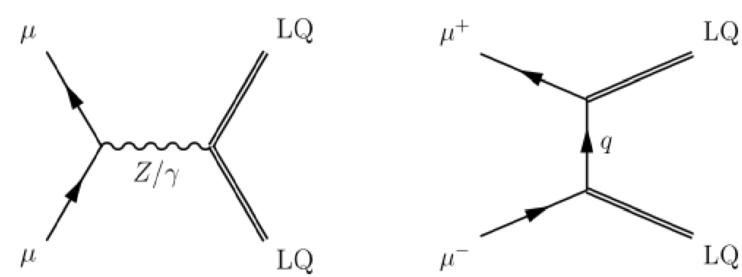
ii) Di-Muon (Tau): $\mu\bar{\mu} \to \mu^+\mu^-$



iii) Mono-lepton plus jet: $\mu\bar{\mu} \to \mu^- j$

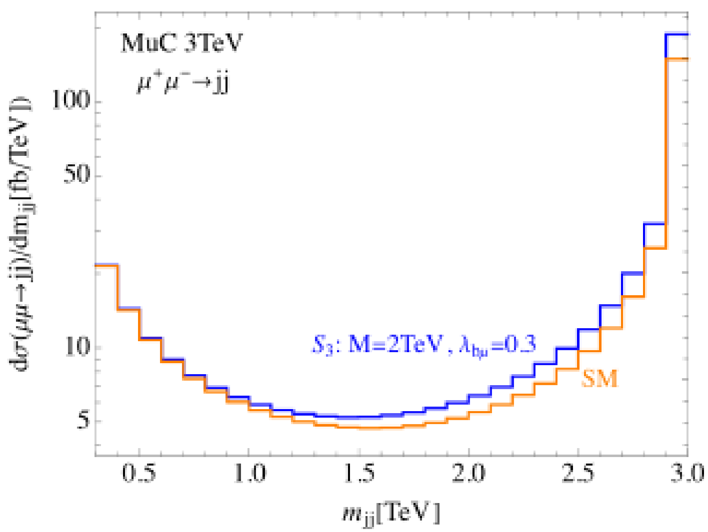


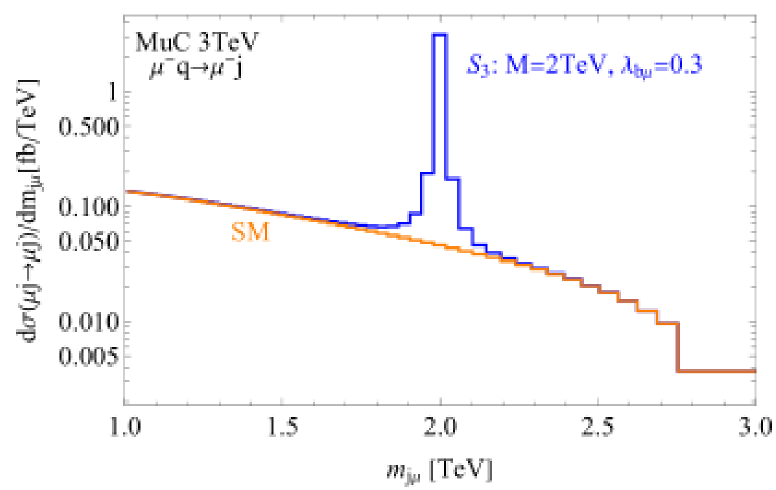
iv) LQ pair production: $\mu\bar{\mu} \to \mathrm{LQ}\overline{\mathrm{LQ}}$



Signatures at a muon collider (sensitivity)

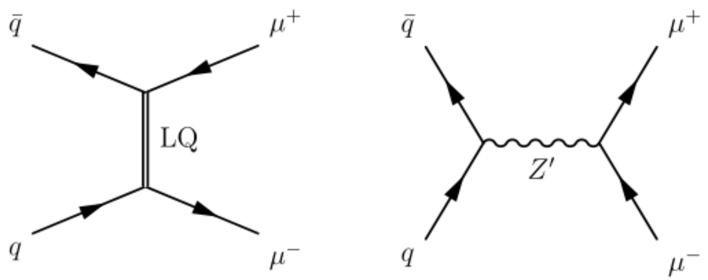
- Due to the luminosities of the valence partons, if the $M_{\text{NP}} < \sqrt{s}$ below the collider energy, the effect is visible both at the shape of the cross-section (resonance peak or *t(u)*-channel exchange) as well as the very precise measurement in the last invariant mass bin.
  For $M_{\text{NP}} > \sqrt{s}$, the sensitivity arises from the latter strategy.



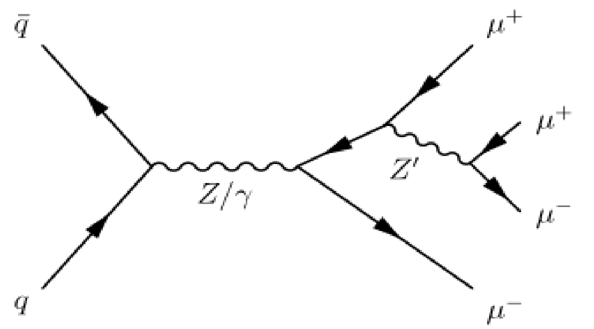


Signatures at a hadron collider(channels)

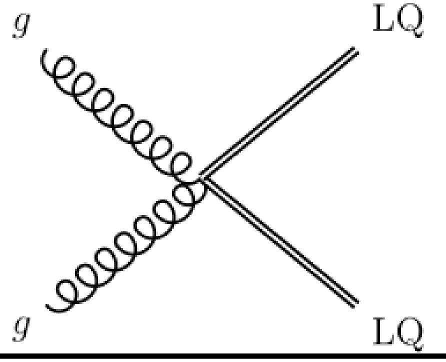
i) Drell-Yan: $pp \to \mu^+\mu^-$



ii) Multilepton: $pp \to 4\mu$



iii) LQ pair production: $pp \to \mathrm{LQ}\overline{\mathrm{LQ}}$

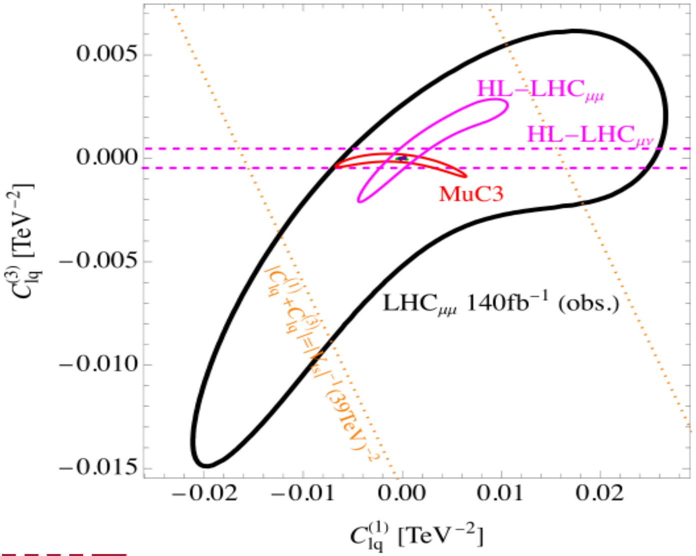


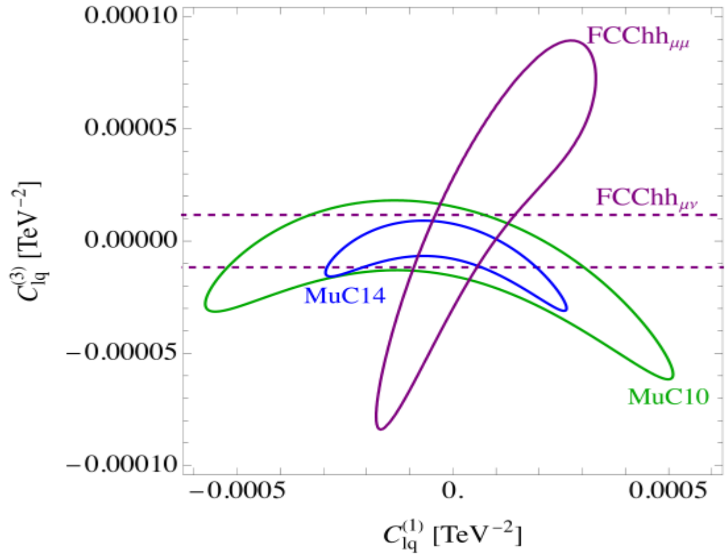
Pessimistic scenario: off-shell NP states (MFV)

- NP states heavier than the accessible energies can still leave a trace in higher-dimensional operators of the SMEFT:

$$\mathcal{L}_{\text{SMEFT}} \supset [C_{\ell q}^{(1)}]_{22ij}(\bar{L}_L^2\gamma_\alpha L_L^2)(\bar{Q}_L^i\gamma^\alpha Q_L^j) + [C_{\ell q}^{(3)}]_{22ij}(\bar{L}_L^2\gamma_\alpha\sigma^a L_L^2)(\bar{Q}_L^i\gamma^\alpha\sigma^a Q_L^j)$$

- **MFV scenario:** $[C_{lq}^{(1)}]_{22ij} = C_{lq}^{(1)}\delta_{ij}$ and $[C_{lq}^{(3)}]_{22ij} = C_{lq}^{(3)}\delta_{ij}$

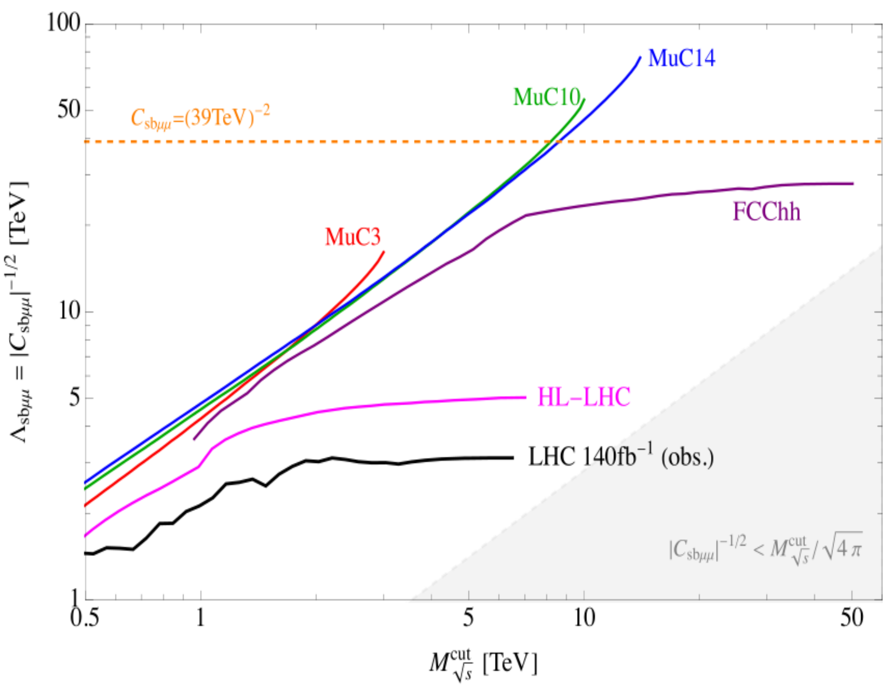


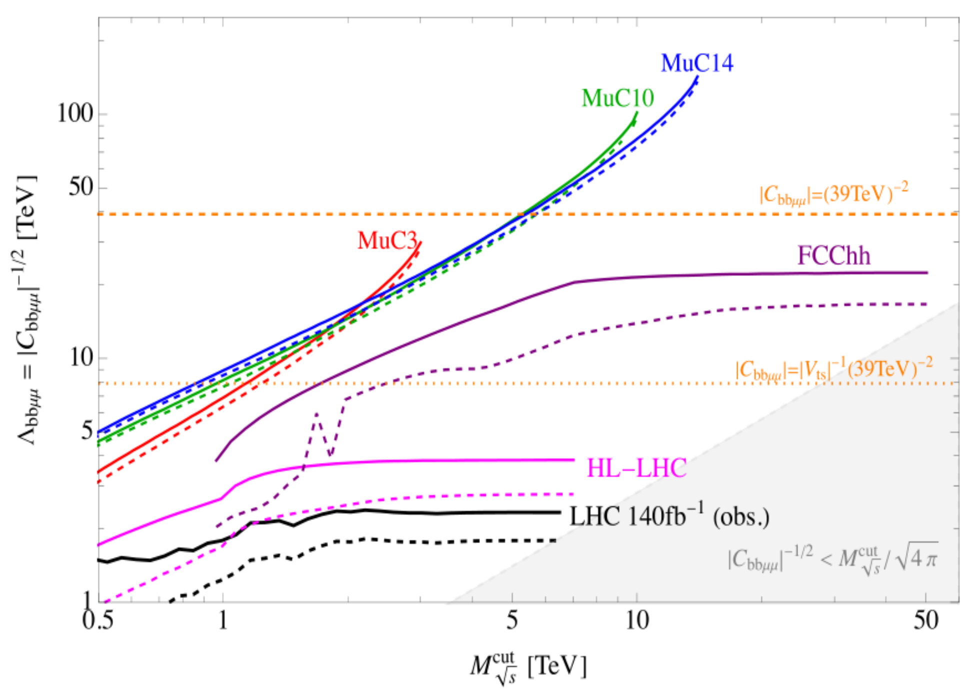


Pessimistic scenario: off-shell NP states ($bs\mu\mu$)

➢ **Addressing $bs\mu\mu$ anomalies:** $C_{sb\mu\mu} = \left([C_{\ell q}^{(1)}]_{2223} + [C_{\ell q}^{(3)}]_{2223} \right)$

Turning on $C_{bb\mu\mu}$ and assuming the alignment $C_{\ell q}^{(1)} = C_{\ell q}^{(3)}$ we obtain:





Z' gauge bosons

We consider models in which the dominant quark coupling is to heavy flavours. There are two qualitatively different scenarios:

1) $g_{sb} \ll g_{bb} \sim g_{\mu\mu}$ realized by gauging $U(1)_{B_3-L_\mu}$:

$$\mathcal{L}^{\rm int}_{Z'_{B_3-L_\mu}} = -\,g_{Z'} Z'_\alpha \left[\frac{1}{3}\bar{Q}^3_L\gamma^\alpha Q^3_L + \frac{1}{3}\bar{b}_R\gamma^\alpha b_R + \frac{1}{3}\bar{t}_R\gamma^\alpha t_R - \bar{L}^2_L\gamma^\alpha L^2_L - \bar{\mu}_R\gamma^\alpha \mu_R + \right.$$
$$\left. + \left(\frac{1}{3}\epsilon_{sb}\bar{Q}^2_L\gamma^\alpha Q^3_L + \text{h.c.}\right) + \mathcal{O}(\epsilon^2_{sb})\right] \,,$$

approximate $U(2)^3$

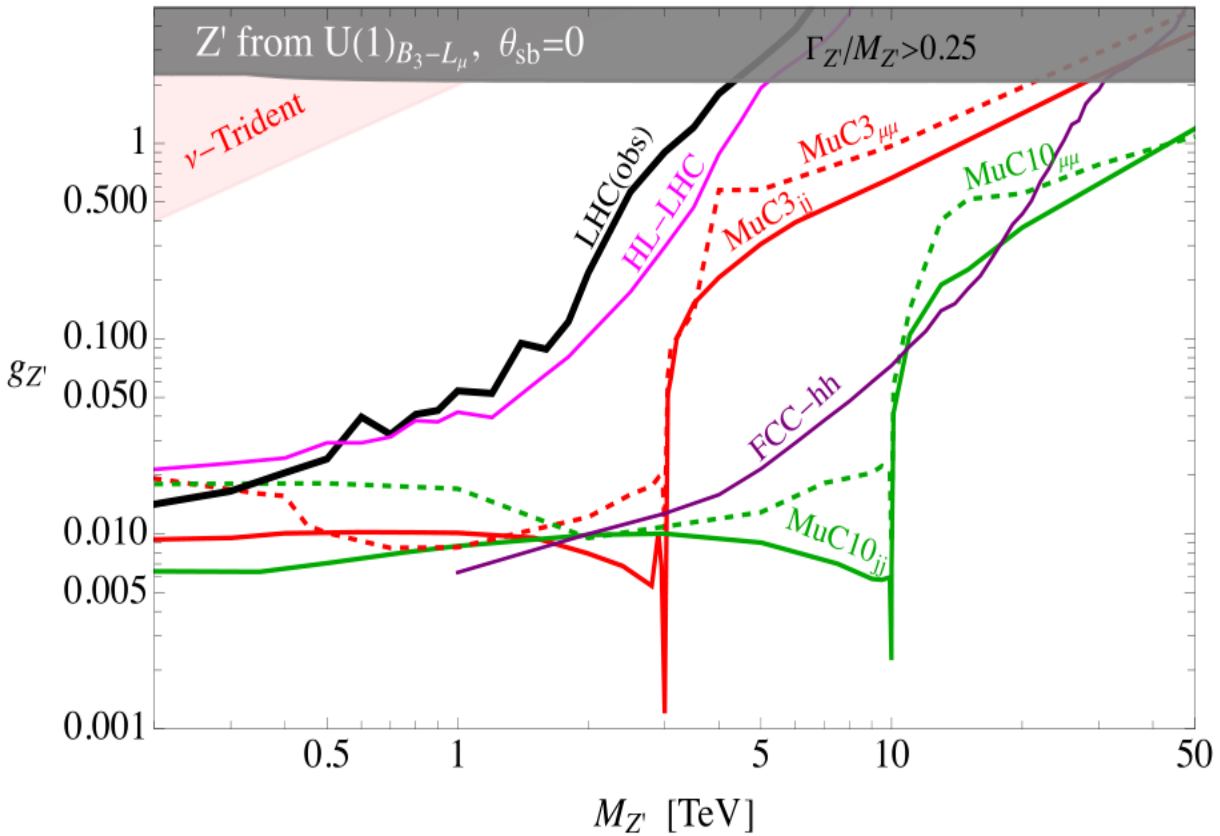
[Greljo et al]
2107.07518

2) $g_{sb} \sim g_{bb} \ll g_{\mu\mu}$ realized by gauging $U(1)_{L_\mu-L_\tau}$:

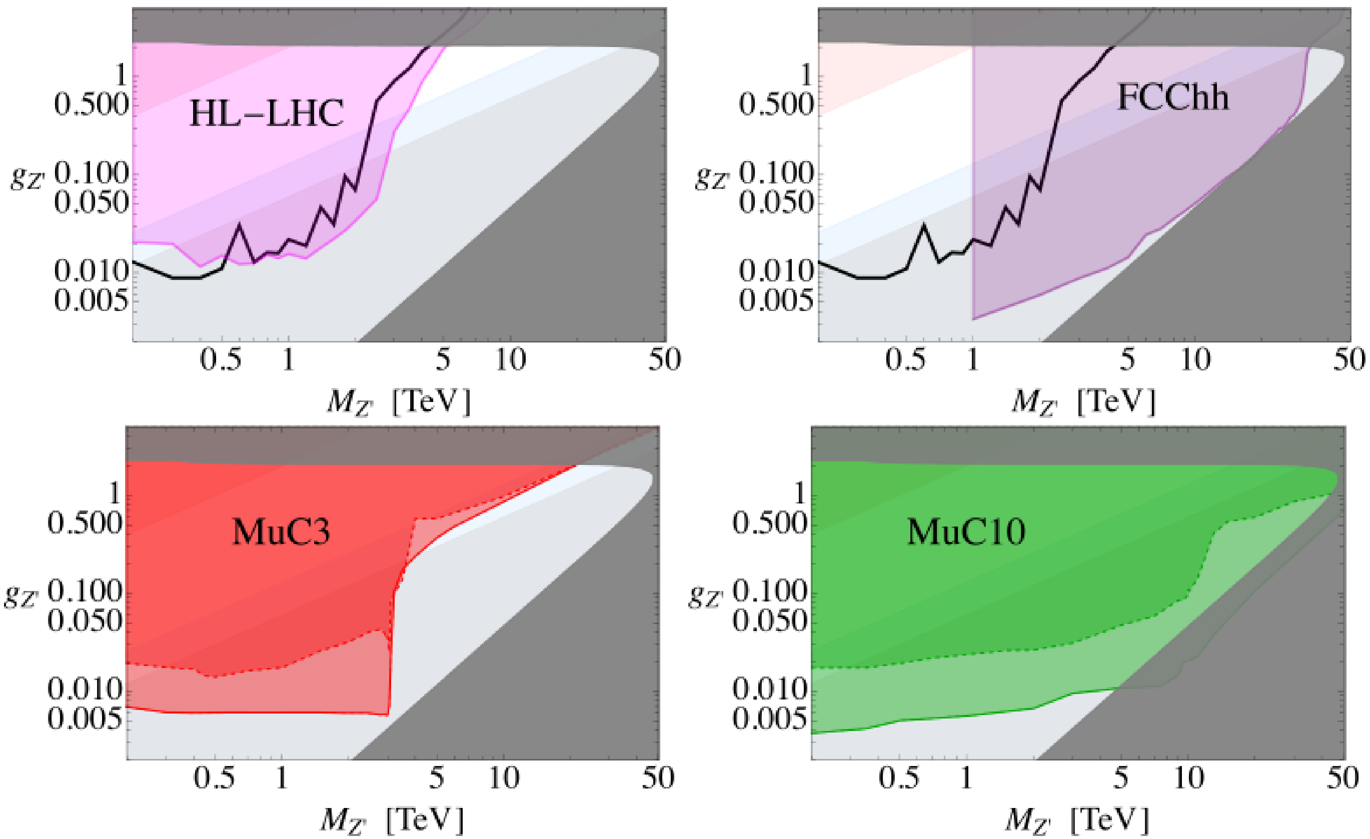
$$\mathcal{L}^{\rm int}_{Z'_{L_\mu-L_\tau}} = -\,g_{Z'} Z'_\alpha \left[\bar{L}^2_L\gamma^\alpha L^2_L + \bar{\mu}_R\gamma^\alpha\mu_R - \bar{L}^3_L\gamma^\alpha L^3_L - \bar{\tau}_R\gamma^\alpha\tau_R + \right.$$
$$\left. + |\epsilon_b|^2\bar{Q}^3_L\gamma^\alpha Q^3_L + |\epsilon_s|^2\bar{Q}^2_L\gamma^\alpha Q^2_L + (\epsilon_b\epsilon_s^*\bar{Q}^2_L\gamma^\alpha Q^3_L + \text{h.c.}) + \ldots\right] \,.$$

quark-phobic (couplings generated via mixing with heavy VLQs)

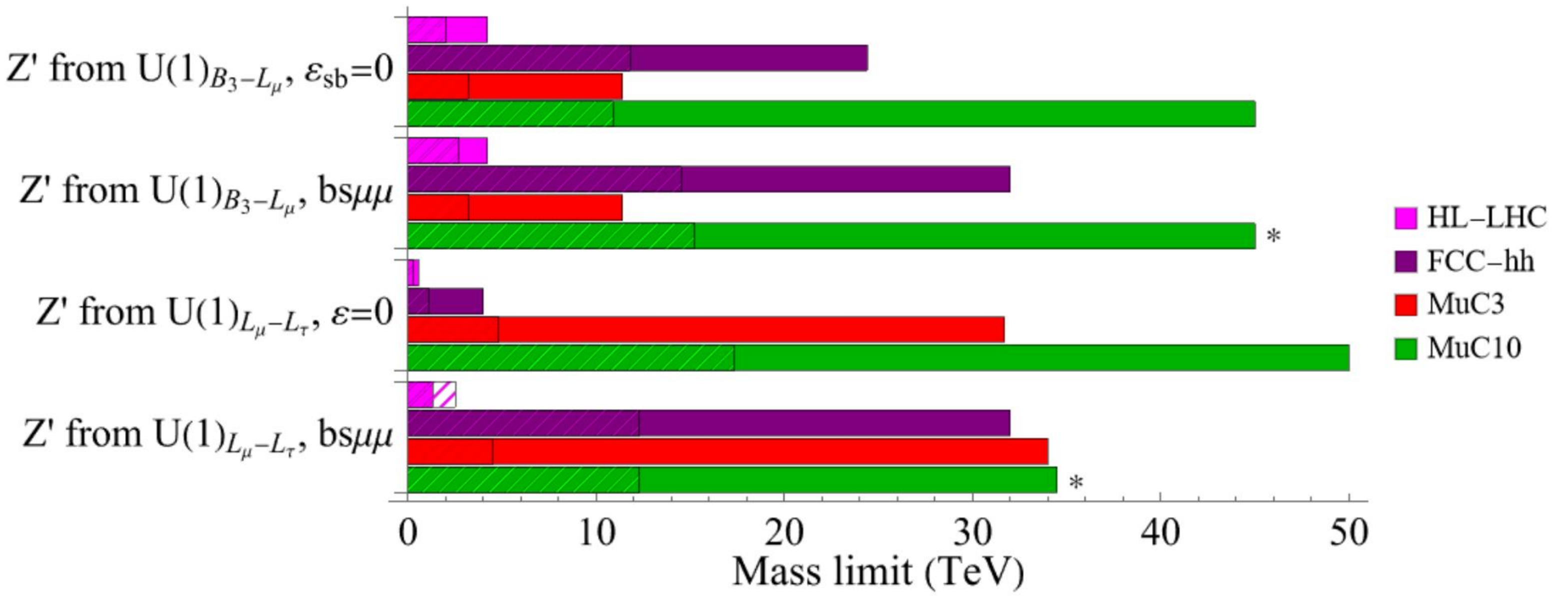
Z' gauge bosons ($U(1)_{B_3-L_\mu}$, no mixing)



Z' from $U(1)_{B_3-L_\mu}$ (addressing $bs\mu\mu$ anomalies)



Z' gauge bosons (prospects)



Leptoquarks

We consider the two viable LQs to the $bs\mu\mu$ anomalies

[Doršner et al] 1603.04993

[Buttazzo et al] 1706.07808

1) Scalar $S_3 \sim (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$

$$\mathcal{L}_{S_3}^{\text{int}} = -\lambda_{i\mu} S_3^{(1/3)} (V_{ji}^* \overline{u_L^{j\,c}} \mu_L + \overline{d_L^{i\,c}} \nu_\mu) + \sqrt{2}\lambda_{i\mu} \left(V_{ji}^* S_3^{(-2/3)} \overline{u_L^{j\,c}} \nu_\mu - S_3^{(4/3)} \overline{d_L^{i\,c}} \mu_L \right) + \text{h.c.}$$

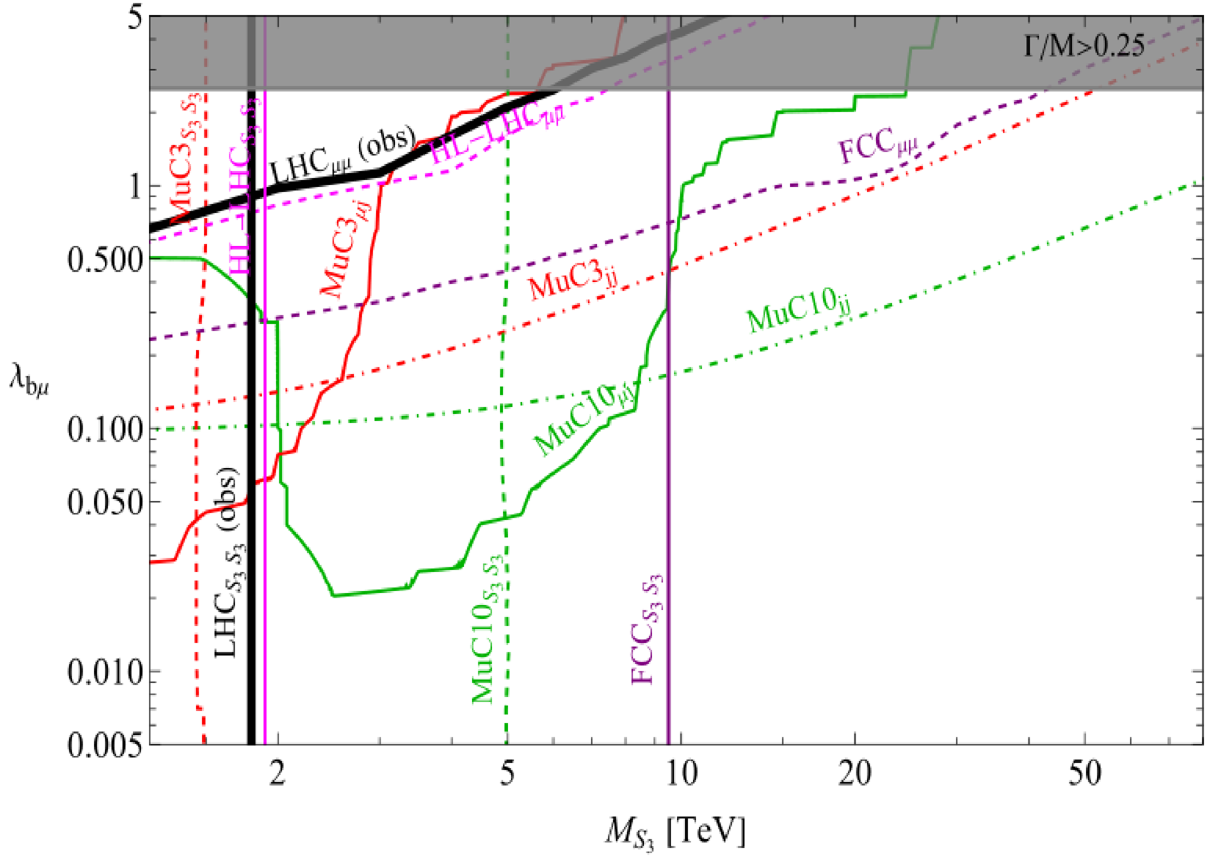
2) Vector $U_1 \sim (\bar{\mathbf{3}}, \mathbf{1}, 2/3)$

$$\mathcal{L}_{U_1}^{\text{int}} = \lambda_{i\mu} U_1^\alpha \left(V_{ji} \bar{u}_L^j \gamma_\alpha \nu_\mu + \bar{d}_L^i \gamma_\alpha \mu_L \right) + \text{h.c.}$$

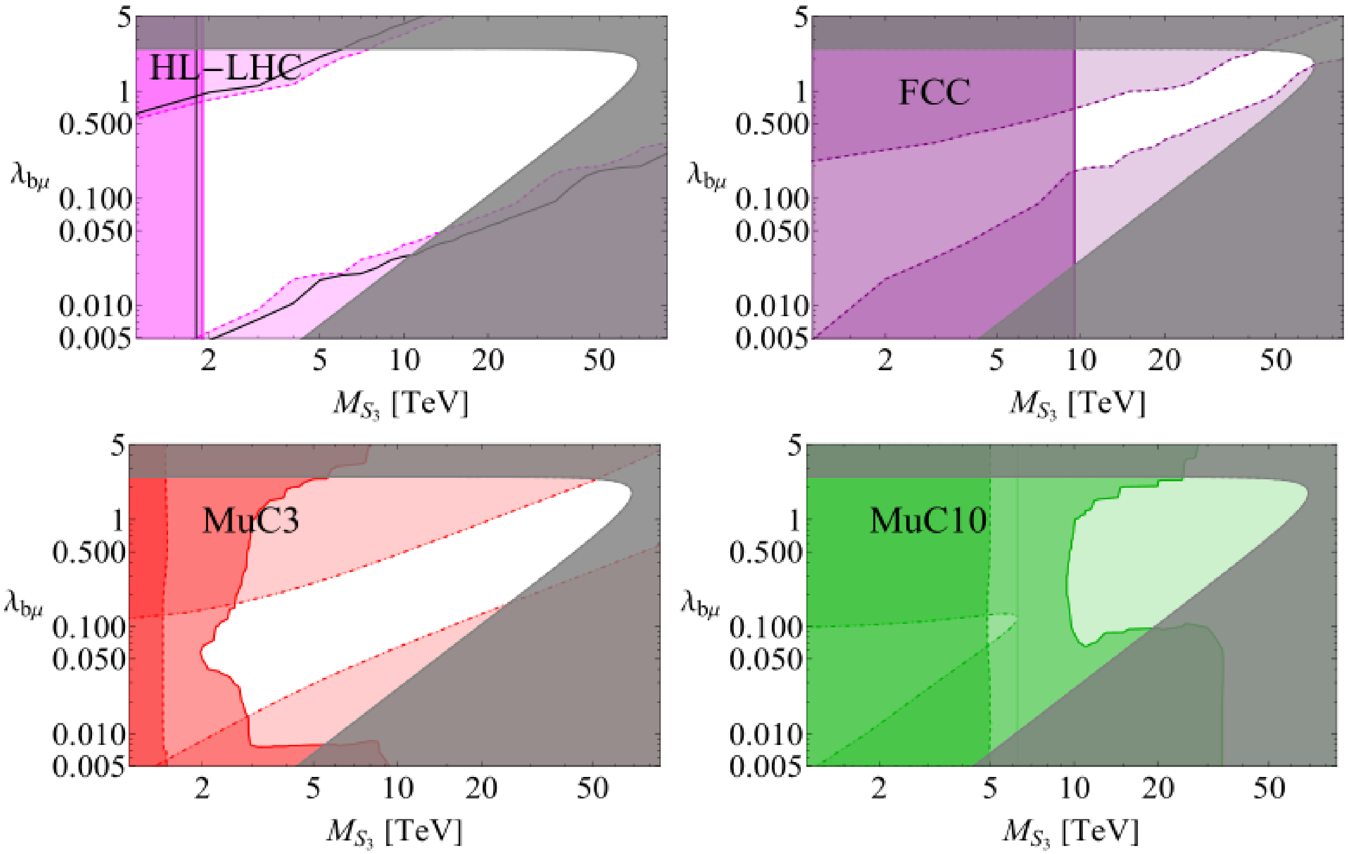
$$\mathcal{L}_{U_1}^{\text{gauge}} = -\frac{1}{2} U_{\mu\nu}^\dagger U^{\mu\nu} - i g_s \kappa_s U_{1\mu}^\dagger T^a U_{1\nu} G^{a\mu\nu} - i g' \frac{2}{3} \kappa_Y U_{1\mu}^\dagger U_{1\nu} B^{\mu\nu}$$

For the flavor structure we assume two scenarios: i) a $U(2)^3$ quark-flavour symmetry and an $U(1)_{\text{LQ}-L_\mu}$ and ii) $U(2)^3 -$ breaking by $\lambda_{s\mu} \neq 0$.

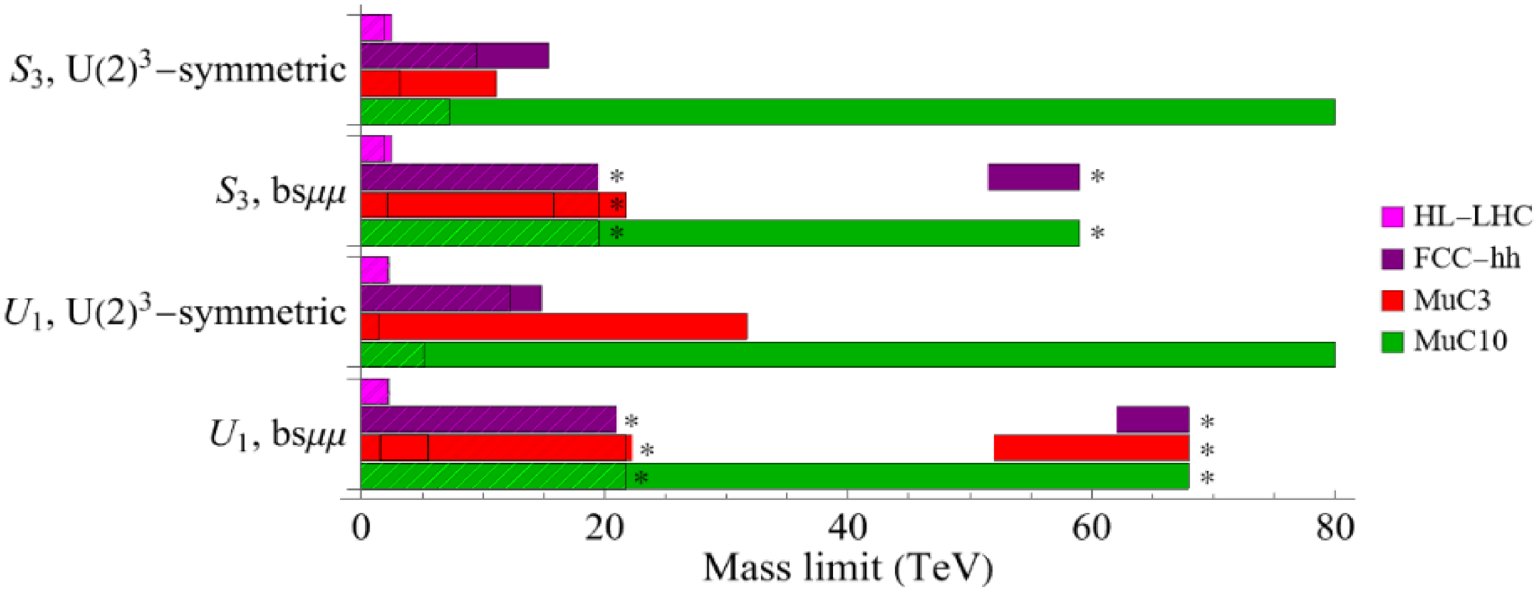
S_3 leptoquark ($U(2)^3$ - symmetric)



S_3 leptoquark (addressing $bs\mu\mu$ anomalies)



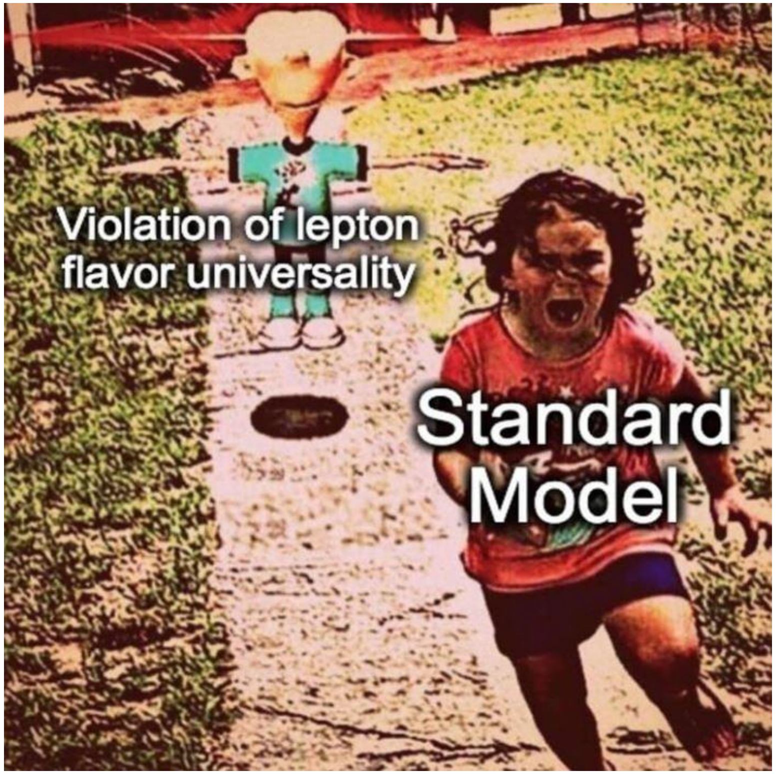
Leptoquarks (prospects)



Conclusions

- The near-term future of particle physics will be charted by precision measurements. The long-term future of the field crucially depends on the decisions we make today about the next generation of high-energy colliders.
- The two most prominent options on the table, namely the FCC-hh and a multi-TeV MuC, will be able to probe most of the parameter space relevant to the *B* meson anomalies (MuC10 probes all scenarios).
- Even beyond the scope of the anomalies, these machines will be able to constraint contact interactions up to scales $\mathcal{O}$(200 TeV) or scrutinize motivated *Z'* and leptoquark models with mediator masses of $\mathcal{O}$(10-100 TeV).

Thank you!!!!



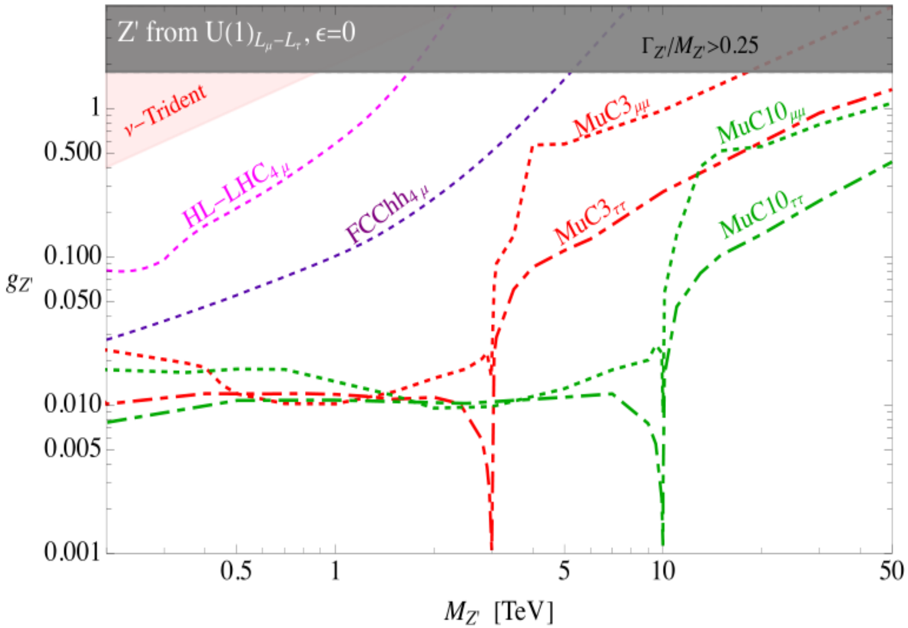
or…

@largememecollider

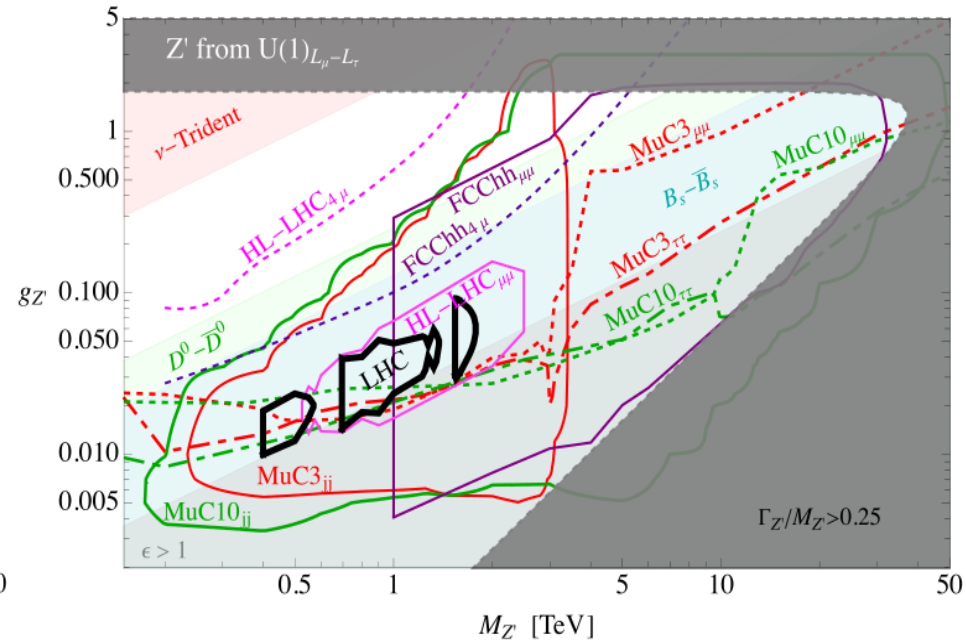
Backup slides

Z' gauge bosons $(U(1)_{L_\mu - L_\tau})$

Quark-phobic scenario:

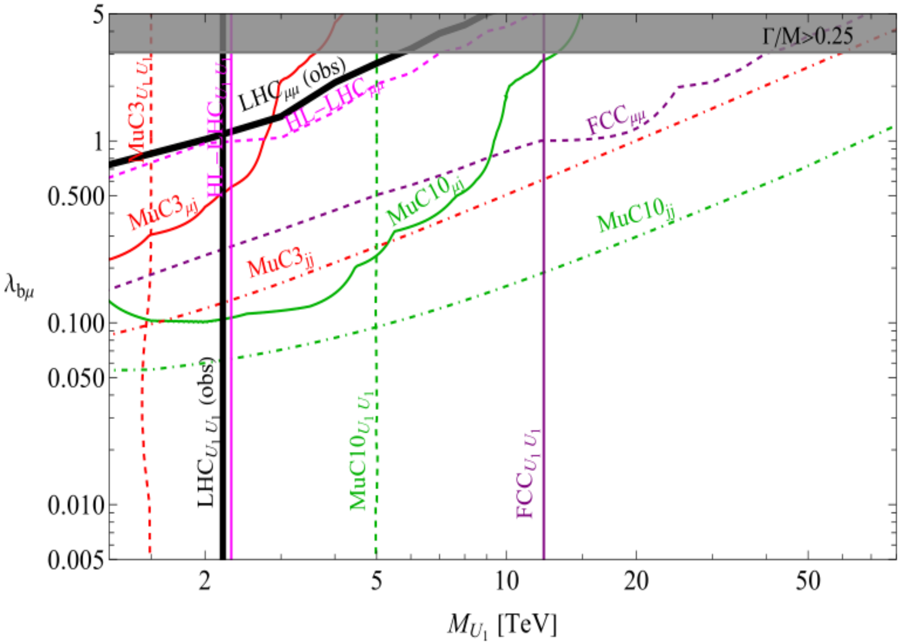


Addressing $bs\mu\mu$ anomalies:

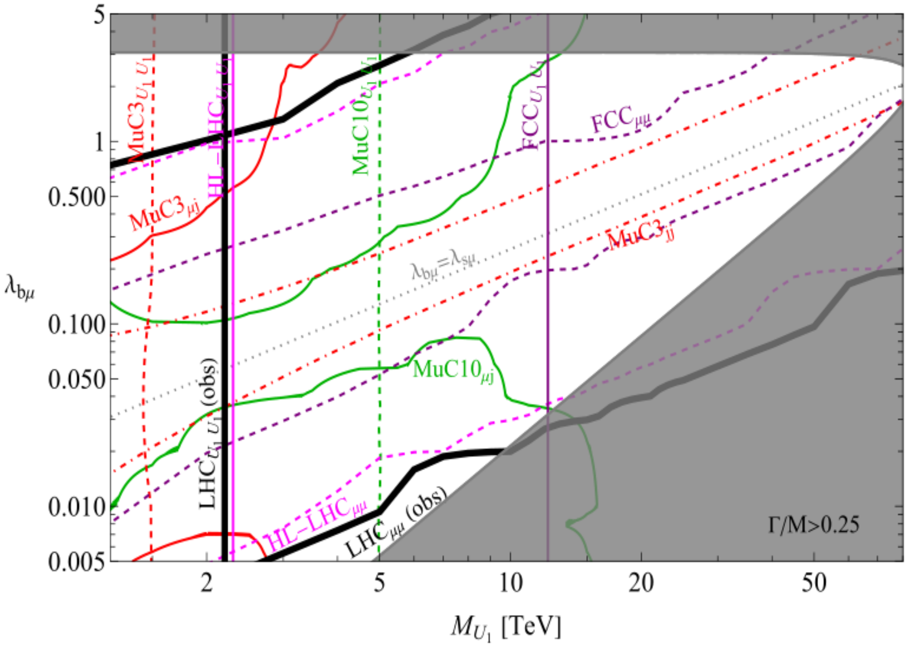


U_1 leptoquark

$U(2)^3$ - symmetric



Addressing $bs\mu\mu$ anomalies:



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Total decay widths

- $U(1)_{B_3-L_\mu}$ Z':

$$\Gamma_{Z'_{B_3-L_\mu}} \approx \frac{M_{Z'} g_{Z'}^2}{24\pi} \left[3 + \frac{N_c}{9}\left(4 + 4|\epsilon_{sb}|^2\right)\right]$$

- $U(1)_{B_3-L_\mu}$ Z':

$$\Gamma_{Z'_{L_\mu-L_\tau}} \approx \frac{M_{Z'} g_{Z'}^2}{24\pi} \left[6 + N_c\left(2|\epsilon_s|^4 + 4|\epsilon_s|^2|\epsilon_b|^2 + 2|\epsilon_b|^4\right)\right]$$

- S_3 leptoquark:

$$\Gamma_{S_3} = \frac{|\lambda_{b\mu}|^2 + |\lambda_{s\mu}|^2}{8\pi} M_{S_3}$$

- U_1 Leptoquark:

$$\Gamma_{U_1} = \frac{|\lambda_{b\mu}|^2 + |\lambda_{s\mu}|^2}{12\pi} M_{U_1}$$

Fixing $bs\mu\mu$ anomalies

- $U(1)_{B_3-L_\mu}$ Z':

$$\epsilon_{sb} = -1.7 \times 10^{-3} \left(\frac{M_{Z'}}{g_{Z'}\mathrm{TeV}}\right)^2 \left(\frac{\Delta C_9^\mu}{-0.73}\right)$$

- $U(1)_{B_3-L_\mu}$ Z':

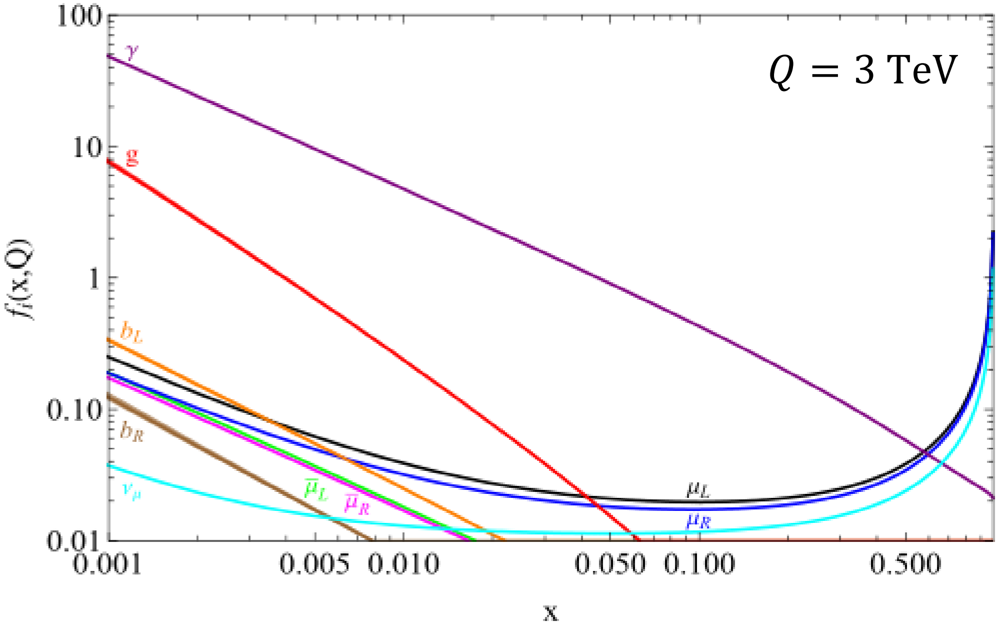
$$\epsilon_b \epsilon_s^* = -5.7 \times 10^{-4} \left(\frac{M_{Z'}}{g_{Z'}\mathrm{TeV}}\right)^2 \left(\frac{\Delta C_9^\mu}{-0.73}\right)$$

- S_3 & U_1 leptoquarks:

$$\lambda_{b\mu}\lambda_{s\mu} = -8.4 \times 10^{-4} \left(\frac{M_{S_3}}{\mathrm{TeV}}\right)^2 \left(\frac{\Delta C_9^\mu}{-0.73}\right)$$

Muon PDFs

- We derive muon PDFs by resumming soft real emissions and virtual radiation, by numerically solving the DGLAP equations (first with QED & QCD until $Q = \mu_{\rm EW}$ and then with the full unbroken SM interactions).



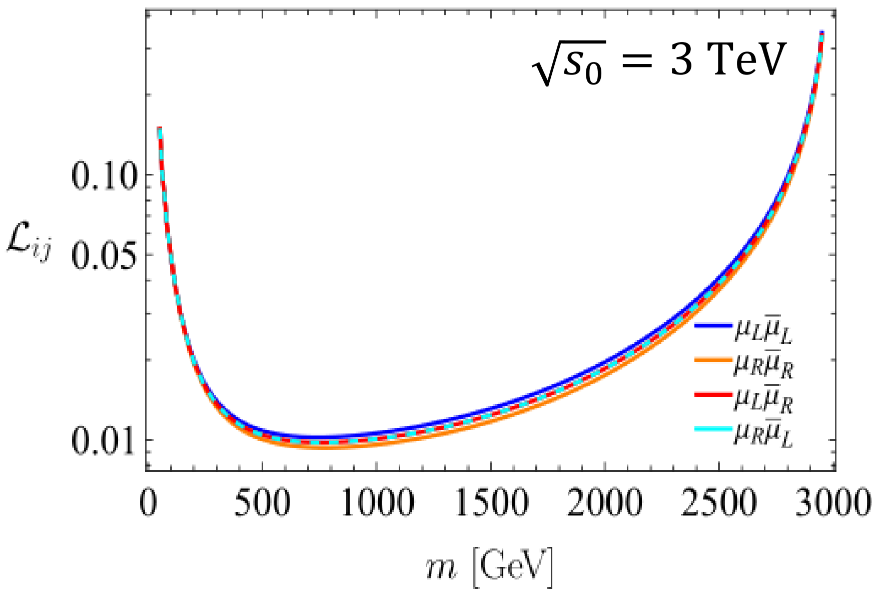
soon to be publicly available!

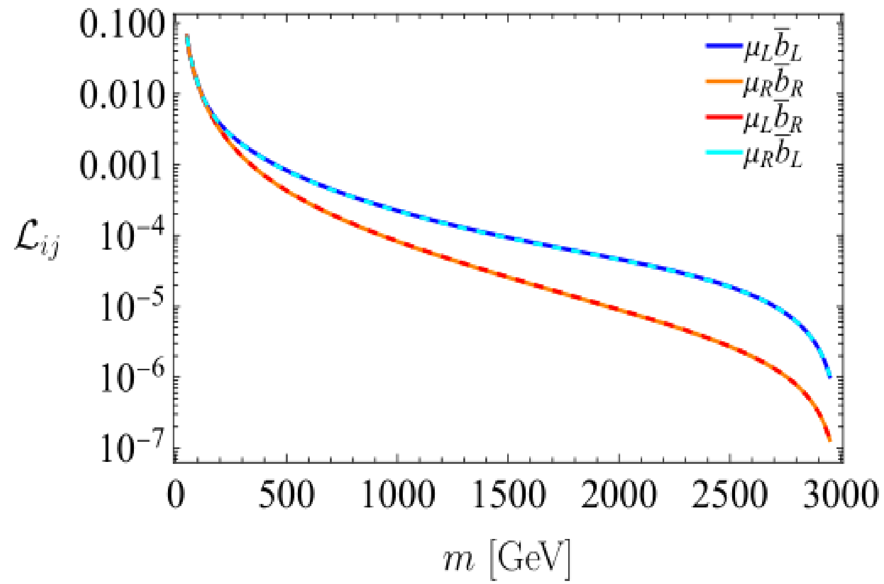
[F. Garosi, D. Marzocca, ST] TBA

Parton Luminosities

➢ The parton luminosities with *m* invariant mass and s_0 collider energy are

$$\mathcal{L}_{ij}(\tau) = \int_\tau^1 \frac{dx}{x} f_i(x,m) f_j\left(\frac{\tau}{x}, m\right), \ \tau = \frac{m^2}{s_0}$$





Cross-sections

- At MuC, the EFT limits can be estimated by the partonic cross-section:

$$\hat{\sigma}(\mu^+\mu^- \to jj)(m_{\mu\mu}) \approx$$

$$\approx \frac{N_c}{48\pi m_{\mu\mu}^2}\left(\sum_{q_X}\sum_{Y=L,R}|g_Z^{q_X} g_Z^{\mu_Y} - e^2 Q^{q_X} + m_{\mu\mu}^2 C_{q_X q_X \mu\mu}|^2 + 2m_{\mu\mu}^4 |C_{sb\mu\mu}|^2\right) =$$

$$\approx \frac{624\,\text{fb}}{(m_{\mu\mu}/\text{TeV})^2}\left(1 + 2.35 C_{bb\mu\mu} m_{\mu\mu}^2 + 12.4 C_{bb\mu\mu}^2 m_{\mu\mu}^4 + 24.8 |C_{sb\mu\mu}|^2 m_{\mu\mu}^4\right)$$

- In scattering processes the differential cross section is defined in the lab frame as

$$\frac{d^3\sigma}{dy_3 dy_4 dm} = f(x_1) f(x_2) \frac{m^3}{2s} \frac{1}{\cosh y_*} \frac{d\sigma}{d\hat{t}}(1+2 \to 3+4)$$, where

$$x_{1,2} = \frac{m}{\sqrt{s_0}} e^{\pm \frac{y_3+y_4}{2}} , \quad y_* = \frac{1}{2}(y_3 - y_4) , \quad \hat{t} = -\frac{m^2}{2}(1 - \cos\theta_*) , \quad \theta_* = \arcsin\left(\frac{1}{\cosh y_*}\right) .$$