Model building and phenomenology with leptoquarks

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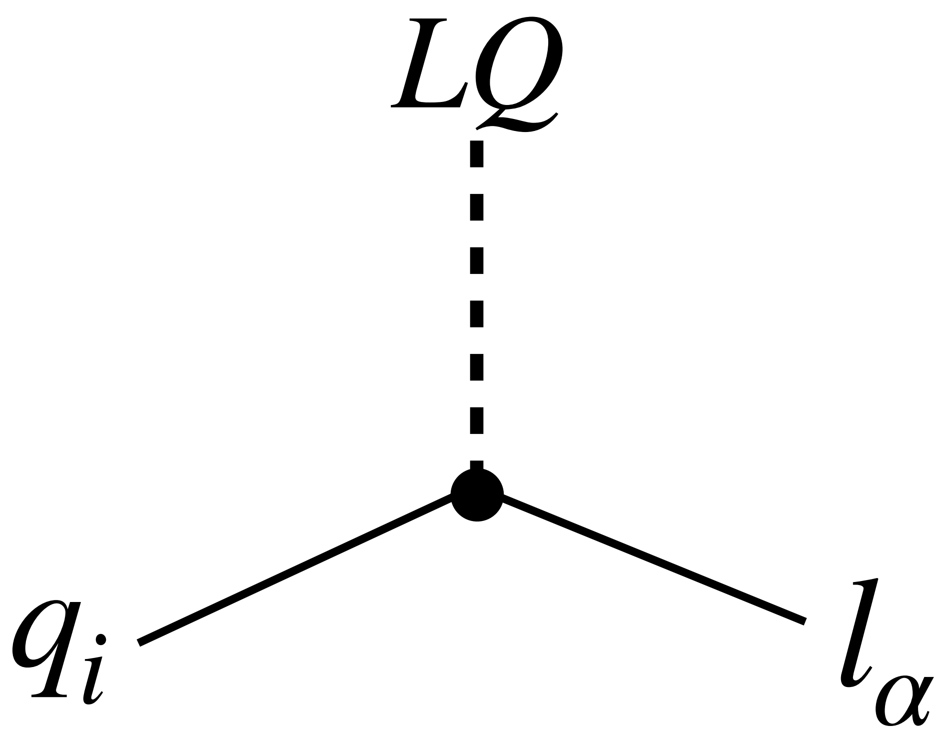
Leptoquarks at the TeV scale?

Doršner, Fajfer, AG, Kamenik, Košnik; 1603.04993 (Physics Reports Review)



Wanted:

- A LQ with a TeV-scale mass and (some) $\mathcal{O}(1)$ couplings

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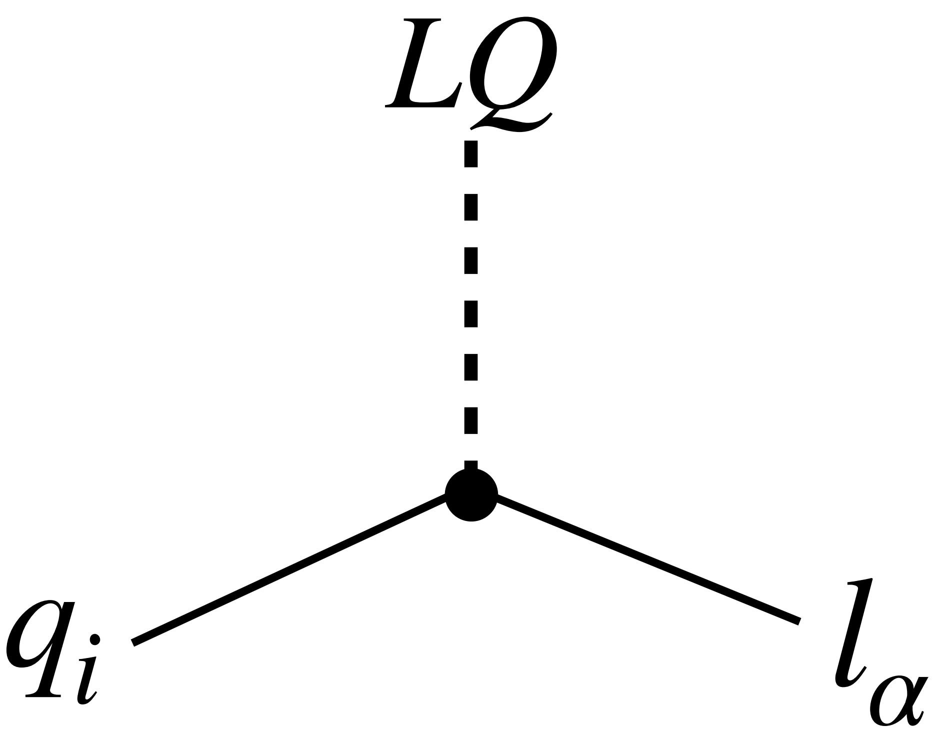

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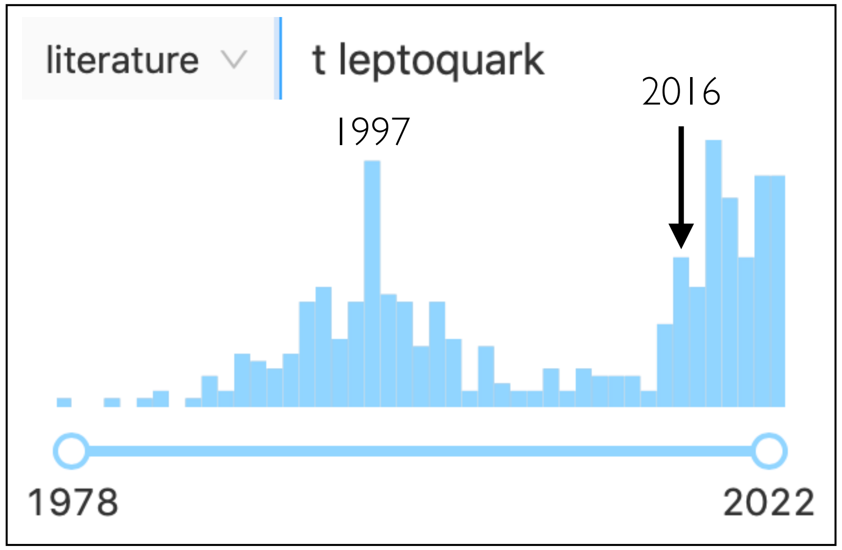
Why?

Phenomenology

- Rich collider and flavor pheno?



Theory

- Quark-lepton unification!

Pati-Salam, SU(5), SO(10) GUT predict LQs but generically not in this mass-coupling range.
New model building directions…

Outline

PART I

- Gauged lepton flavour: Selection rules for a TeV-scale leptoquark

Davighi, AG, Thomsen; 2202.05275

AG, Stangl, Thomsen; 2103.13991

PART II

- A catalog of lepton flavour gauged $U(1)_X$ models and applications

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

Outline (Backup)

PART I

- Phenomenology of a light lepton flavoured $U(1)_X$ gauge boson

AG, Stangl, Thomsen, Zupan; 2203.13731

PART II

- Interpretation of $b \to s\ell\ell$ anomalies after the recent LHCb update

AG, Salko, Smolkovic, Stangl; 2212.10497

PART III

- Future colliders: FCC-hh versus Muon Collider

Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; 2205.13552

Accidental Symmetries in the SM

$q_i, \ell_i, U_i, D_i, E_i$ *flavour* $i = 1,2,3$

$\mathscr{L}_{\rm SM}$ sans Yukawa: $U(3)_q \times U(3)_\ell \times U(3)_U \times U(3)_D \times U(3)_E$

$$-\mathscr{L}_{\rm Yuk} = \bar{q} V^\dagger \hat{Y}_u \tilde{H} U + \bar{q} \hat{Y}_d H D + \bar{\ell} \hat{Y}_e H E$$

[$U(3)^5$ transformation and a singular value decomposition theorem]

$\mathscr{L}_{\rm SM}$: $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$

- $B - L$ and $L_i - L_j$ are exact
- $B + L$ is anomalous: non-perturbative dynamics implies a selection rule $\Delta B = \Delta L = 0\,({\rm mod}\,3)$

TeV-scale BSM?

- A viable model at the TeV-scale should not (*excessively*) violate the accidental symmetries.

- Not a generic case!

Example: Leptoquarks

$\dim[\mathcal{O}] = 4$

$$\mathcal{L}_4 \mathrel{+}= y_{ij}\, Q^i L^j S + z_{ij}\, Q^i Q^j S^\dagger$$

$B(S) = -\frac{1}{3}$ $\qquad$ $B(S) = \frac{2}{3}$

~~$U(1)_B$~~ Proton decay $[z \cdot y]$ $\quad \tau_p \gtrsim 10^{34}$ years

~~$U(1)_e \times U(1)_\mu \times U(1)_\tau$~~ $\mu \to e \gamma$ $[i \neq j]$ $\quad BR(\mu \to e\gamma) \lesssim 10^{-13}$

* Dim-5 $qlS\phi$ can also be problematic.

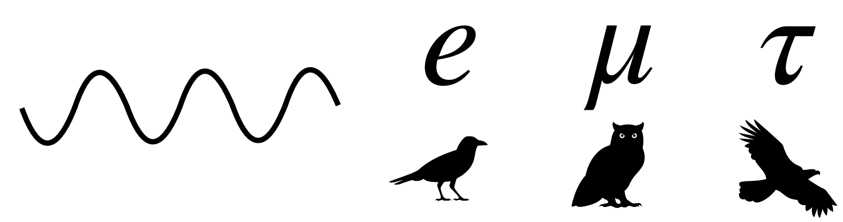
* Global symmetries are a low-energy property. Quantum gravity breaks them.

- Generic TeV-scale LQs are dead!

PART I

Gauged $U(1)_X$

+ leptoquarks



The storyline

- Selection rules for a TeV-scale leptoquark
- Neutrino masses
- Proton stability
- Unification

A $U(1)_X$ model

- The initial model $U(1)_{B-3L_\mu}$ AG, Stangl, Thomsen; 2103.13991

- The generalisation

$$X = 3m(B-L) - n\,(2L_\mu - L_e - L_\tau)\ , \quad \mathrm{gcd}(m,n) = 1$$

Davighi, AG, Thomsen; 2202.05275

A $U(1)_X$ model

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Davighi, AG, Thomsen; 2202.05275

	Fields	$\mathrm{U}(1)_X$
Quarks	$q_i,\ u_i,\ d_i$	m
Electrons and taus	$\ell_{1,3},\ e_{1,3},\ \nu_{1,3}$	$n-3m$
Muons	$\ell_2,\ e_2,\ \nu_2$	$-2n-3m$
Higgs	H	0
Leptoquarks	$S_3,\ S_1$	$2m+2n$
Scalars (SM singlets)	$\phi_{e\tau}$ ϕ_μ	$6m-2n$ $6m+n$

$(\bar{\mathbf{3}}, \mathbf{3}/\mathbf{1})_{1/3}$ — Leptoquarks

Selection rules

Gauge symmetry selection rules:

✔ $q\mu S$

✘ $qqS^\dagger, qeS, q\tau S$

"Muoquark"

$\Longrightarrow$ The accidental symmetry of $\mathscr{L}_{LQ}$ is $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$ and the LQ charge is $(-1/3, 0, -1, 0)$

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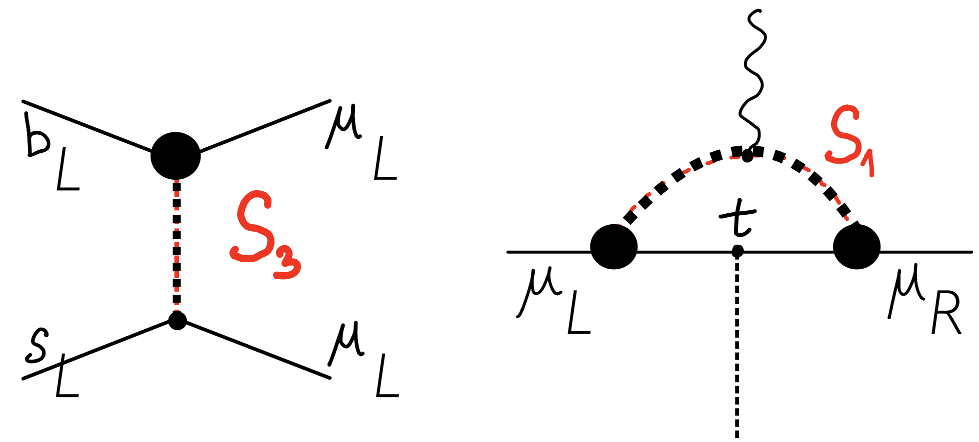

- $b \to s\mu\mu$ & $(g-2)_\mu$

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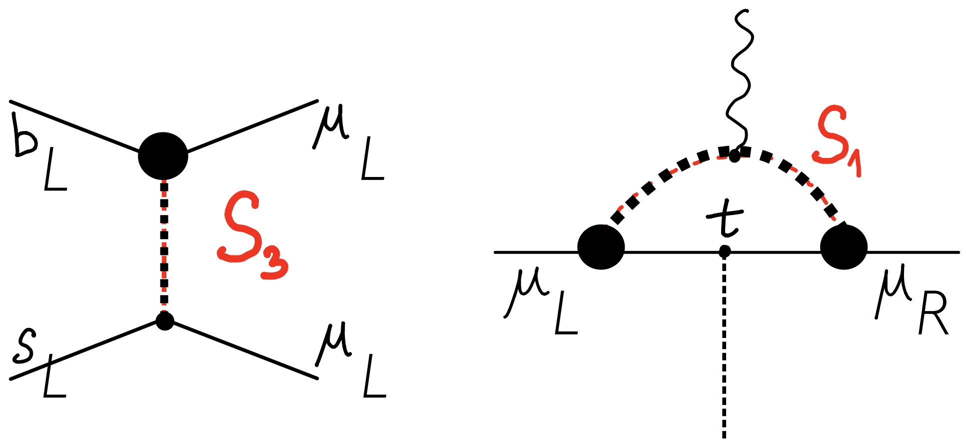
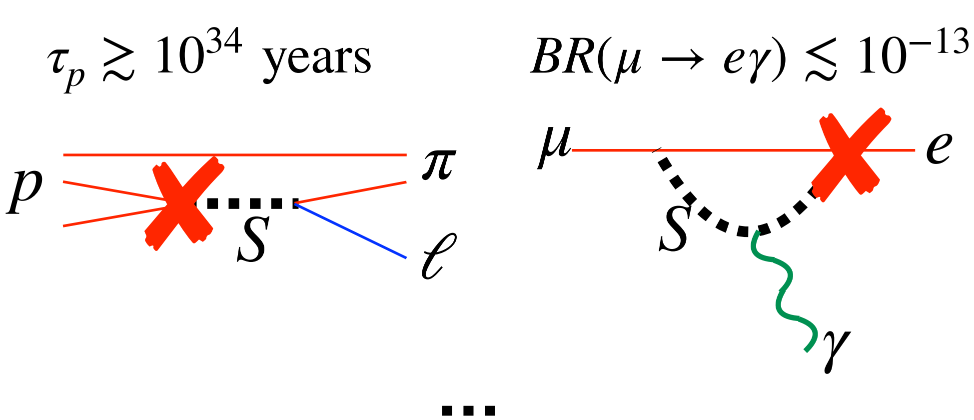
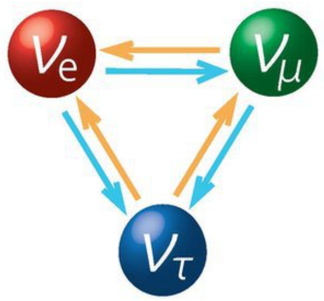


- $b \to s\mu\mu$ & $(g-2)_\mu$

- No proton decay & cLFV



Neutrino Masses



- The PMNS is full of $\mathcal{O}(1)$ elements.
- The correct neutrino masses and mixings dictate the $U(1)_X$ breaking.

- A *dense* Majorana mass matrix needs two SM-singlet scalar fields with charges $6m - 2n$ and $6m + n$ to get a VEV

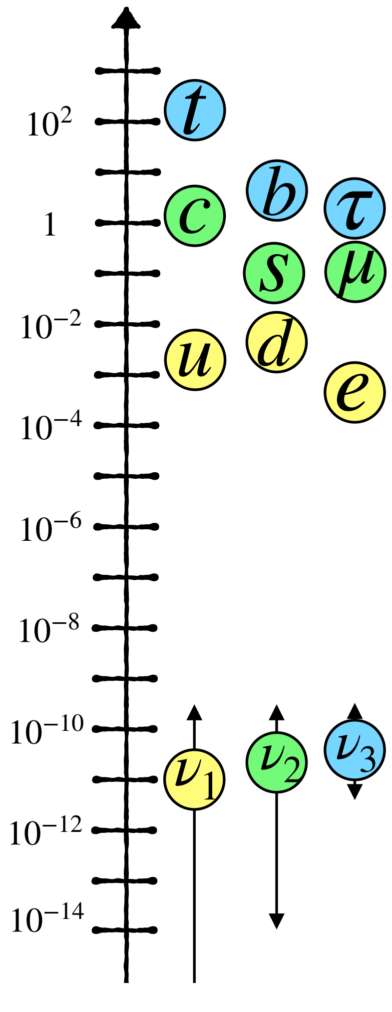
Type-I seesaw mechanism

$$Y_\nu \sim \begin{pmatrix} \times & 0 & \times \\ 0 & \times & 0 \\ \times & 0 & \times \end{pmatrix} \quad ; \quad \mathcal{L} \supset \bar{\nu}_{\mathrm{R}}^{i\,c} \nu_{\mathrm{R}}^{j} (\xi^{ij}_{e\tau} \phi_{e\tau} + \xi^{ij}_{\mu} \phi_{\mu}) \implies \frac{M_\nu}{v_X} \sim \begin{pmatrix} \times & \times & \times \\ \times & 0 & \times \\ \times & \times & \times \end{pmatrix}$$

- More general than two-zero minor structure type D_1^R Asai; 1907.04042
- This is enough to accommodate for:
  - *Neutrino oscillations data,*
  - *The Planck limit on the sum of neutrino masses,*
  - *The absence of neutrinoless double beta decay.*

AG, Stangl, Thomsen; 2103.13991
Davighi, AG, Thomsen; 2202.05275

Neutrino Masses



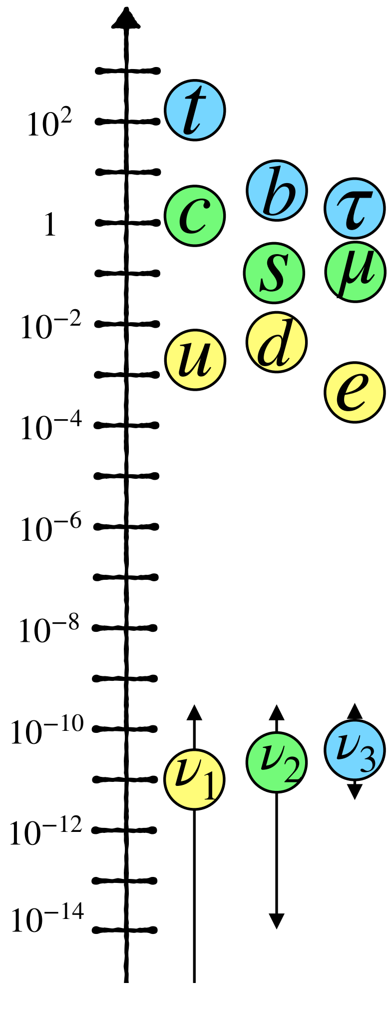
$U(1)_X$ breaking at the high scale?

The mass gap is explained if $\langle \phi_{e\tau} \rangle, \langle \phi_\mu \rangle \gg \langle H \rangle$

Standard thermal leptogenesis at high scale

Davighi, AG, Thomsen; 2202.05275

Neutrino Masses



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Standard thermal leptogenesis at high scale

but

In the $U(1)_X$ broken phase one can ***naively*** write "renormalisable" terms qqS^* and $q_i \ell_j S$ that violate $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$

- What happens?
- Is there proton decay? cLFV?

Davighi, AG, Thomsen; 2202.05275

The IR: discrete gauge subgroup

$\phi_{e\tau}$	$6m - 2n$
ϕ_{μ}	$6m + n$

- Fixed by neutrinos

Davighi, AG, Thomsen; 2202.05275

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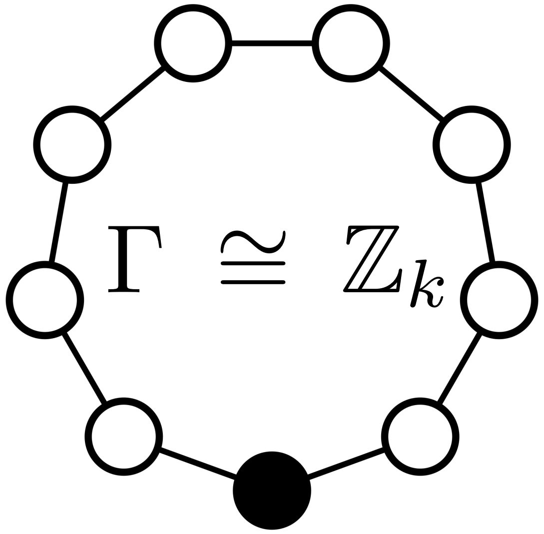
$$k = \mathrm{gcd}\left([\phi_{e\tau}]_X,\, [\phi_\mu]_X\right)$$

$$e^{i\frac{2\pi}{k}[\phi]_X}\phi = \phi$$



- The scalars $\phi_{e\tau}$ and ϕ_{μ} are Γ singlets
- An unbroken discrete subgroup $\Gamma \subset U(1)_X$ acting on matter in the IR

Davighi, AG, Thomsen; 2202.05275

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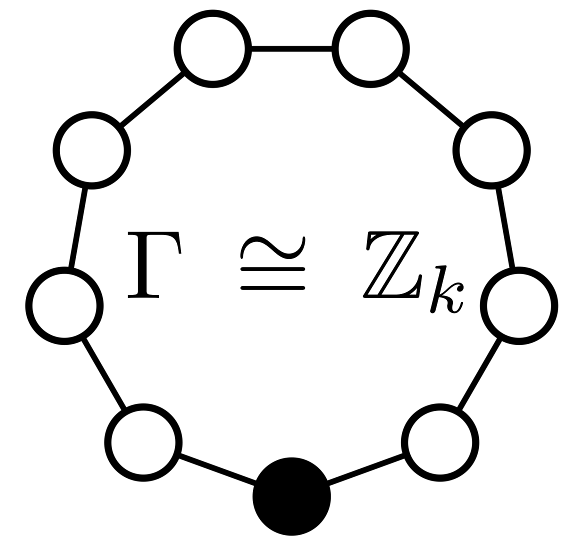

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- The diquark operators qqS^* are banned by Γ when:

$$\begin{gathered}(m,\, n) = \big(3a + r,\, 9b + 3r\big), \quad \text{for} \quad r \in \{1,\, 2\}, \\ (a,\, b) \in \mathbb{Z}^2,\ \text{and}\ \mathrm{gcd}\big(3a + r,\, b - a\big) = 1\,.\end{gathered}$$

$$\Gamma \cong \begin{cases} \mathbb{Z}_9, & \text{for } b + r \in 2\mathbb{Z} + 1 \\ \mathbb{Z}_{18}, & \text{for } b + r \in 2\mathbb{Z} \end{cases}$$

Davighi, AG, Thomsen; 2202.05275

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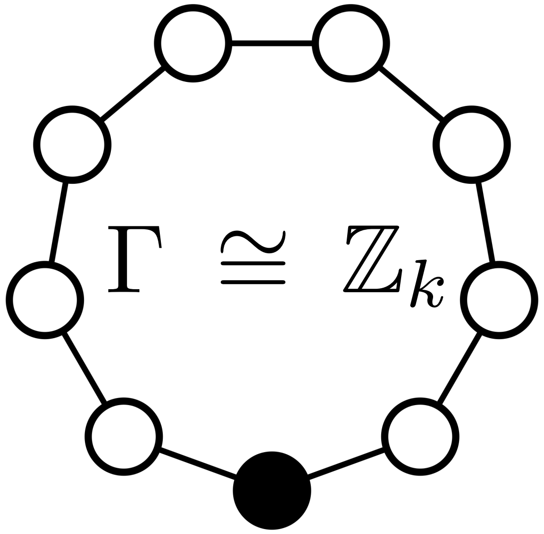

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- No proton decay!

- Both B − L and the lepton-flavoured factor required! $X = 3m(B-L) - n\,(2L_\mu - L_e - L_\tau)$

Davighi, AG, Thomsen; 2202.05275

The IR: discrete gauge subgroup

$b+r \pmod 2$	Γ	ℓ	q	S	$qS\ell$	qS^*q
0	$\mathbb{Z}_{18}$	$9(b-a)$	$3a+r$	$6a+8r$	0	$12r$
1	$\mathbb{Z}_9$	0	$3a+r$	$6a+8r$	0	$3r$

Charges under the remnant discrete symmetry Γ

Davighi, AG, Thomsen; 2202.05275

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Charges under the remnant discrete symmetry Γ

- The Γ protection goes beyond just banning the diquark operators. Integrate out S. Selection rule:

$$\Delta B = 0 \pmod 3$$

Exact proton stability to all orders in the SMEFT!

✗ $qqq\ell$ and so on

Davighi, AG, Thomsen; 2202.05275

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- Neutron—antineutron oscillations also forbidden
- ΔB = 3 processes are allowed, in analogy to sphalerons.

Davighi, AG, Thomsen; 2202.05275

What about cLFV?

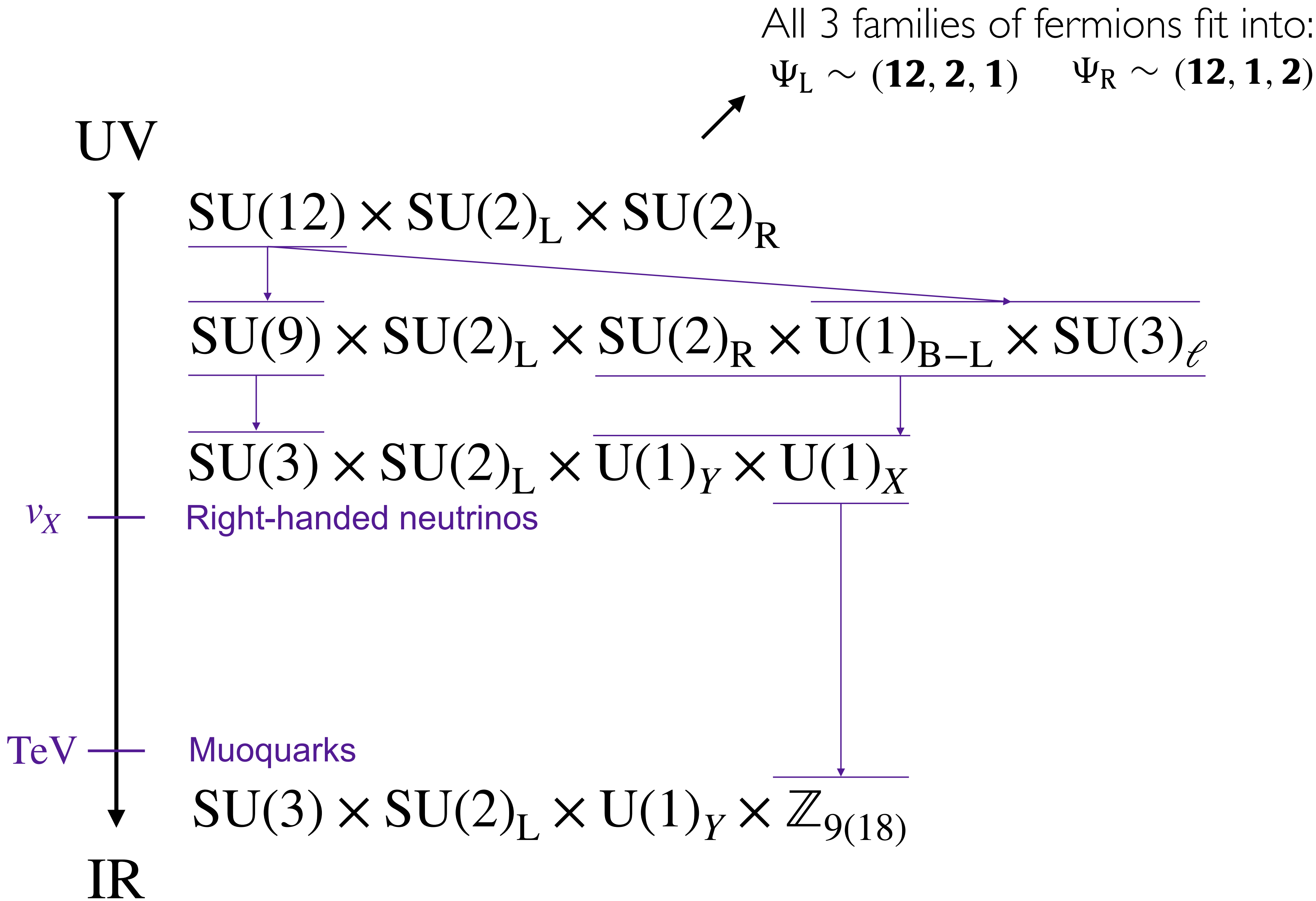
- Γ is lepton flavour universal, otherwise no PMNS.
- cLFV through higher-dim. operators in the $U(1)_X$-invariant effective theory:

$$\frac{1}{\Lambda^2}\phi_{e\tau}\phi^*_\mu\, q S_{1/3}\ell_{1,3} \qquad \frac{1}{\Lambda^2}\phi_{e\tau}\phi^*_\mu\, u S_1 e_{1,3}$$

- A modest scale separation is sufficient to suppress cLFV processes to a level compatible with current bounds.

Davighi, AG, Thomsen; 2202.05275

Deeper into the UV: Unification

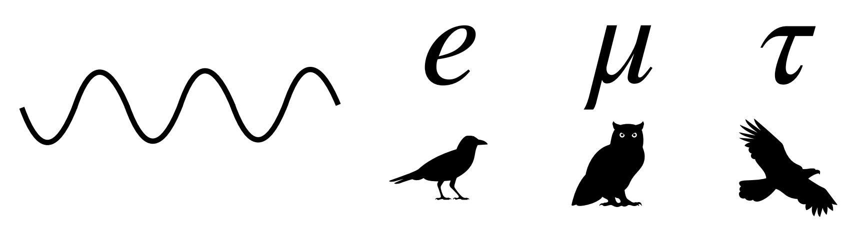


Tentative gauge–flavour unification scenario.

Davighi, AG, Thomsen; 2202.05275

PART II

Gauged $U(1)_X$



+ leptoquarks

<u>The storyline</u>

- A catalog of models
- Radiative lepton masses and magnetic moments

The $U(1)_X$ atlas

- 18 chiral fermions

$$
\begin{aligned}
&Q_i \sim (\mathbf{3},\mathbf{2},\tfrac{1}{6},X_{Q_i}), \qquad && U_i \sim (\mathbf{3},\mathbf{1},\tfrac{2}{3},X_{U_i}), \qquad && D_i \sim (\mathbf{3},\mathbf{1},-\tfrac{1}{3},X_{D_i}),\\
&L_i \sim (\mathbf{1},\mathbf{2},-\tfrac{1}{2},X_{L_i}), && E_i \sim (\mathbf{1},\mathbf{1},-1,X_{E_i}), && N_i \sim (\mathbf{1},\mathbf{1},0,X_{N_i}).
\end{aligned}
$$

The $U(1)_X$ atlas

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- Six anomaly cancelation conditions:

$$\begin{aligned}
\mathrm{SU}(3)_C^2\times\mathrm{U}(1)_X:&\quad \sum_{i=1}^{3}(2X_{Q_i}-X_{U_i}-X_{D_i})=0\ ,\\
\mathrm{SU}(2)_L^2\times\mathrm{U}(1)_X:&\quad \sum_{i=1}^{3}(3X_{Q_i}+X_{L_i})=0\ ,\\
\mathrm{U}(1)_Y^2\times\mathrm{U}(1)_X:&\quad \sum_{i=1}^{3}(X_{Q_i}+3X_{L_i}-8X_{U_i}-2X_{D_i}-6X_{E_i})=0\ ,\\
\mathrm{Gravity}^2\times\mathrm{U}(1)_X:&\quad \sum_{i=1}^{3}(6X_{Q_i}+2X_{L_i}-3X_{U_i}-3X_{D_i}-X_{E_i}-X_{N_i})=0\ ,\\
\mathrm{U}(1)_Y\times\mathrm{U}(1)_X^2:&\quad \sum_{i=1}^{3}(X_{Q_i}^2-X_{L_i}^2-2X_{U_i}^2+X_{D_i}^2+X_{E_i}^2)=0\ ,\\
\mathrm{U}(1)_X^3:&\quad \sum_{i=1}^{3}(6X_{Q_i}^3+2X_{L_i}^3-3X_{U_i}^3-3X_{D_i}^3-X_{E_i}^3-X_{N_i}^3)=0\ .
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$$\begin{aligned}
\mathrm{SU}(3)_C^2 \times \mathrm{U}(1)_X &: \sum_{i=1}^{3}(2X_{Q_i} - X_{U_i} - X_{D_i}) = 0 \ , \\
\mathrm{SU}(2)_L^2 \times \mathrm{U}(1)_X &: \sum_{i=1}^{3}(3X_{Q_i} + X_{L_i}) = 0 \ , \\
\mathrm{U}(1)_Y^2 \times \mathrm{U}(1)_X &: \sum_{i=1}^{3}(X_{Q_i} + 3X_{L_i} - 8X_{U_i} - 2X_{D_i} - 6X_{E_i}) = 0 \ , \\
\mathrm{Gravity}^2 \times \mathrm{U}(1)_X &: \sum_{i=1}^{3}(6X_{Q_i} + 2X_{L_i} - 3X_{U_i} - 3X_{D_i} - X_{E_i} - X_{N_i}) = 0 \ , \\
\mathrm{U}(1)_Y \times \mathrm{U}(1)_X^2 &: \sum_{i=1}^{3}(X_{Q_i}^2 - X_{L_i}^2 - 2X_{U_i}^2 + X_{D_i}^2 + X_{E_i}^2) = 0 \ , \\
\mathrm{U}(1)_X^3 &: \sum_{i=1}^{3}(6X_{Q_i}^3 + 2X_{L_i}^3 - 3X_{U_i}^3 - 3X_{D_i}^3 - X_{E_i}^3 - X_{N_i}^3) = 0 \ .
\end{aligned}$$

- Integer charges: $-10 \leq X_{F_i} \leq 10$ Allanach, Davighi, Melville; 1812.04602

21'546'920 inequivalent solutions (up to flavour permutation, etc)

The $U(1)_X$ atlas

- The symmetry breaking scalar fields:

$$H = (\mathbf{1}, \mathbf{2}, \frac{1}{2}, X_H) \, , \qquad \phi = (\mathbf{1}, \mathbf{1}, 0, X_\phi)$$

$X_H = 0$

- Without loss of generality

* By field redefinitions, shifting $X_f \to X_f - aY_f$ for all fields, gives an equivalent theory.

$$\mathcal{L} \supset -\frac{1}{4} F_{i\mu\nu} h^{-1}_{ij} F^{\mu\nu}_j \, , \qquad D^f_\mu = \partial_\mu - i q^f_i A_{i\mu}$$

$$\mathrm{U}(1)^n = \mathrm{U}(1)_1 \times \cdots \times \mathrm{U}(1)_n$$

Field redefinitions
$A^\mu_i \to L_{ij} A^\mu_j$

$$\mathcal{L} \supset -\frac{1}{4} F_{i\mu\nu} \tilde{h}^{-1}_{ij} F^{\mu\nu}_j \, , \qquad D^f_\mu = \partial_\mu - i \tilde{q}^f_i A_{i\mu} ,$$

$$\tilde{h} = L^{-1} h (L^{-1})^\intercal \qquad \tilde{q}^f = L^\intercal q^f$$

$$\tilde{q}_f = L^\intercal q_f \quad \text{where} \quad L = \begin{pmatrix} 1 & -a \\ 0 & 1 \end{pmatrix} .$$

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

Lepton-flavoured catalog

Quark flavour universal class

$$-10 \leq X_{F_i} \leq 10$$

[276 inequivalent solutions]

- $Y_{u,d}$ are allowed => $X_{Q_i} = X_{U_j} = X_{D_k}$
  $(X_H = 0)$

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  $(X_H = 0)$

- Leptoquark selection rules

  eg. S_3 LQ: $X_{L_2} \neq \{X_{L_{1,3}}, -3X_q\}$ [273 inequivalent solutions]

  * For all other LQs up to dim-5, see the paper.

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- Further classification:

  Y_e allowed => $\textbf{vector category}: \quad X_{L_i} = X_{E_i}$ [252 inequivalent solutions]

  $\textbf{chiral category}: \quad \text{the rest.}$ [21 inequivalent solutions]

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

Lepton-flavoured catalog

Quark flavour universal class

$-10 \leq X_{F_i} \leq 10$

- $Y_{u,d}$ are allowed => $X_{Q_i} = X_{U_j} = X_{D_k}$ $(X_H = 0)$ [276 inequivalent solutions]
- Leptoquark selection rules
  eg. S_3 LQ: $X_{L_2} \neq \{X_{L_{1,3}}, -3X_q\}$ [273 inequivalent solutions]
- Further classification:

Y_e allowed => **vector category :** $X_{L_i} = X_{E_i}$ [252 inequivalent solutions]

chiral category : the rest. [21 inequivalent solutions]

$$x_f = c_e L_e + c_\mu L_\mu + c_\tau L_\tau - \left(\frac{c_e + c_\mu + c_\tau}{3}\right) B + \sum_i c_{N_i} L_{N_i}$$

ACC: $(c_e + c_\mu + c_\tau = \sum_i c_{N_i}$ and $c_e^3 + c_\mu^3 + c_\tau^3 = \sum_i c_{N_i}^3)$

See backup

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

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$\mathbf{chiral\ category}: \quad \text{the rest.}$ [21 inequivalent solutions]

→ Next example

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

Chiral models: Radiative y_μ

- The dimension-4 muon Yukawa is forbidden by $U(1)_X$

$$X_{L_2} \neq X_{E_2} \quad (X_H = 0)$$

Example:

$\tilde{L}_{\mu-\tau}$ **model:**

$$\begin{aligned} (X_{L_1}, X_{L_2}, X_{L_3}) &= (0, 7, -7), \\ (X_{N_1}, X_{N_2}, X_{N_3}) &= (5, 3, 8), \\ (X_{E_1}, X_{E_2}, X_{E_3}) &= (\text{-}3, 8, \text{-}5), \\ X_{Q_i, D_i, U_i} &= 0. \end{aligned}$$

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

Chiral models: Radiative y_μ

- The dimension-4 muon Yukawa is forbidden by $U(1)_X$

$$X_{L_2} \neq X_{E_2} \quad (X_H = 0)$$

- Introduce two scalar muoquarks $S_\pm = (\mathbf{3}, \mathbf{2}, 7/6, X_{S_\pm})$

$$\mathcal{L} \supset \eta_{\rm L}\, \bar{t}_{\rm R} \ell^2_{\rm L}\, i\sigma_2 S_+ - \eta_{\rm R}\, \bar{q}^3_{\rm L}\, \mu_{\rm R}\, S_-$$

Charges:

$$X_{S_+} = -X_{L_2} + X_{U_i}$$
$$X_{S_-} = -X_{E_2} + X_{Q_i}$$

Example:

$\tilde{\boldsymbol{L}}_{\boldsymbol{\mu-\tau}}$ **model:**

$$(X_{L_1}, X_{L_2}, X_{L_3}) = (0, 7, -7),$$
$$(X_{N_1}, X_{N_2}, X_{N_3}) = (5, 3, 8),$$
$$(X_{E_1}, X_{E_2}, X_{E_3}) = (\text{-}3, 8, \text{-}5),$$
$$X_{Q_i, D_i, U_i} = 0.$$

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

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- Mix them via $U(1)_X$ breaking

$$\mathcal{L} \supset -A\phi S_+^\dagger S_-$$

Charges:

$$X_{S_+} = -X_{L_2} + X_{U_i}$$
$$X_{S_-} = -X_{E_2} + X_{Q_i}$$
$$X_\phi = -X_{S_-} + X_{S_+}$$

Example:

$\tilde{L}_{\mu-\tau}$ **model:**

$$(X_{L_1}, X_{L_2}, X_{L_3}) = (0, 7, -7),$$
$$(X_{N_1}, X_{N_2}, X_{N_3}) = (5, 3, 8),$$
$$(X_{E_1}, X_{E_2}, X_{E_3}) = (\text{-}3, 8, \text{-}5),$$
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AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

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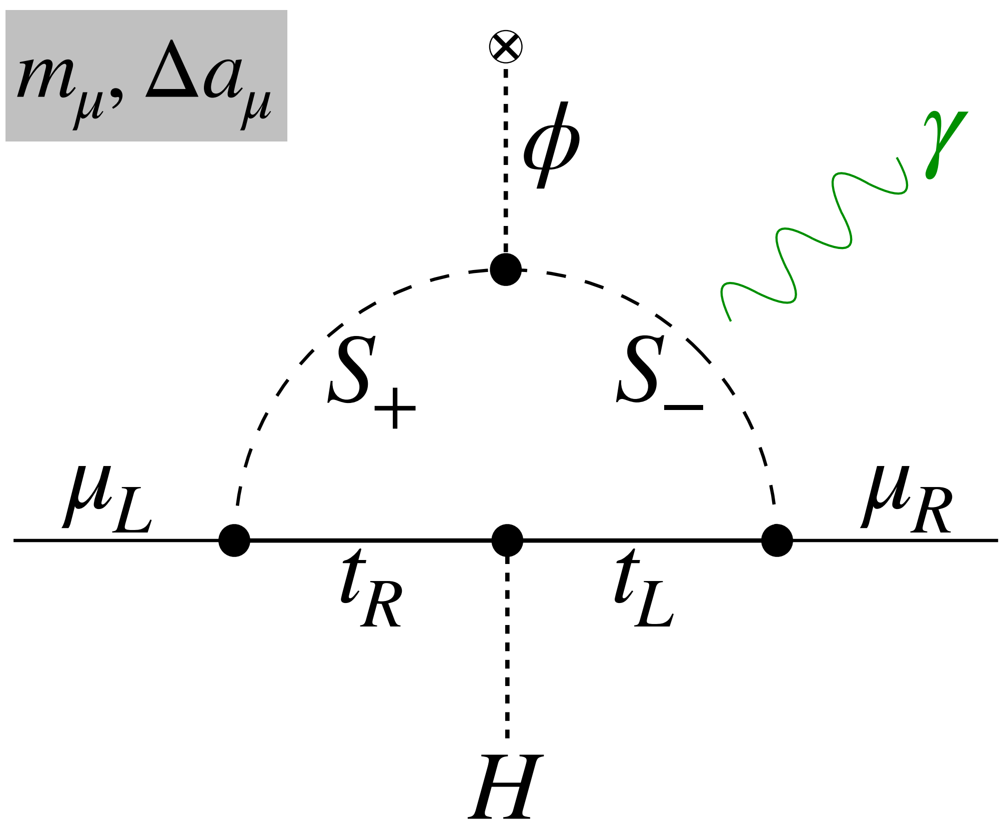

$$\Longrightarrow \quad \Delta a_\mu = \frac{m_\mu^2}{m_t^2}\, \tilde{F}\left(\frac{m_{S_1}^2}{m_t^2}, \frac{m_{S_2}^2}{m_t^2}\right)$$

$$\tilde{F}(x_1, x_2) = \left(\frac{x_1 \log x_1}{1-x_1} - \frac{x_2 \log x_2}{1-x_2}\right)^{-1} \left[\frac{3x_1 - 1}{(1-x_1)^2} - \frac{3x_2 - 1}{(1-x_2)^2} + \frac{2x_1^2 \log x_1}{(1-x_1)^3} - \frac{2x_2^2 \log x_2}{(1-x_2)^3} + 2Q_S\left(\frac{1}{1-x_1} - \frac{1}{1-x_2} + \frac{x_1 \log x_1}{(1-x_1)^2} - \frac{x_2 \log x_2}{(1-x_2)^2}\right)\right]$$

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

Chiral models: Radiative y_μ

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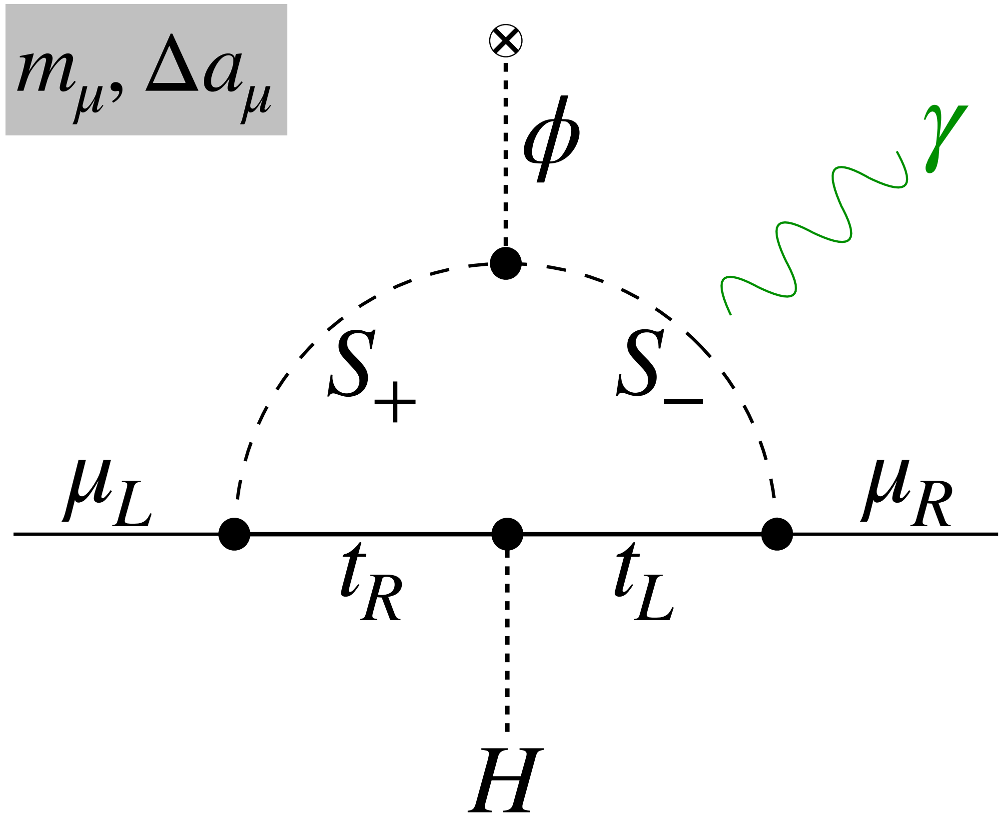
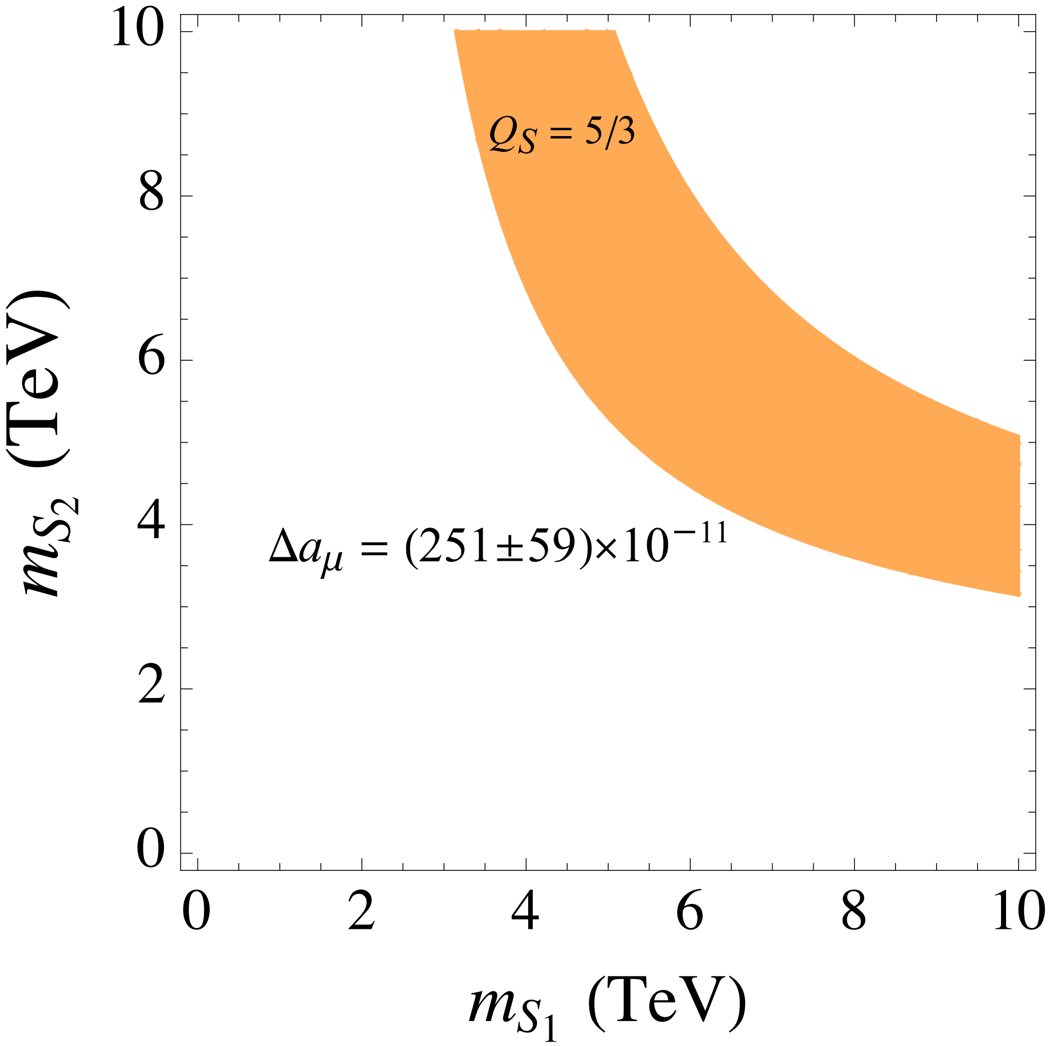
- Mix them via $U(1)_X$ breaking

$$\mathcal{L} \supset -A\phi S^\dagger_+ S_-$$

$m_\mu, \Delta a_\mu$



$\Longrightarrow$



AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

Conclusions

- Gauged lepton flavour $\Longrightarrow$ Selection rules for TeV-scale Leptoquarks

- A mechanism to render the proton ***exactly*** stable to all orders in EFT:

  Spontaneously broken lepton-flavoured gauged $U(1)$ in the UV to generate neutrino masses, leaving a discrete symmetry in the IR

- A catalog of anomaly-free lepton flavour $U(1)$ gauge models yet to fully be explored

Backup

PART I

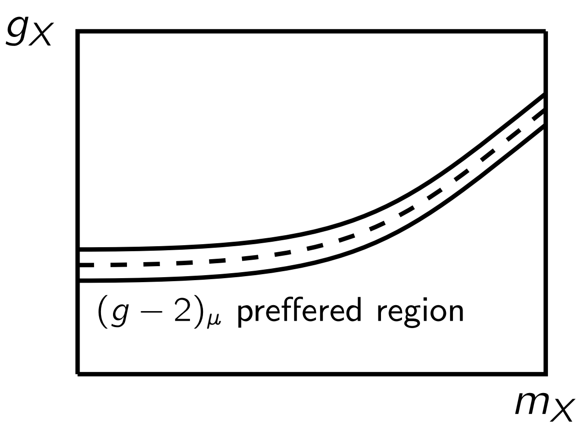
Light $\mathrm{U(1)_X}$ gauge boson

The storyline

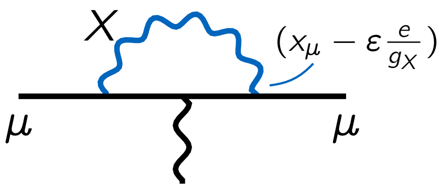
- In the context of $(g-2)_\mu$

- Vector category: $x_f = c_e L_e + c_\mu L_\mu + c_\tau L_\tau - \left(\frac{c_e + c_\mu + c_\tau}{3}\right) B + \sum_i c_{N_i} L_{N_i}$

Muon $(g-2)_\mu$



x_f: charge of fermion f
ε: kinetic mixing of X and γ



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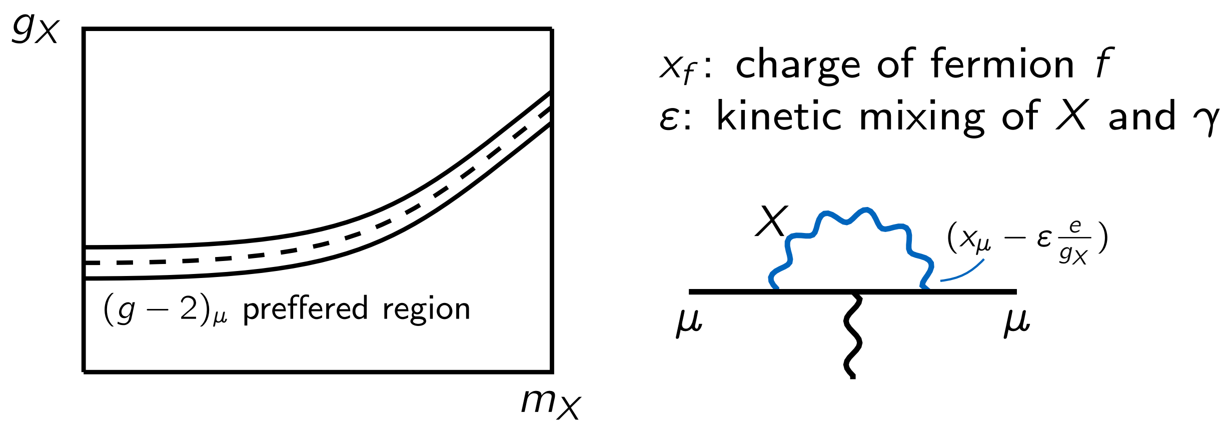

Targeted mass range 10 MeV — 1 TeV

- Renormalisable models

$$m_X \lesssim 4\,\text{GeV} \qquad (\text{trident}+T)$$

AG, Stangl, Thomsen, Zupan; 2203.13731

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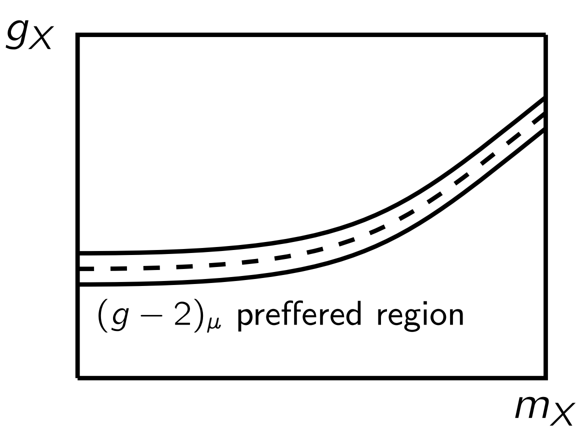

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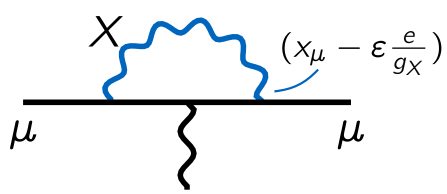

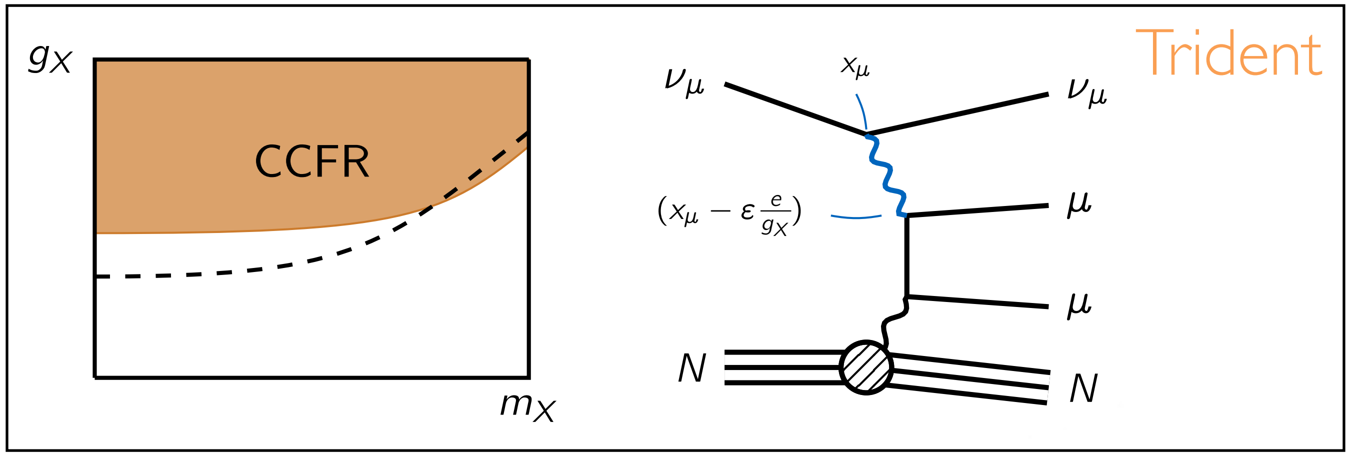

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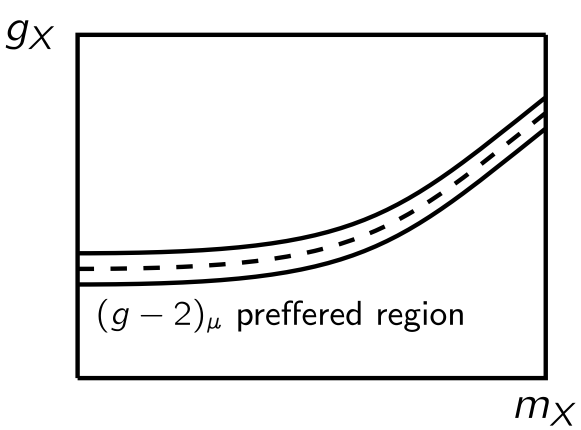

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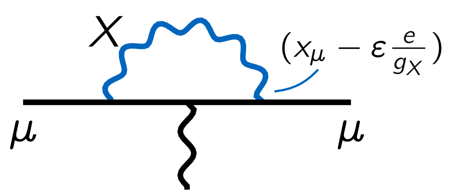

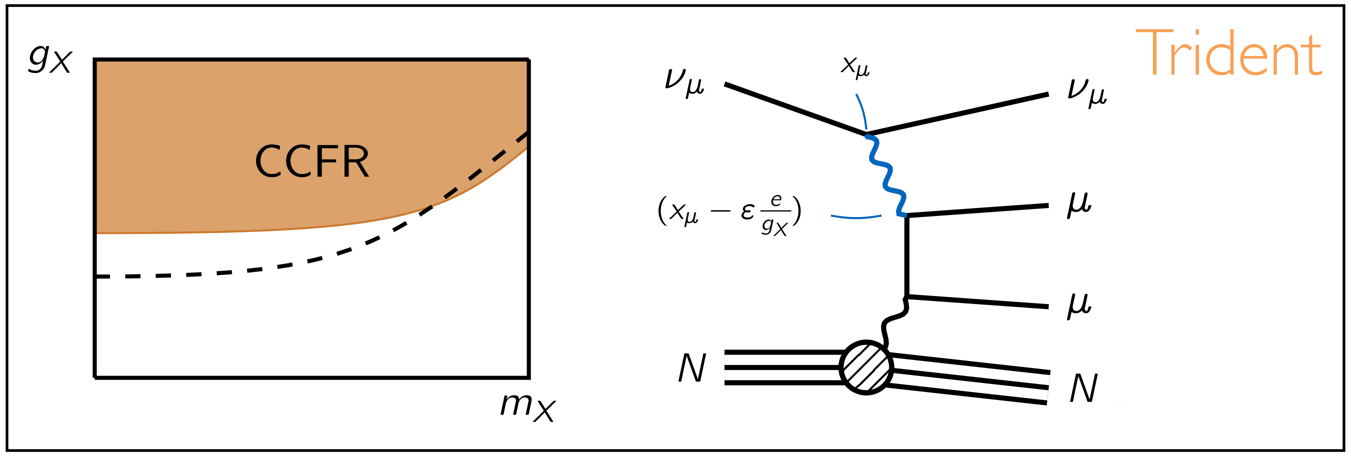

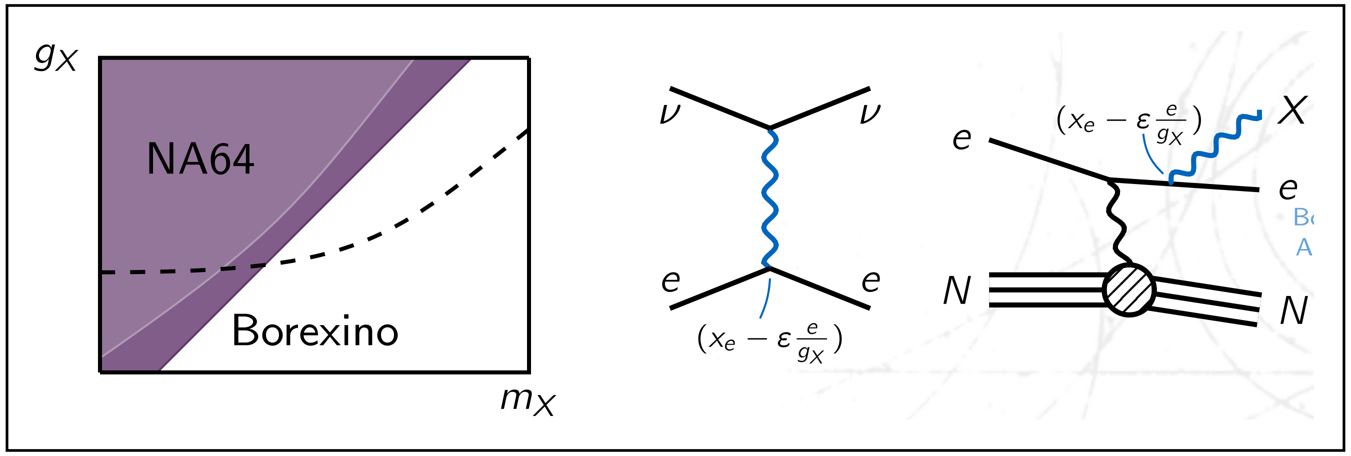

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AG, Stangl, Thomsen, Zupan; 2203.13731

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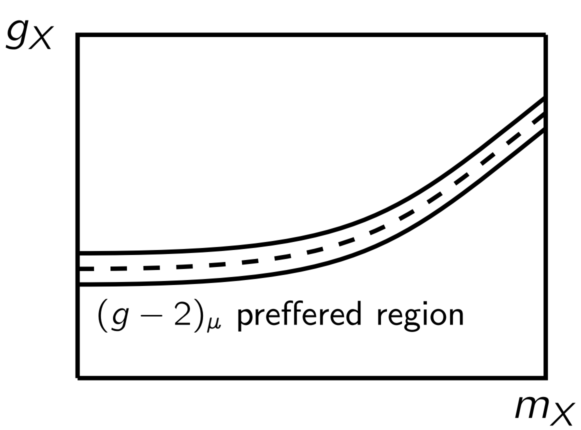

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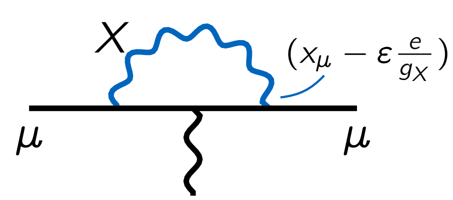

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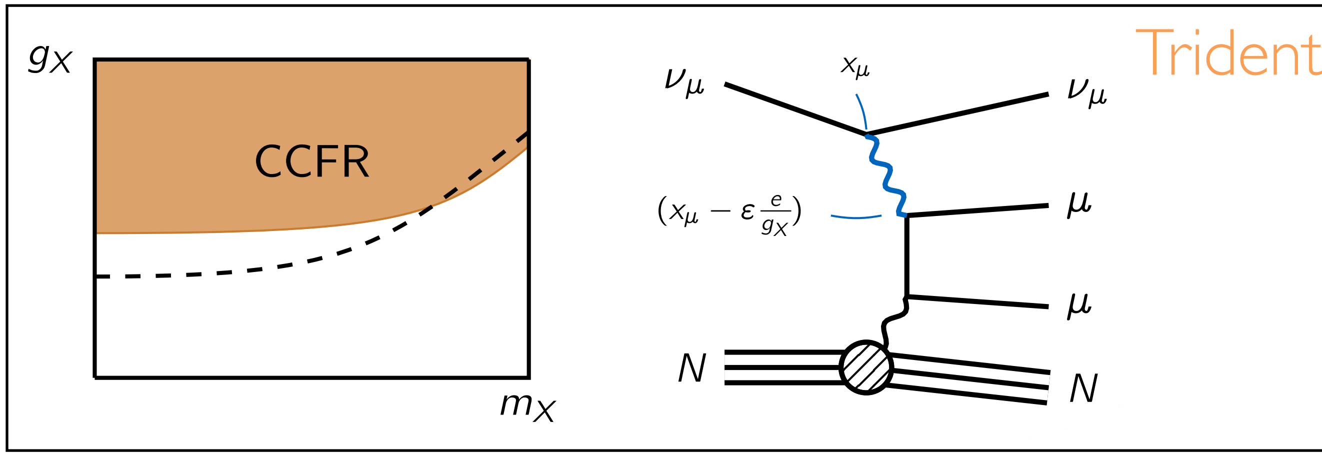
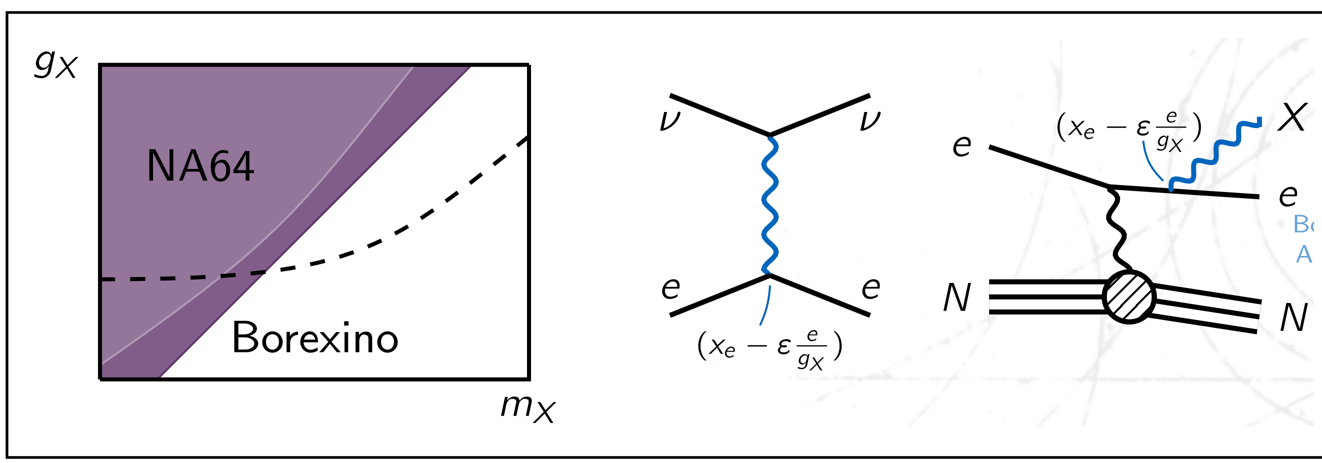
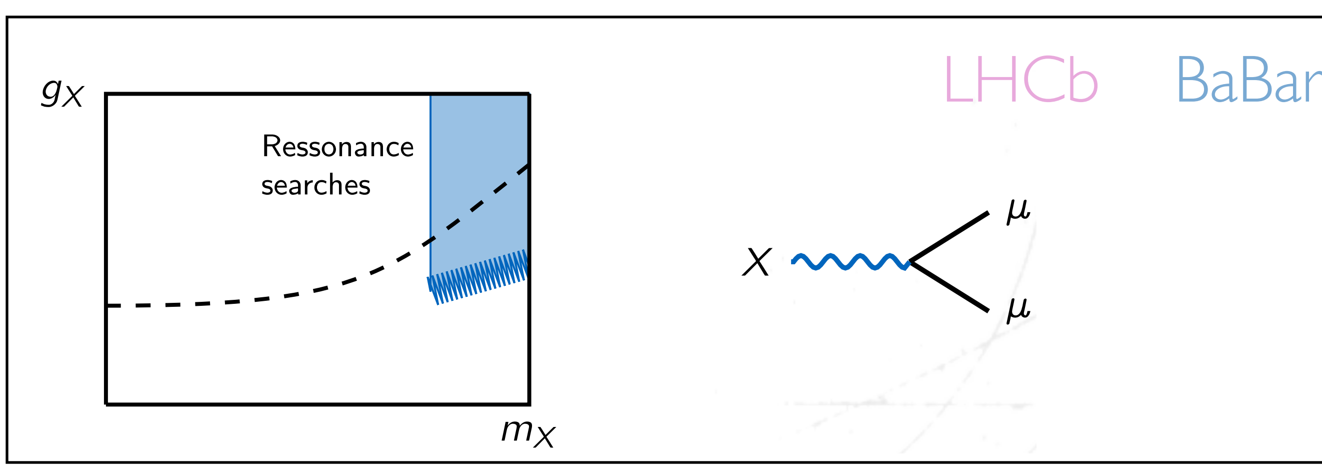
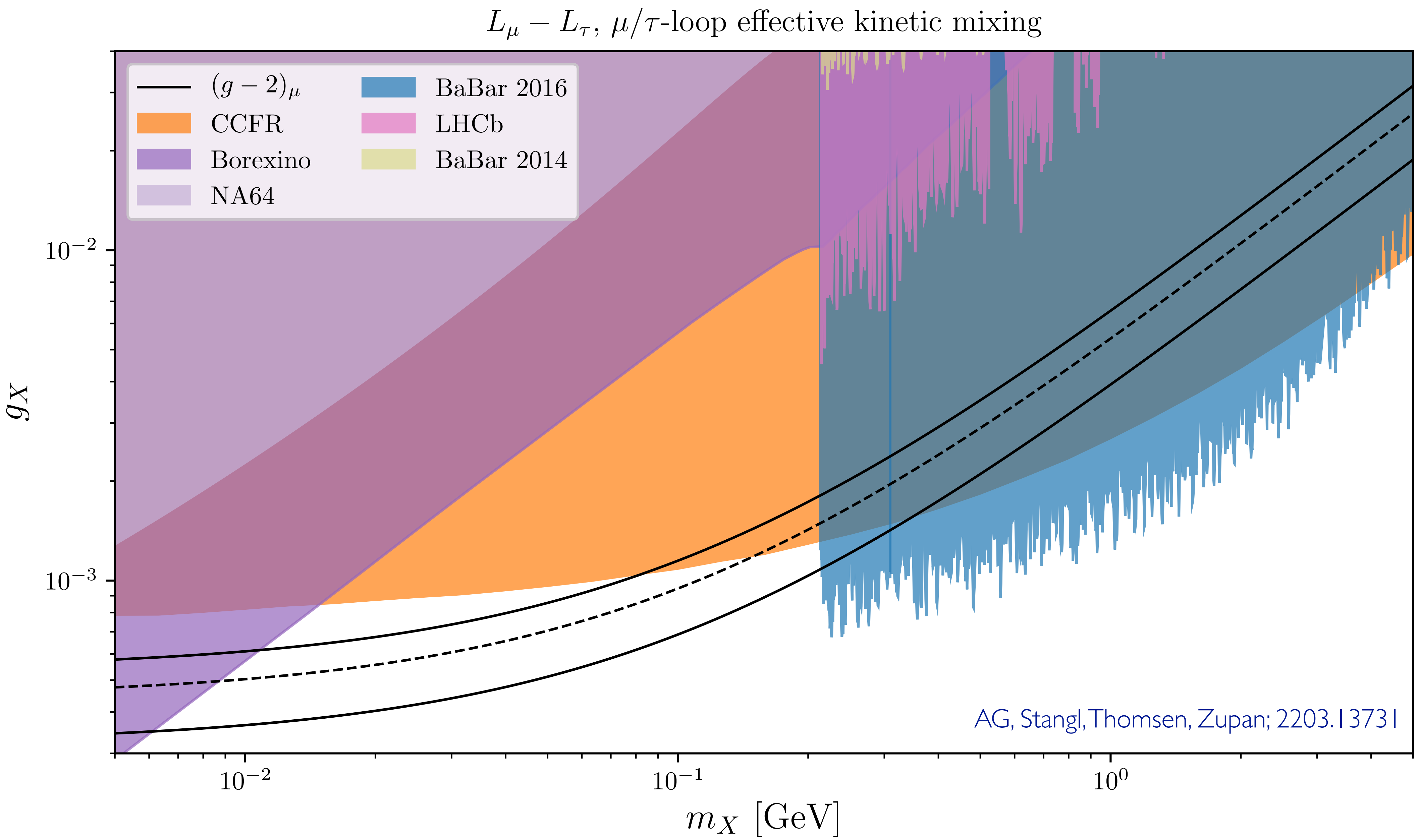






Muon $(g-2)_\mu$



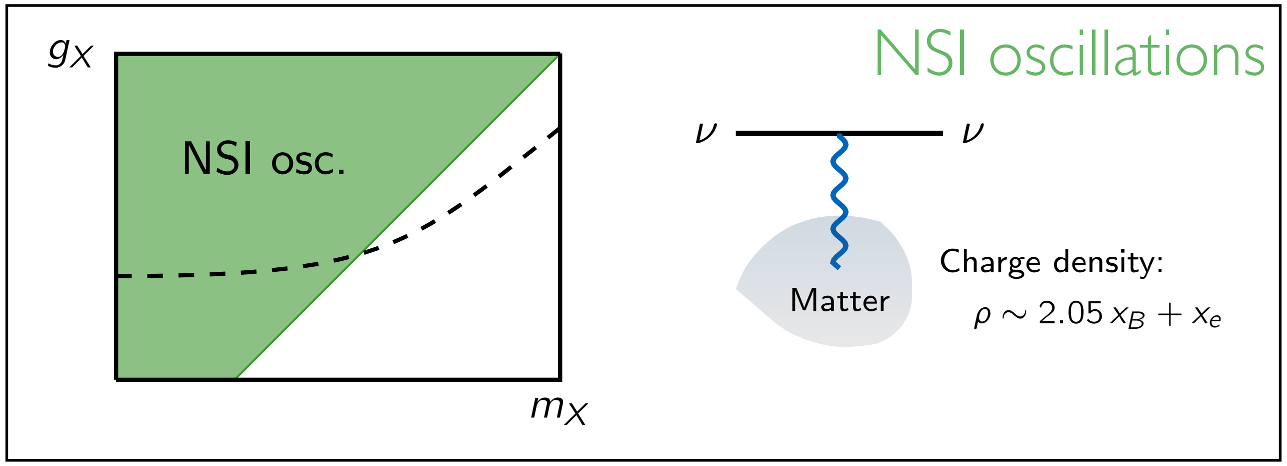
- A well-known example

$$L_\mu - L_\tau$$

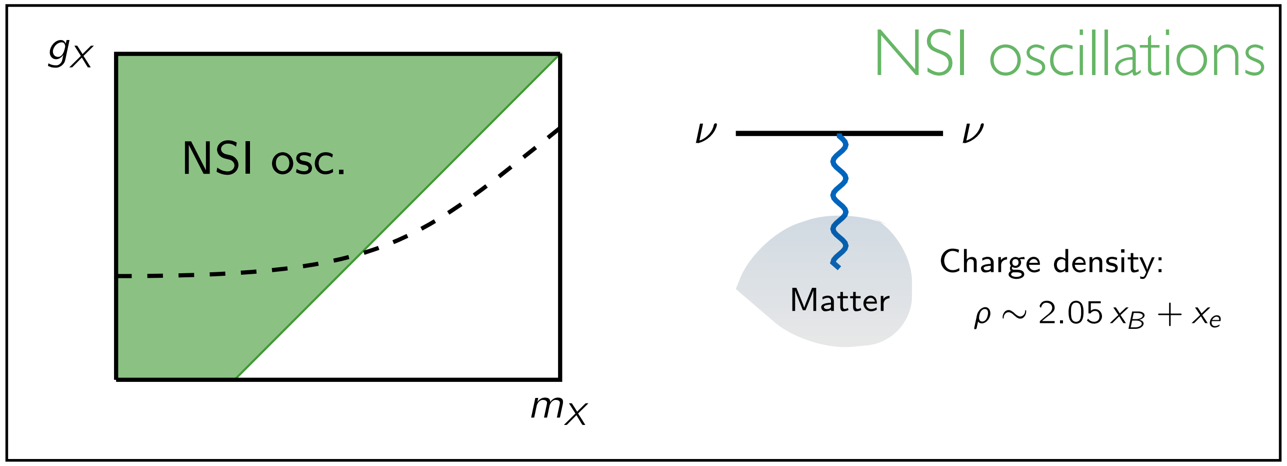
Baek *et al.* [hep-ph/0104141];
Ma, Roy, Roy [hep-ph/0110146];
many, many more...

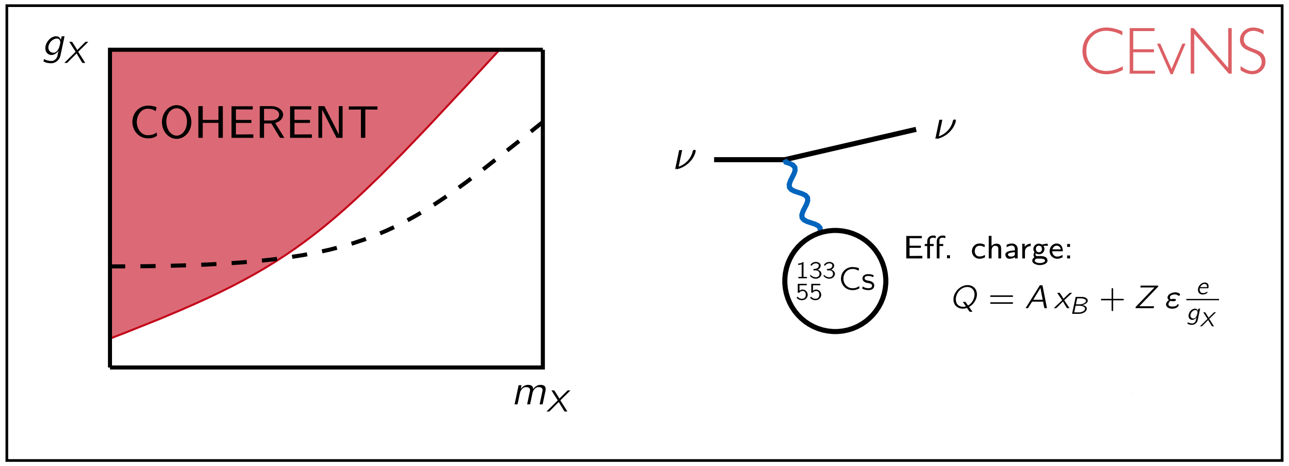
- Other $U(1)_X$?

Other constraints



Other constraints



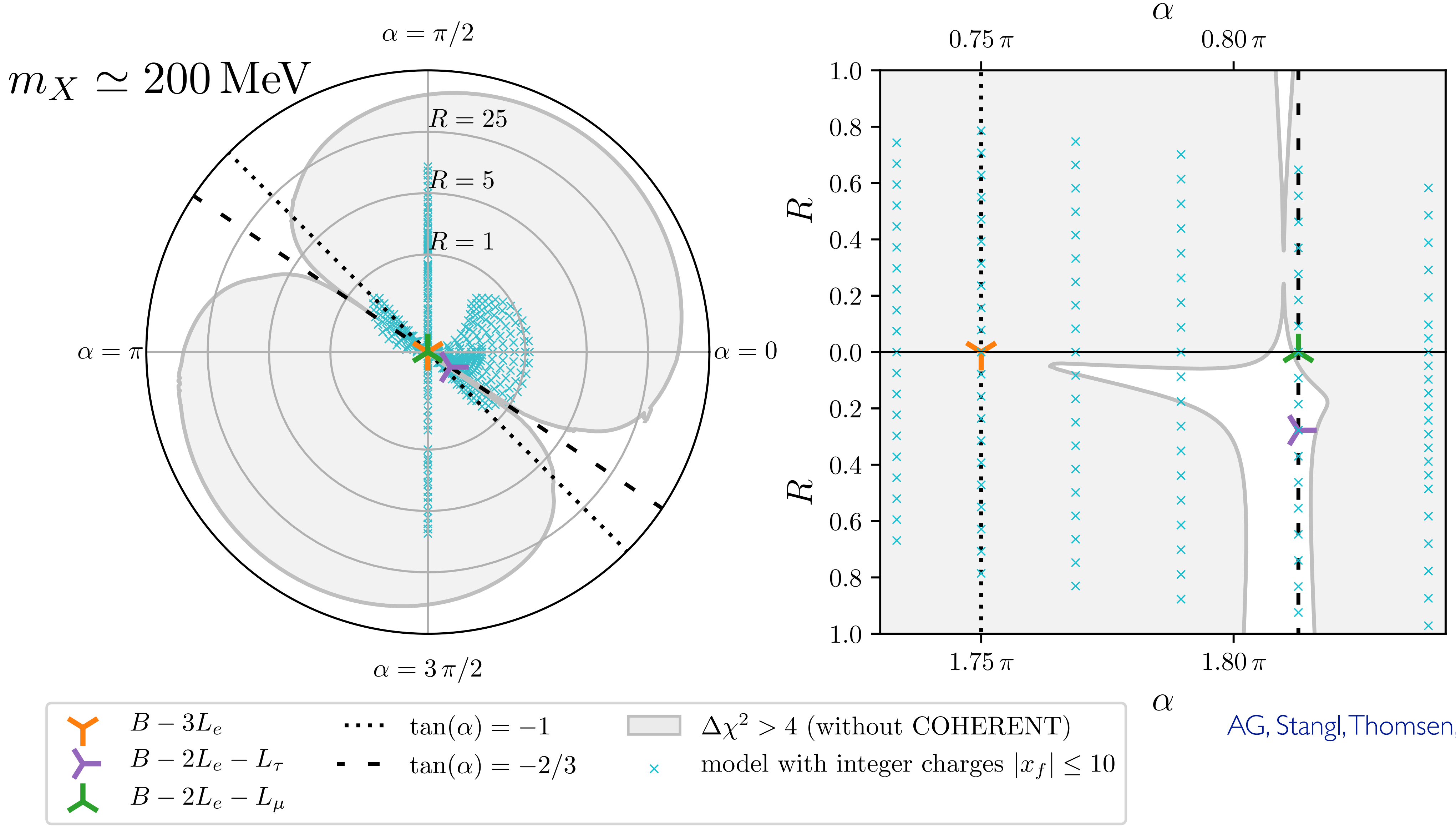


The impact of NSI

- Vector category

$$x_f \propto \sin(\alpha)(L_e - L_\mu) + \cos(\alpha)(B/3 - L_\mu) + R(L_\mu - L_\tau)$$

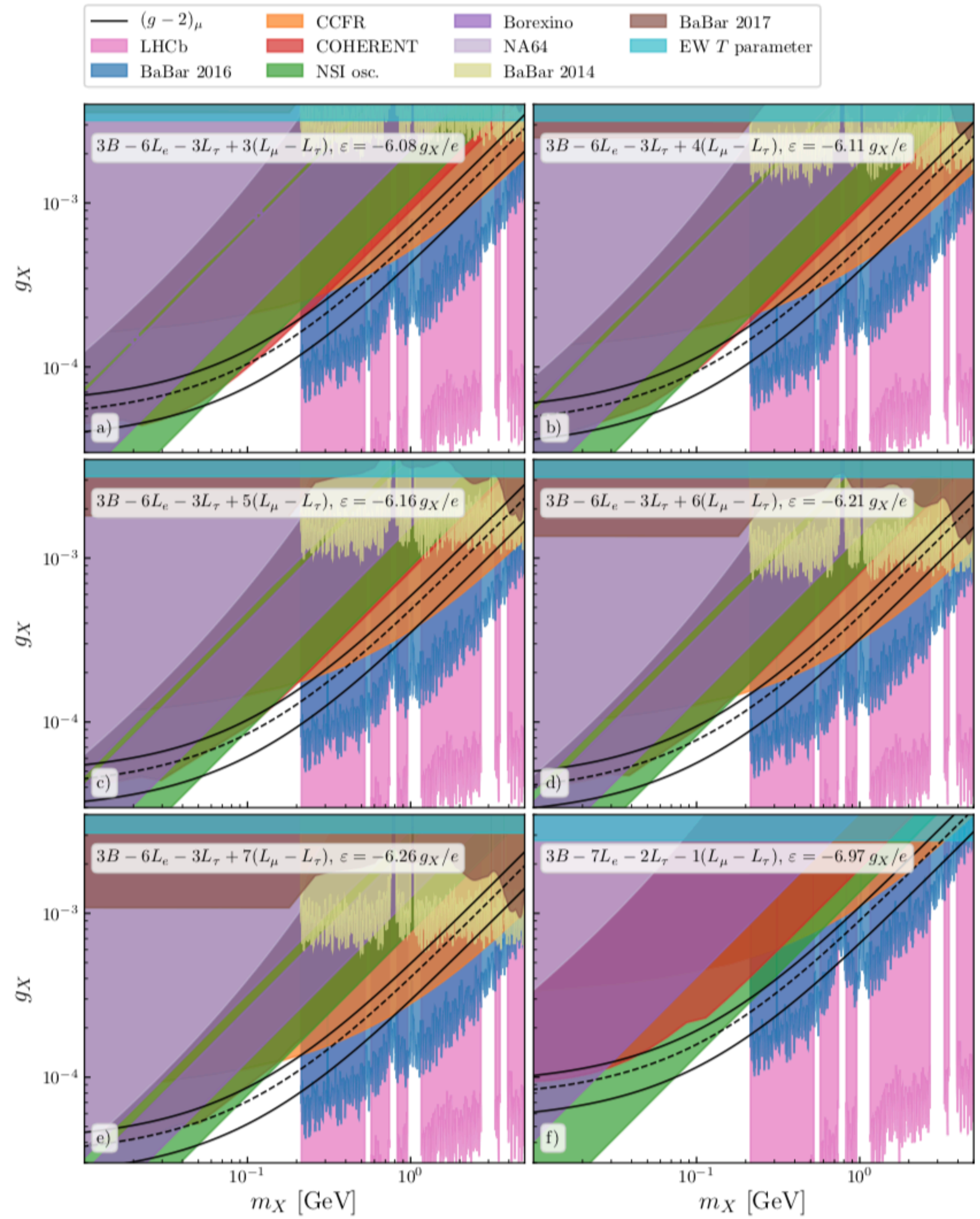
$m_X \simeq 200\,\mathrm{MeV}$



AG, Stangl, Thomsen, Zupan; 2203.13731

- Finally, including also COHERENT:
  Out of 419 models with $|x_f| \leq 10$, only 7 survive $(g-2)_\mu$ (in the narrow mass region).

The impact of NSI



- Finally, including also COHERENT:
  Out of 419 models with $|x_f| \leq 10$, only 7 survive $(g-2)_\mu$ (in the narrow mass region).

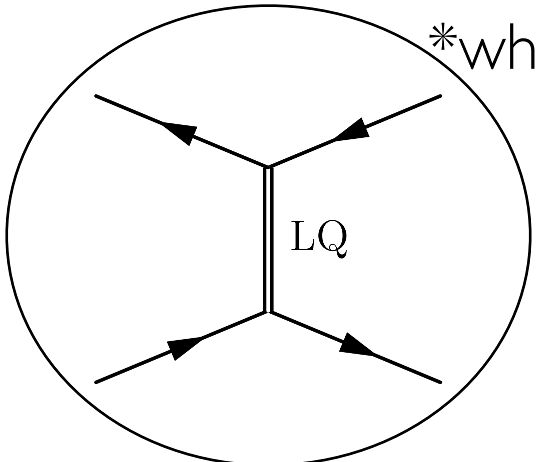
PART II

Comments on $R_{K^{(*)}}$

The storyline

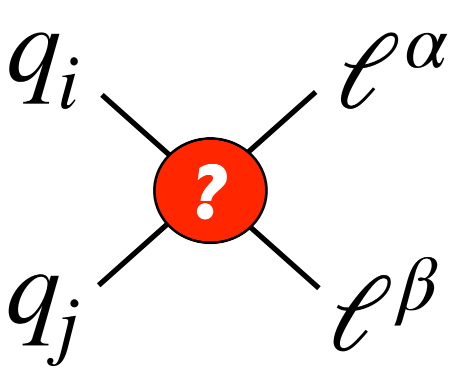
- Interpretation of $b \to s\ell\ell$ anomalies after the recent LHCb update

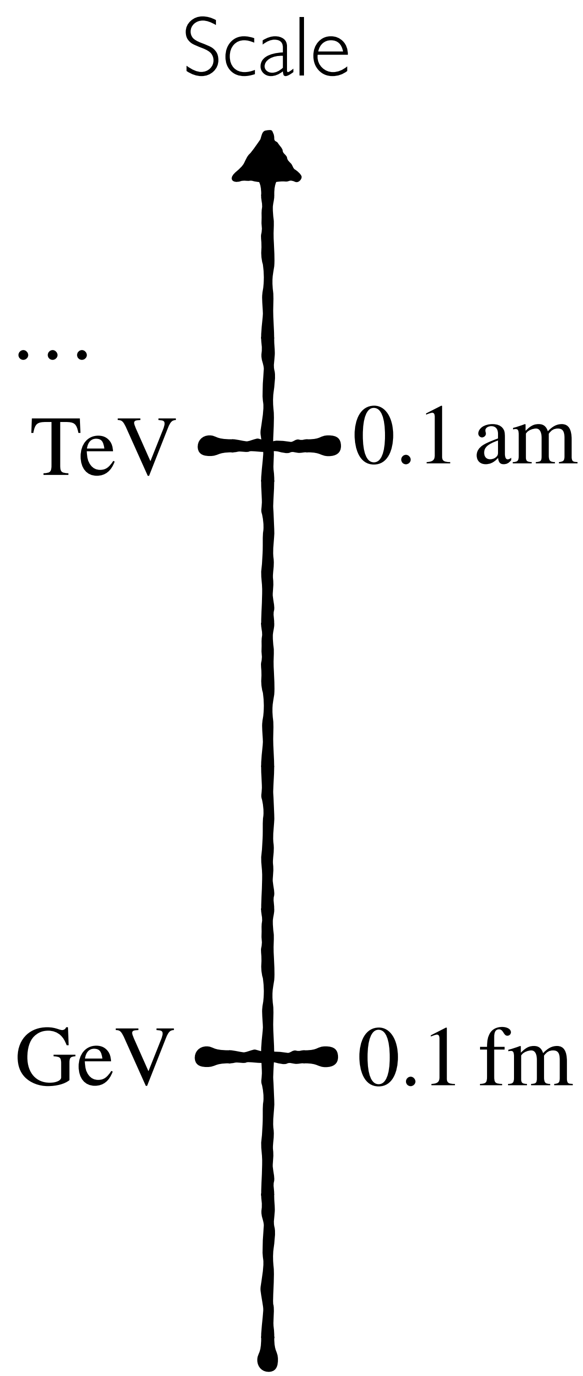
Drell-Yan versus B-decays



*when LQs are too heavy

$$pp \to \ell_\alpha^+ \ell_\beta^- (j), \; \ldots$$





Example: $b \to s\mu\mu$ vs Drell-Yan
AG, Marzocca; 1704.09015

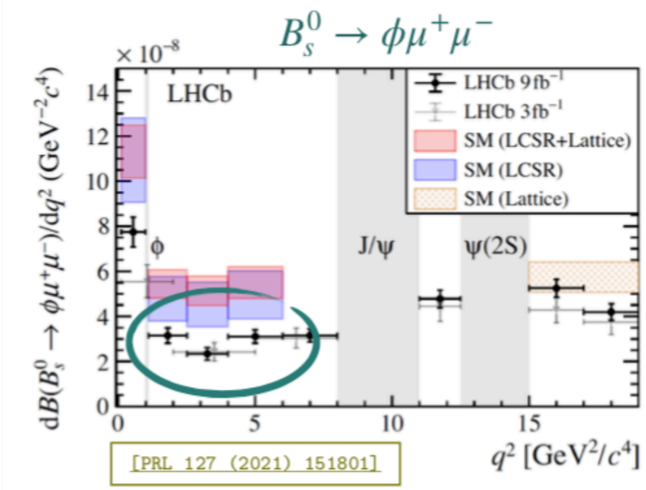
Systematic SMEFT study using `flavio`
AG, Salko, Smolkovic, Stangl; 2212.10497

The status of $b \to s\ell\ell$ anomalies

- Anomalies in $b \to s\mu\mu$

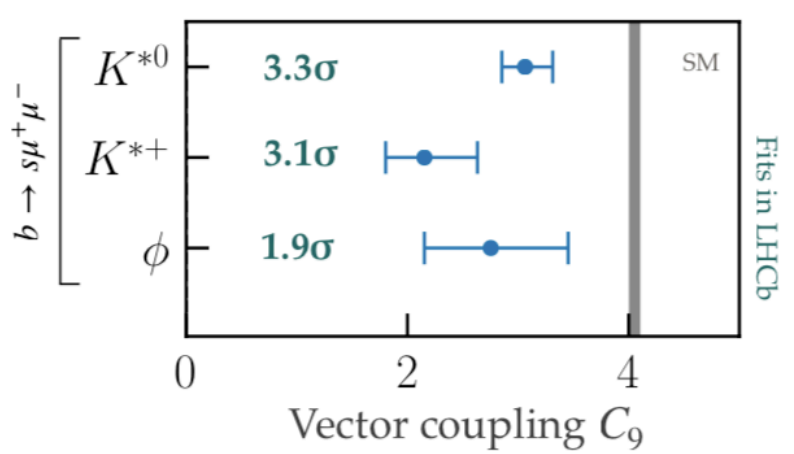
cf. Renato Quagliani, CERN seminar 20.12.2022.

$b \to s\mu^+\mu^-$ ***differential decay rates***



+ ...

$b \to s\mu^+\mu^-$ ***angular analyses***

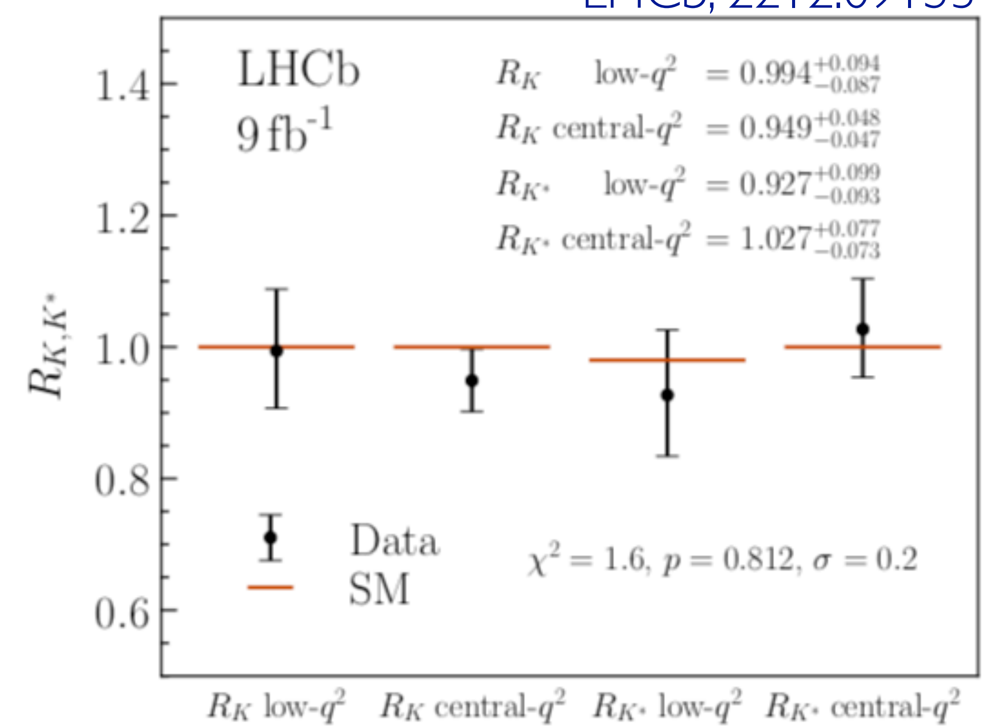


✦ Intriguing coherent and consistent pattern

- However, *charm-loops* can mimic shift in C_9

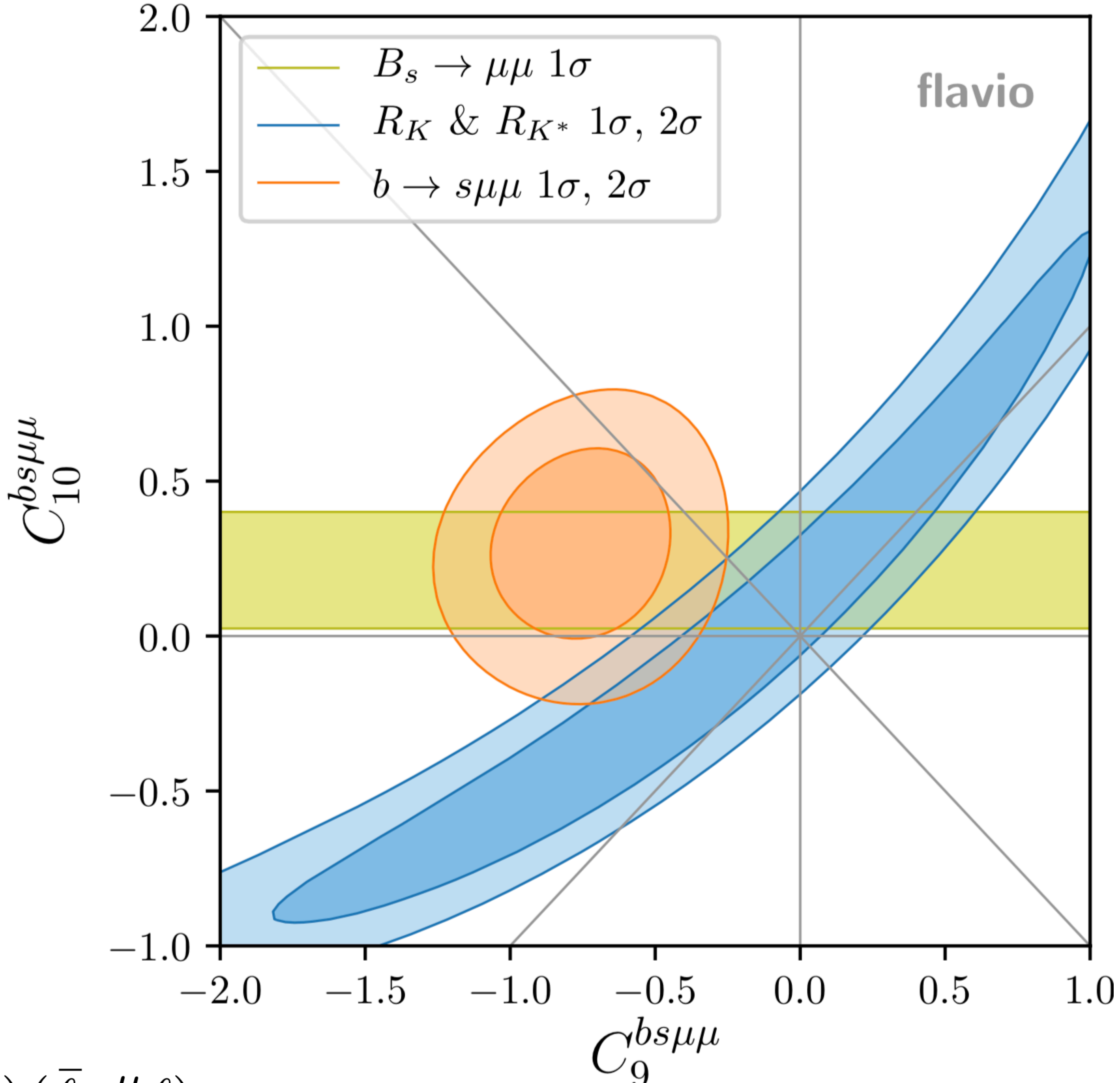
- But **L**epton **F**lavor **U**niversality ratios are SM-like

LHCb, 2212.09153



The EFT fit

AG, Salko, Smolkovic, Stangl; 2212.10497



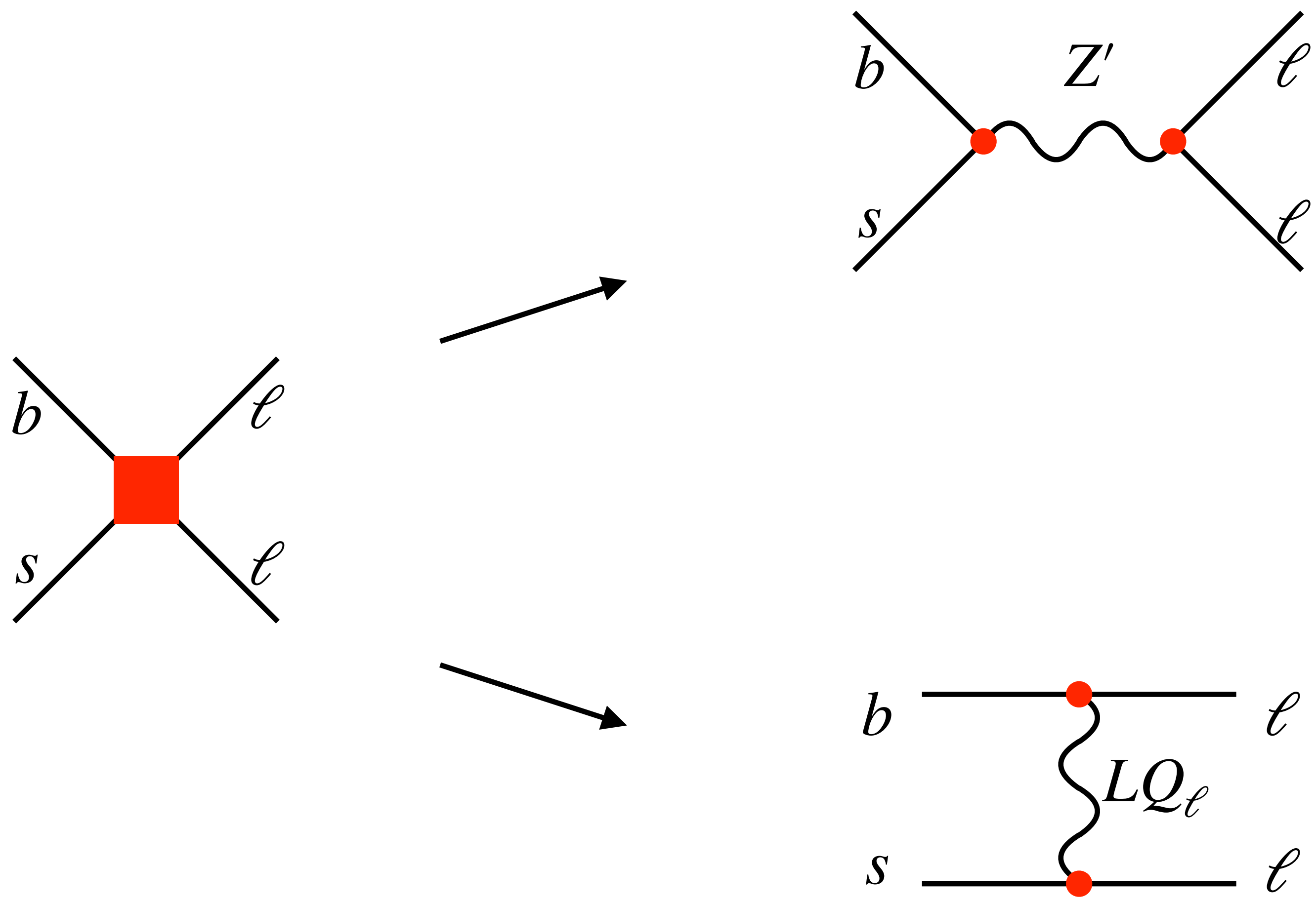
Tension!

$$O_9^{bq\ell\ell} = (\bar{q}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,,$$

$$O_{10}^{bq\ell\ell} = (\bar{q}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

LFU models for $b \to s\ell\ell$

Tree-level models



- LFU Z'

  $U(1)_{B-L}$

  $U(1)_{3B_3-L}$

  ...

- LFU LQ *Single LQ $\Longrightarrow$ cLFV

  $(\bar{\mathbf{3}}, \mathbf{3}, 1/3) \times 2 = LQ_e + LQ_\mu$

  $U(1)_e \times U(1)_\mu \times Z_2^{\rm LFU}$

  $\downarrow$

  $LQ_e \leftrightarrow LQ_\mu$

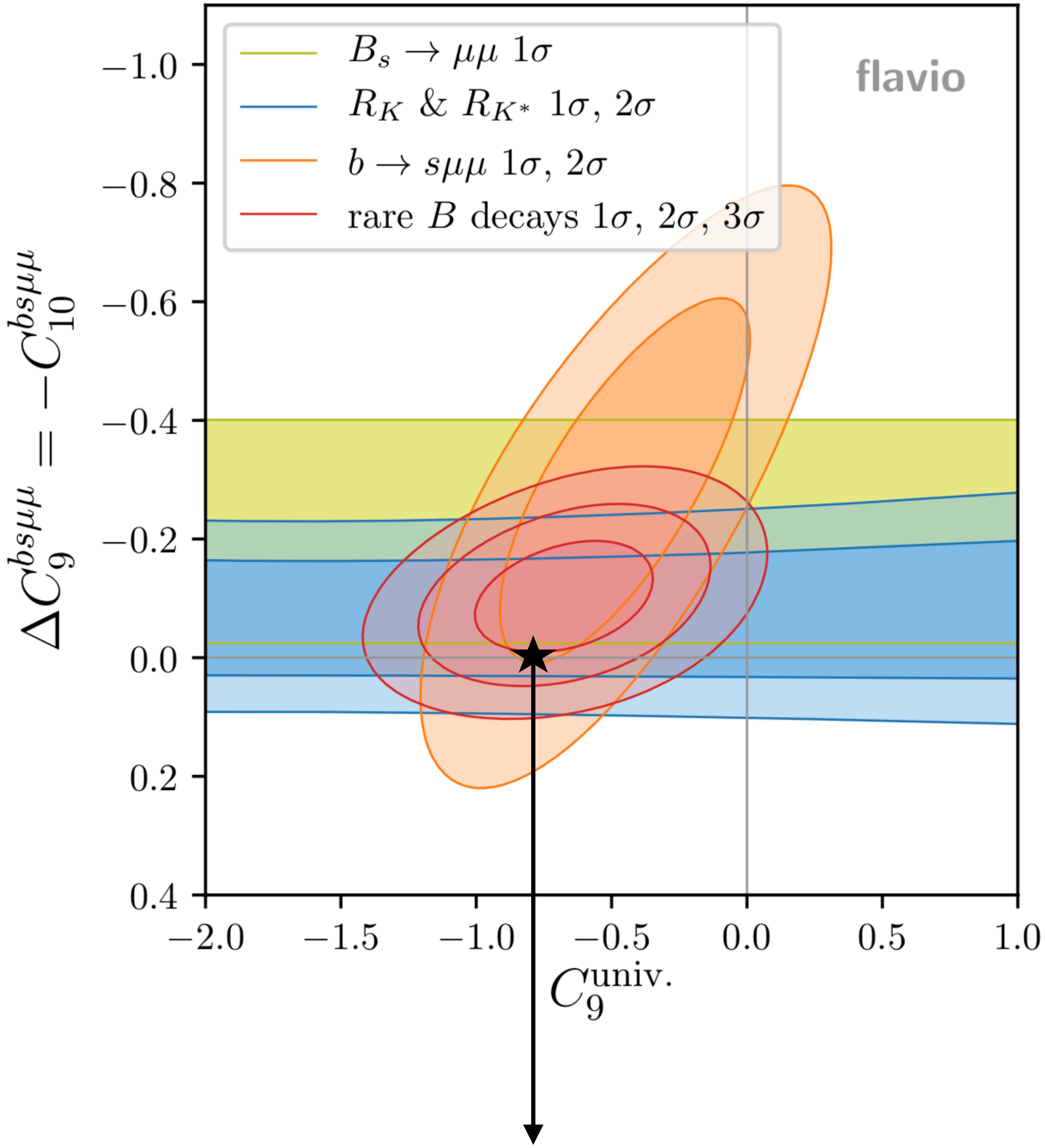
  $e \leftrightarrow \mu$

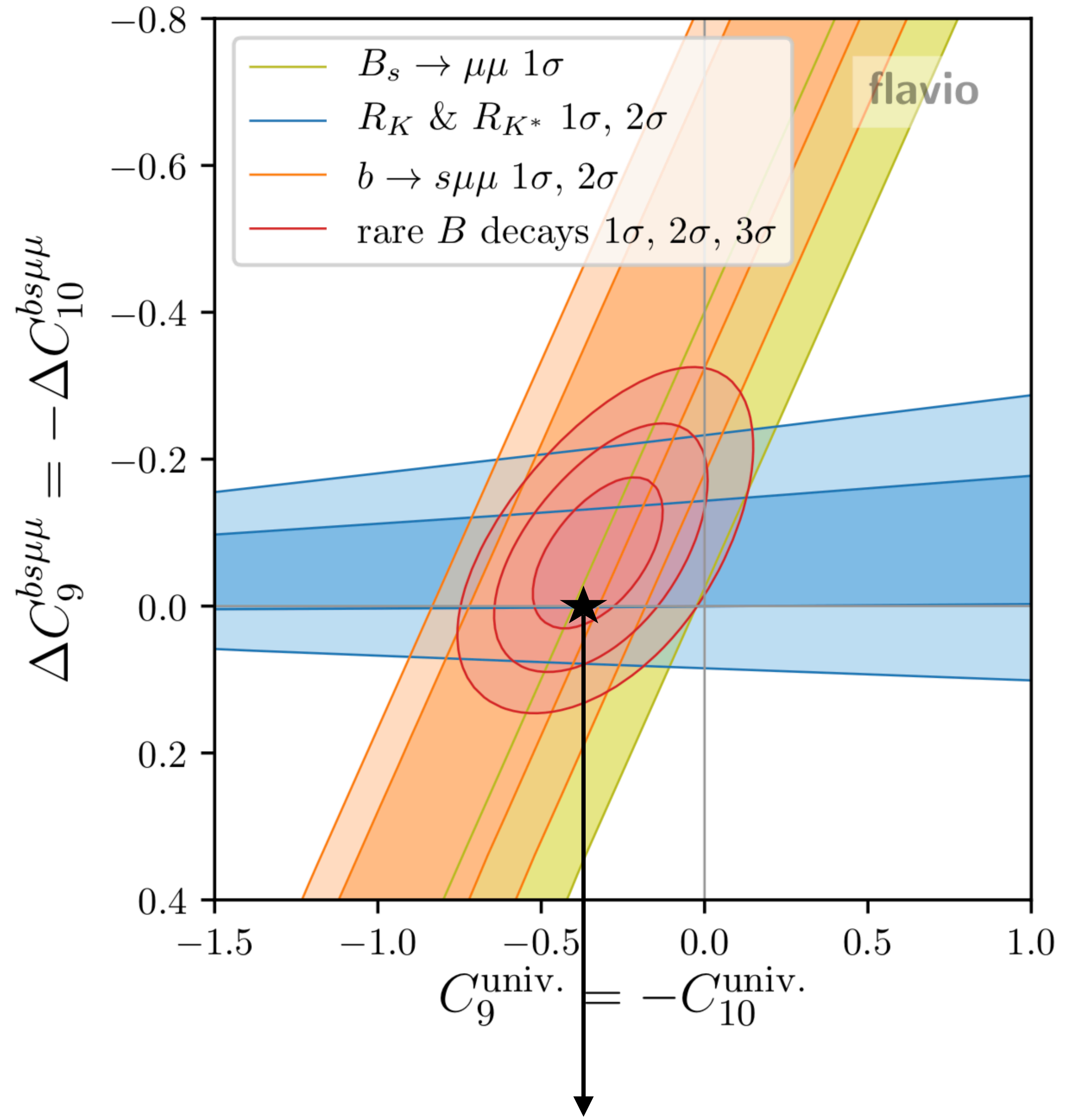
Mass/Coupling degeneracy

Gauged flavour (Part I) ?

The EFT fit

AG, Salko, Smolkovic, Stangl: 2212.10497

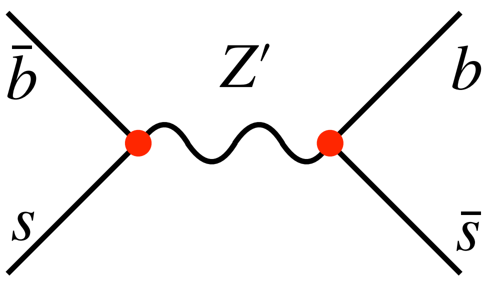




- LFU Z'
- LFU LQ

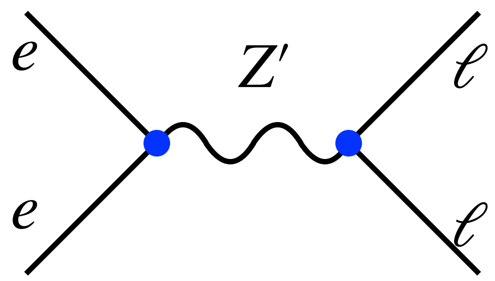
LFU models: Z'

- The bounds from



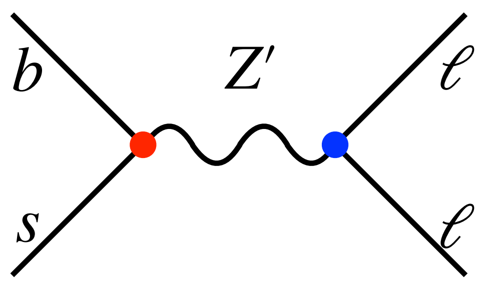
Meson mixing

+



LEP II

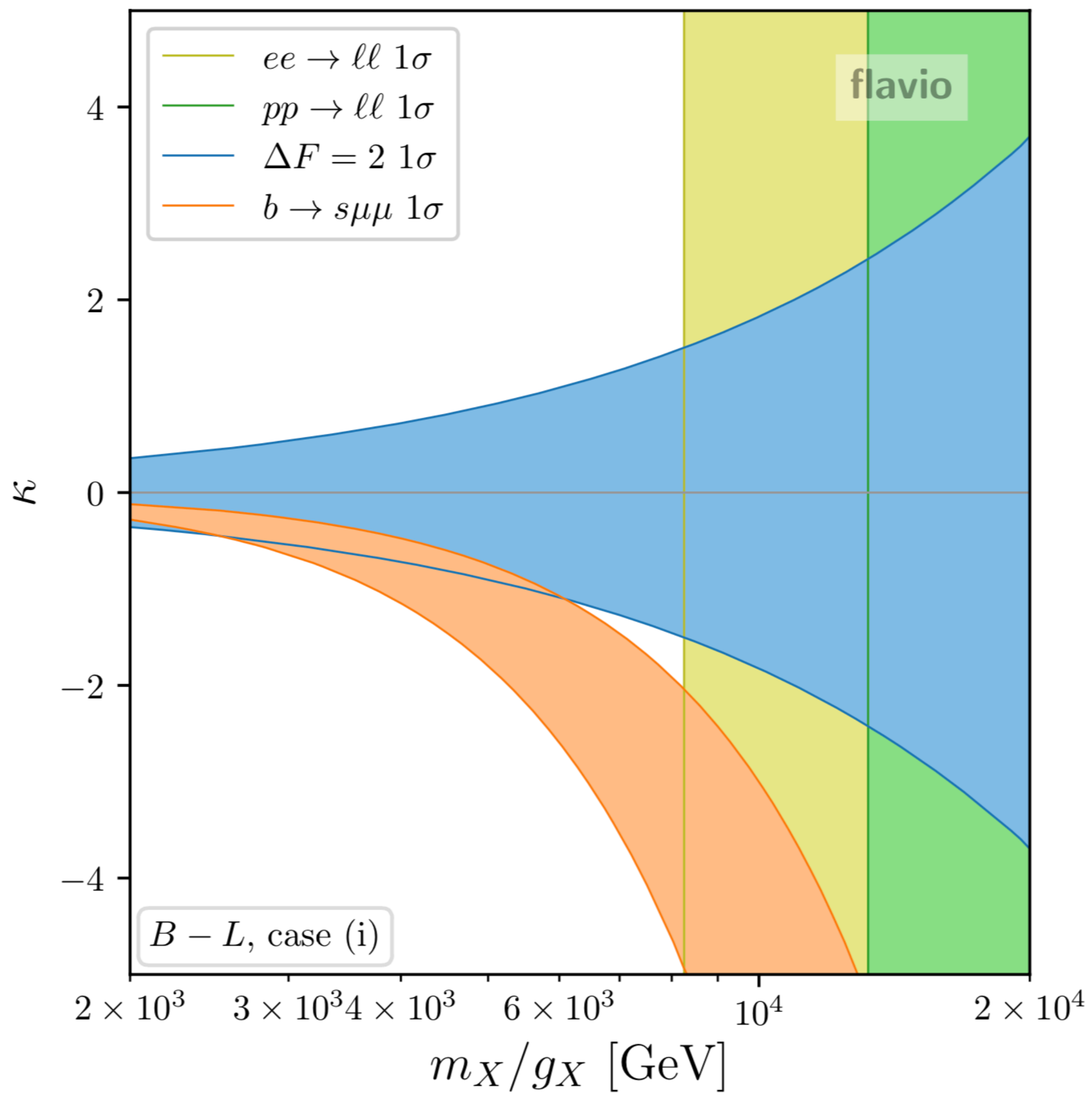
are constraining



!

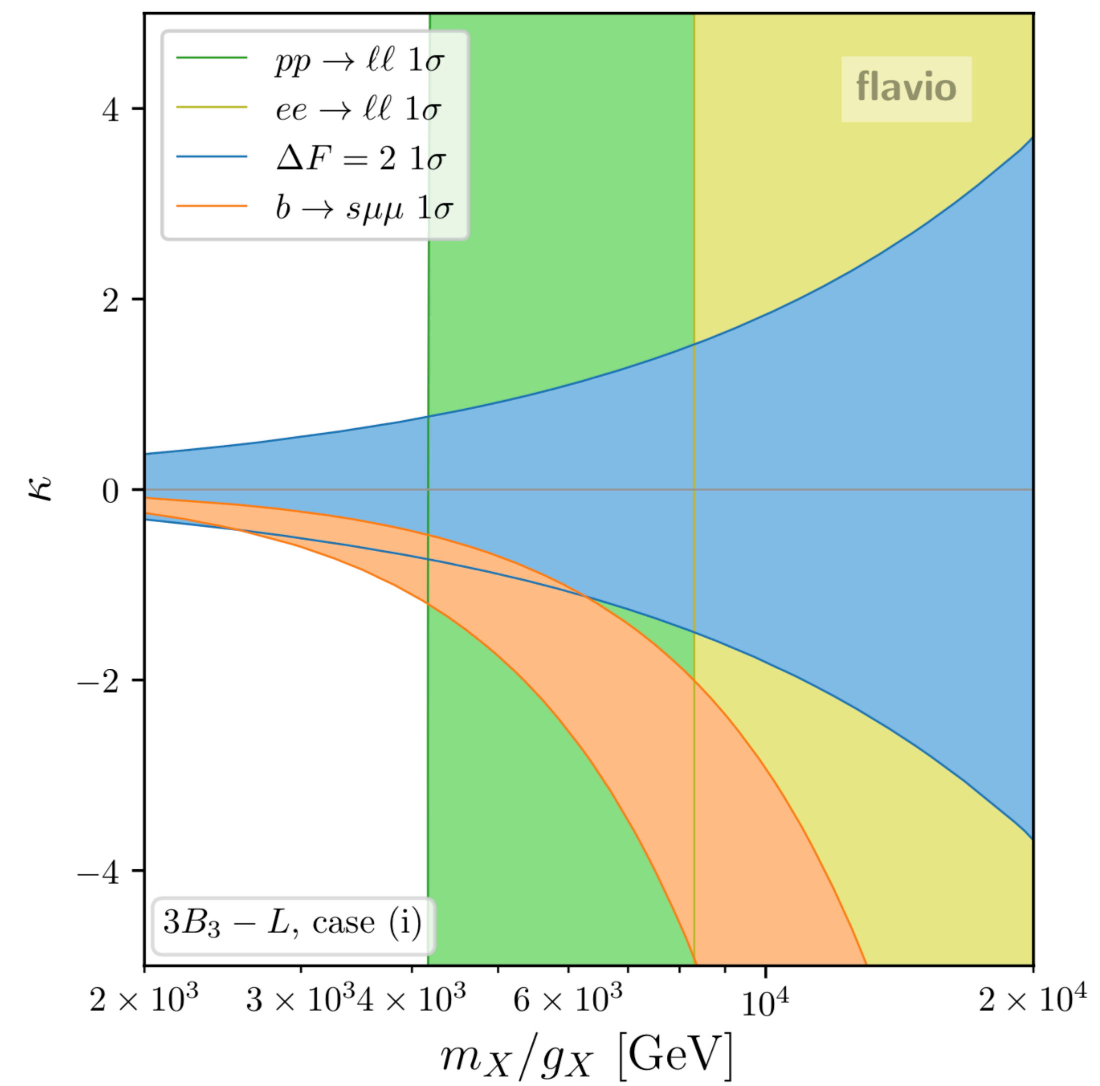
LFU models: Z'

$B-L$



$$J_X^\mu = J_{B-L}^\mu + \frac{1}{3}\epsilon_{ij}\,\bar{q}_i\gamma^\mu q_j$$

$3B_3-L$



$$J_X^\mu = J_{3B_3-L}^\mu + \frac{1}{3}\epsilon_{ij}\,\bar{q}_i\gamma^\mu q_j$$

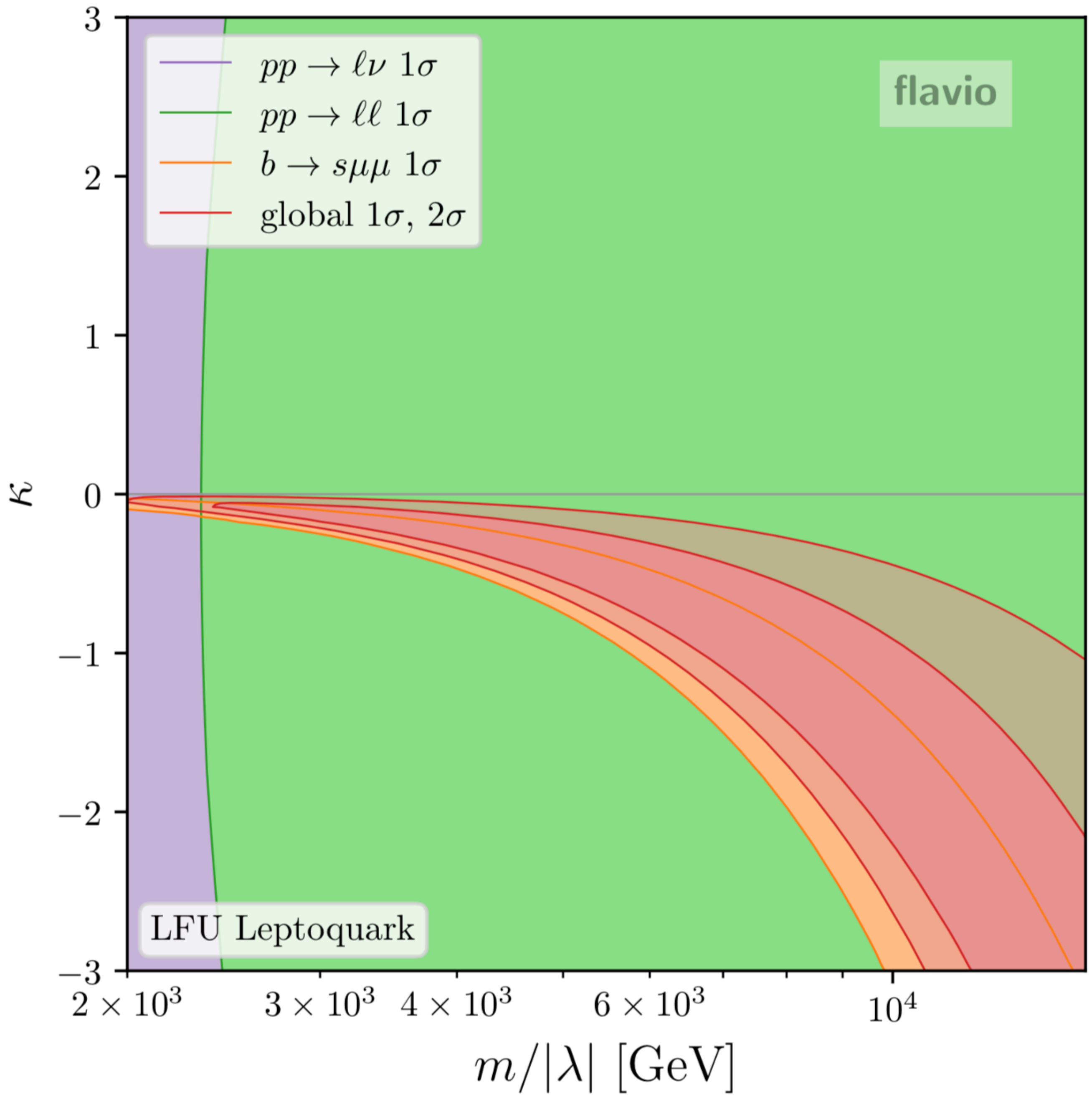
$$\epsilon_{ij} = -\kappa\,|V_{ts}|(\delta_{i2}\delta_{j3} + \delta_{i3}\delta_{j2})$$

Tension!

LFU leptoquark

$$\mathcal{L} \supset (D_\mu S^\alpha)^\dagger (D^\mu S^\alpha) - m^2 S^{\alpha\dagger} S^\alpha - (\lambda_i\, \bar{q}_i^c l_\alpha S^\alpha + \text{h.c.})$$

$$\lambda_i = \lambda\,(\kappa V_{td}, \kappa V_{ts}, 1)$$



- Tree-level $2q2\ell$,
- Loop-suppressed $4q$ and 4ℓ ✔

PART III

Future Colliders

The storyline

- New physics in $b \to s\mu\mu$: FCC-hh versus a Muon Collider

Motivation

- Short-distance $bs\mu\mu$ contact interaction at the level of $\mathcal{O}(10^{-5})G_F$

$\Longrightarrow$ the violation of perturbative unitarity $\lesssim 100\,\mathrm{TeV}$

$\Longrightarrow$ **Future Colliders**

Competitors

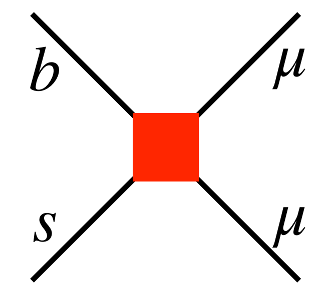
Collider	C.o.m. Energy	Luminosity	Label
LHC Run-2	13 TeV	140 fb^{-1}	LHC
HL-LHC	14 TeV	6 ab^{-1}	HL-LHC
FCC-hh	100 TeV	30 ab^{-1}	FCC-hh
Muon Collider	3 TeV	1 ab^{-1}	MuC3
Muon Collider	10 TeV	10 ab^{-1}	MuC10
Muon Collider	14 TeV	20 ab^{-1}	MuC14

Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; 2205.13552

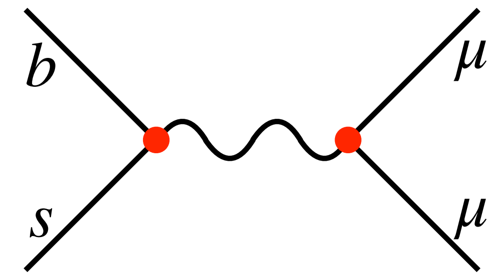
The scope

- New Physics benchmarks:

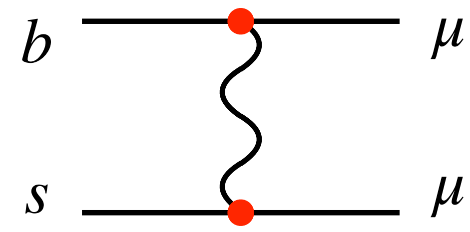
1. Semileptonic 4F interactions



2. Z'



3. LQ



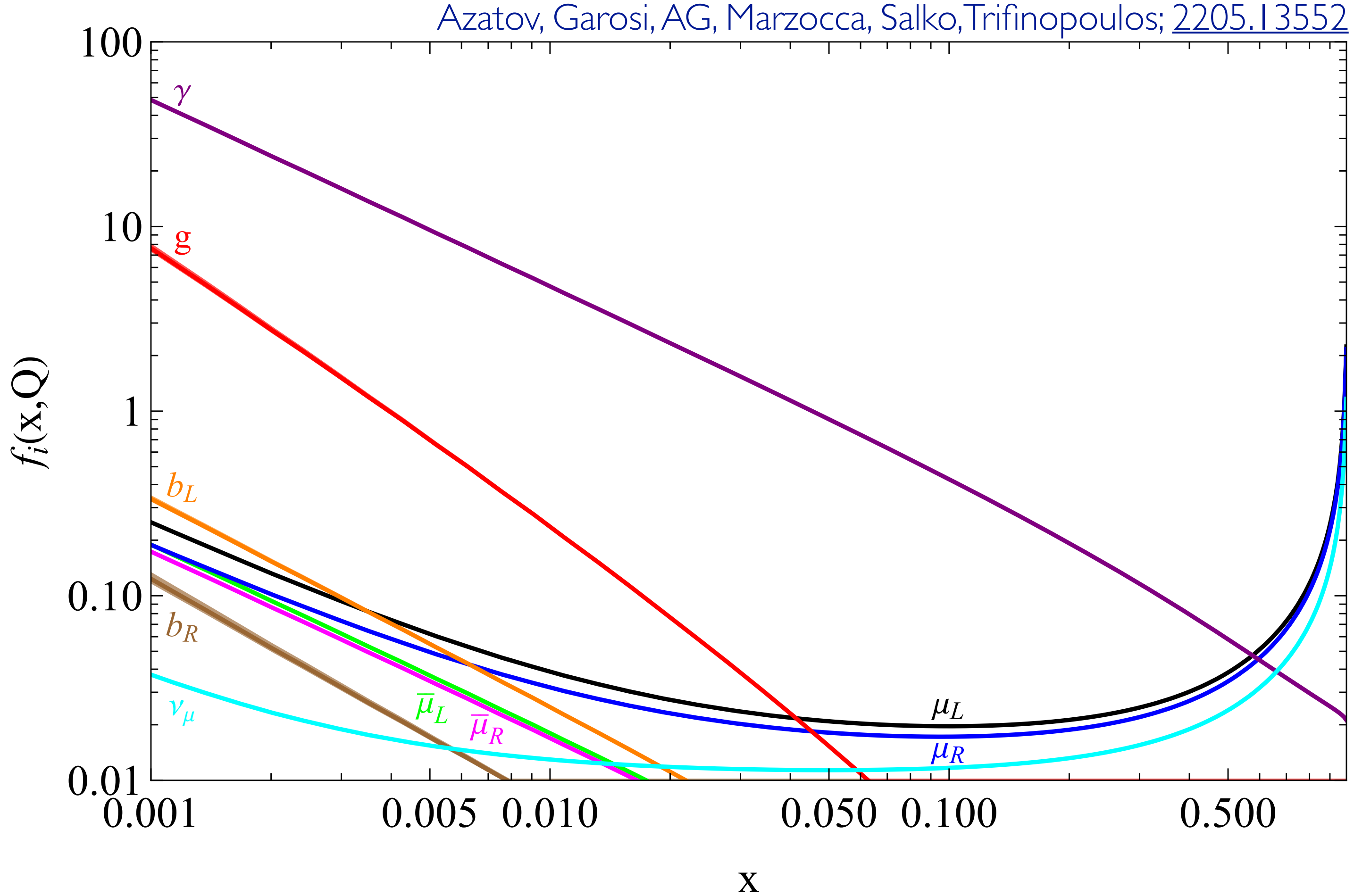
[See backup slides]

Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; 2205.13552

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 $Q = 3\,\mathrm{TeV}$:

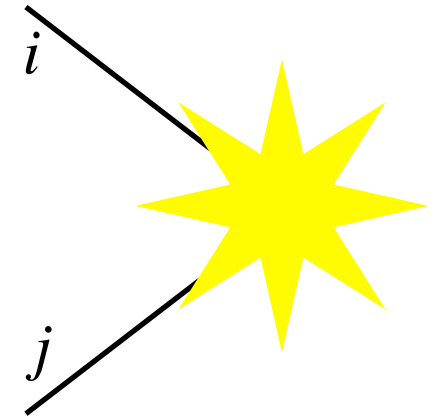
Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; 2205.13552



The Muon Beam

- Parton luminosities

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



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

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

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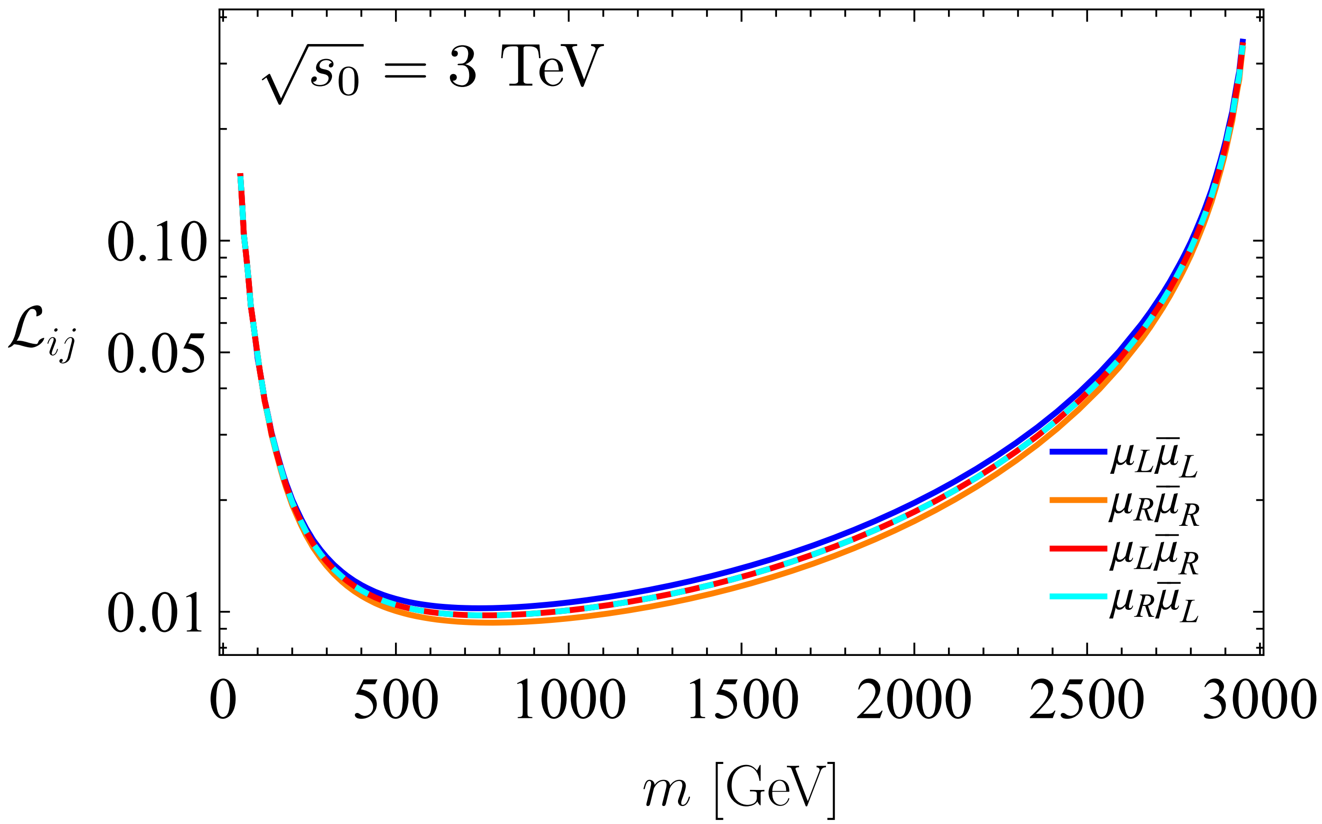
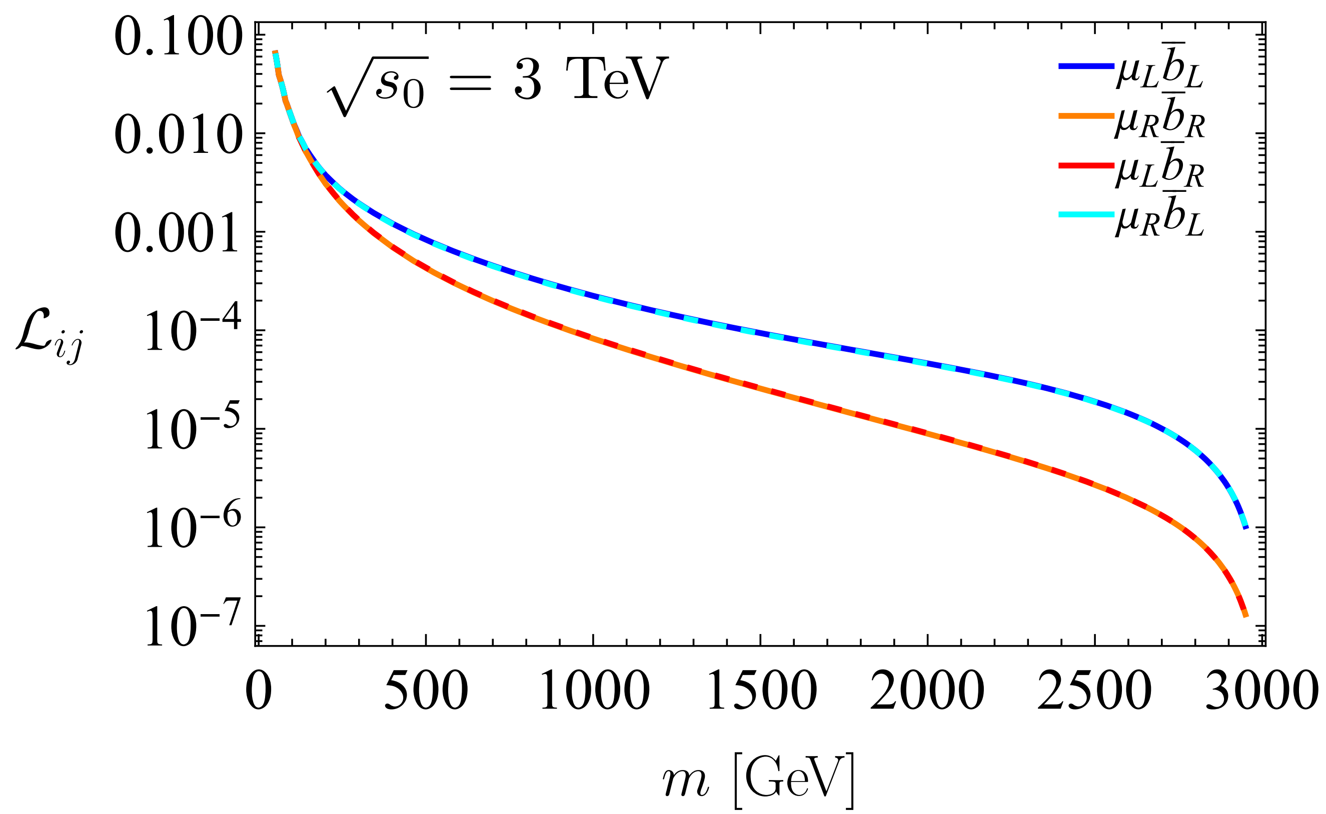
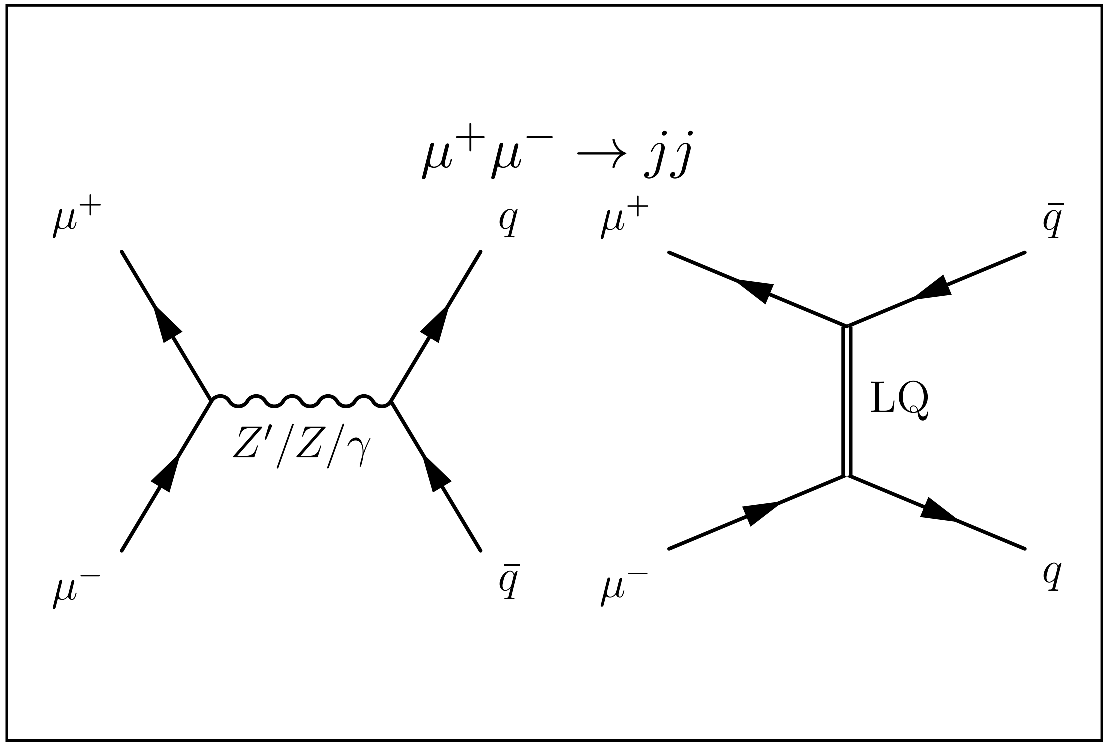
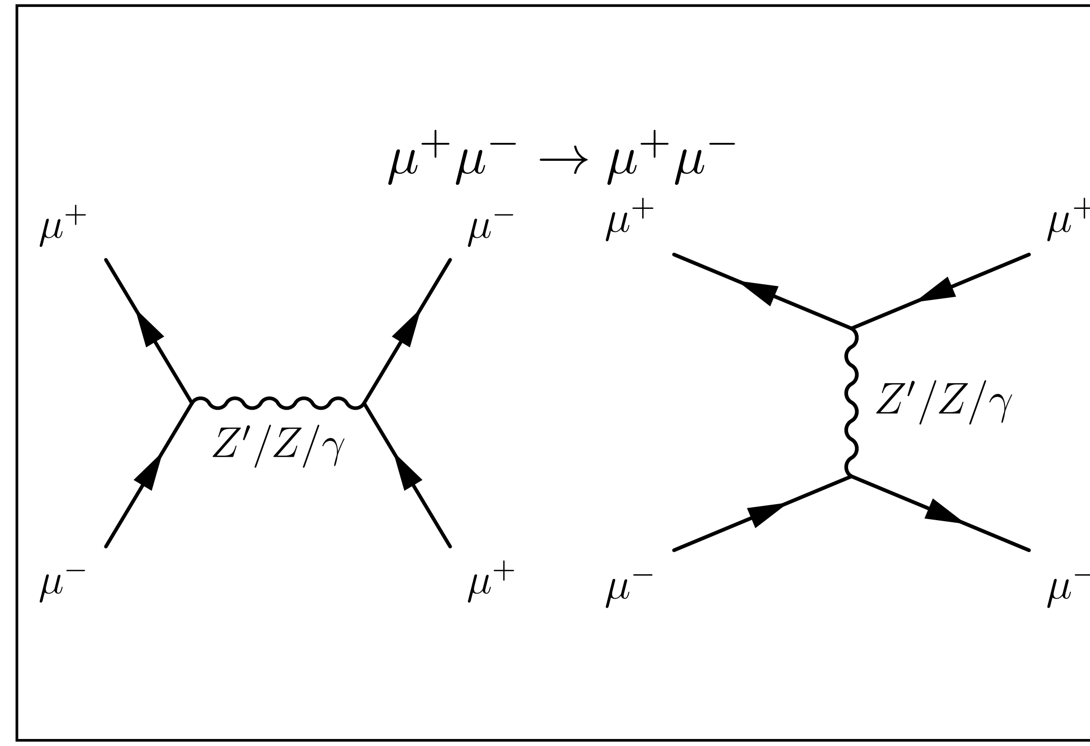
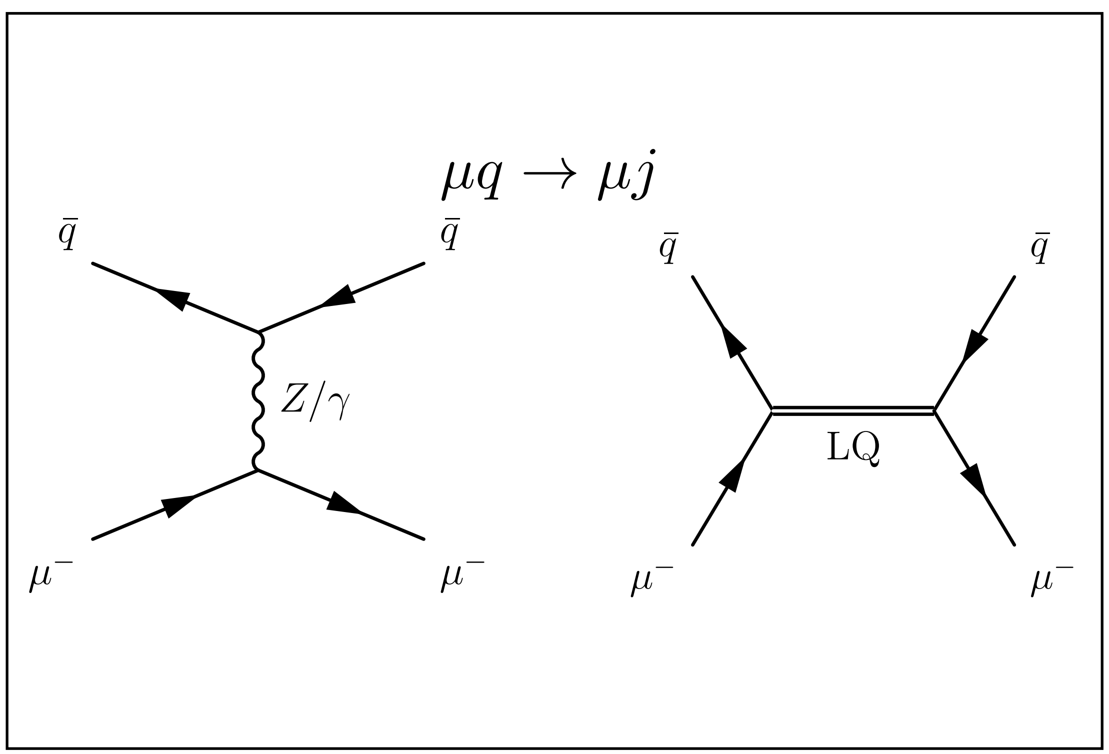


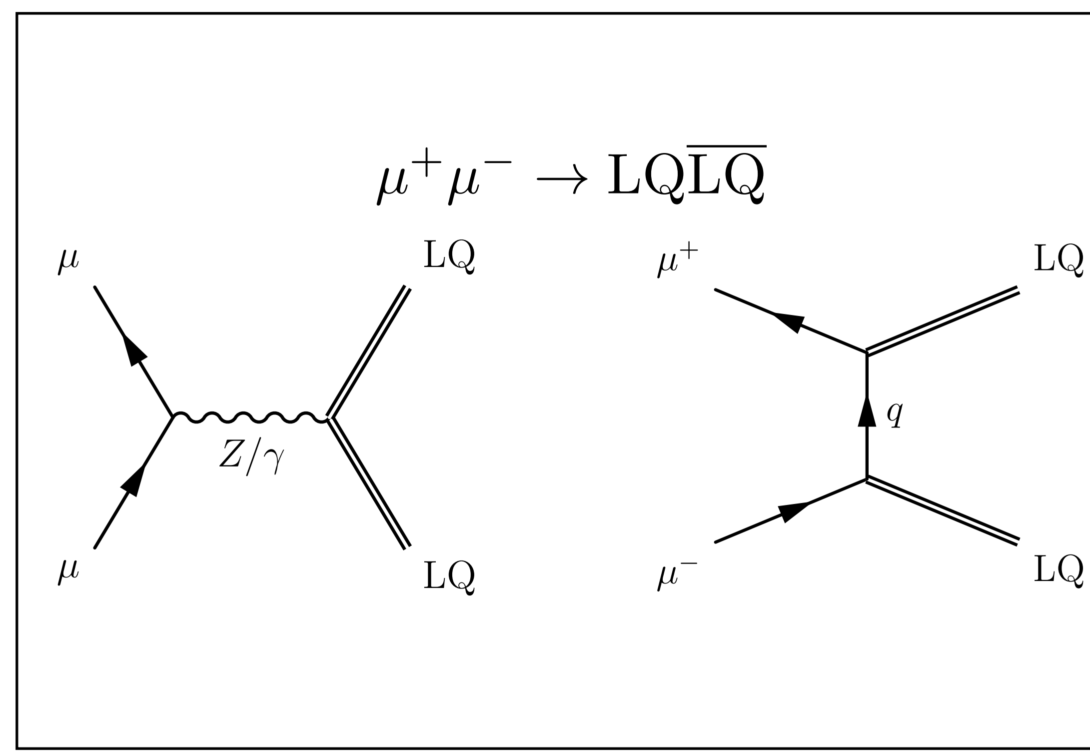


The signatures at MuC







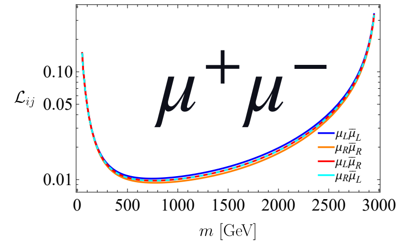


The signatures at MuC

$m_X < \sqrt{s_0}$

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

- Only effective at MuC due to

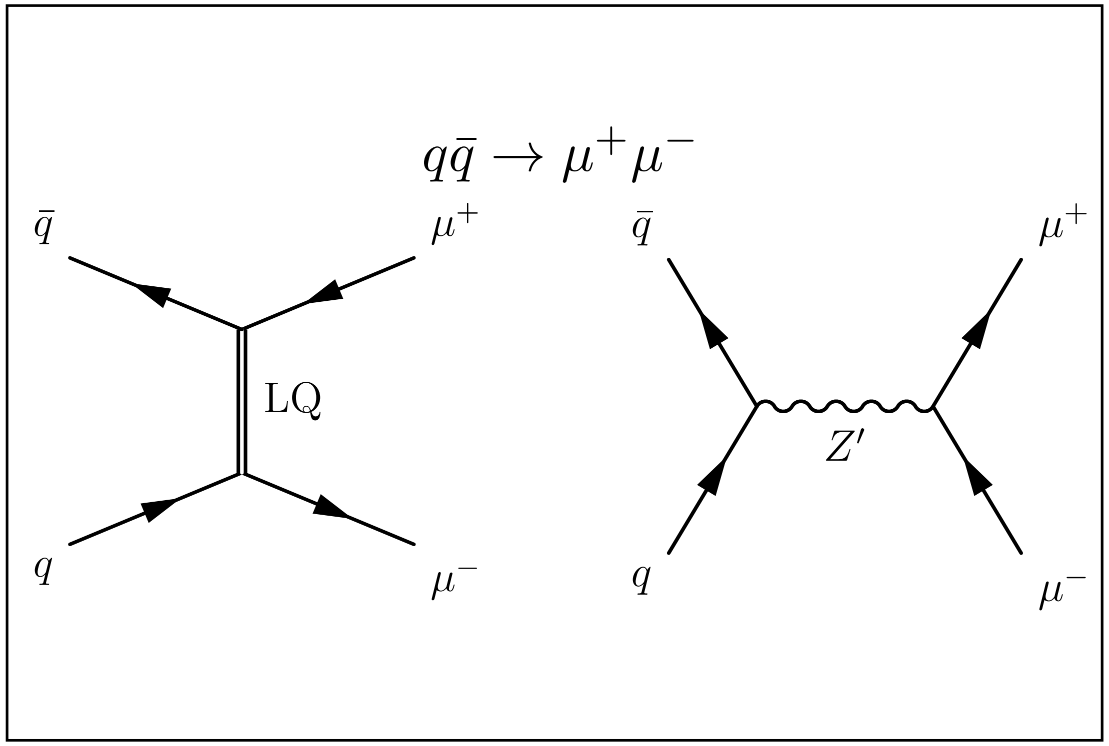


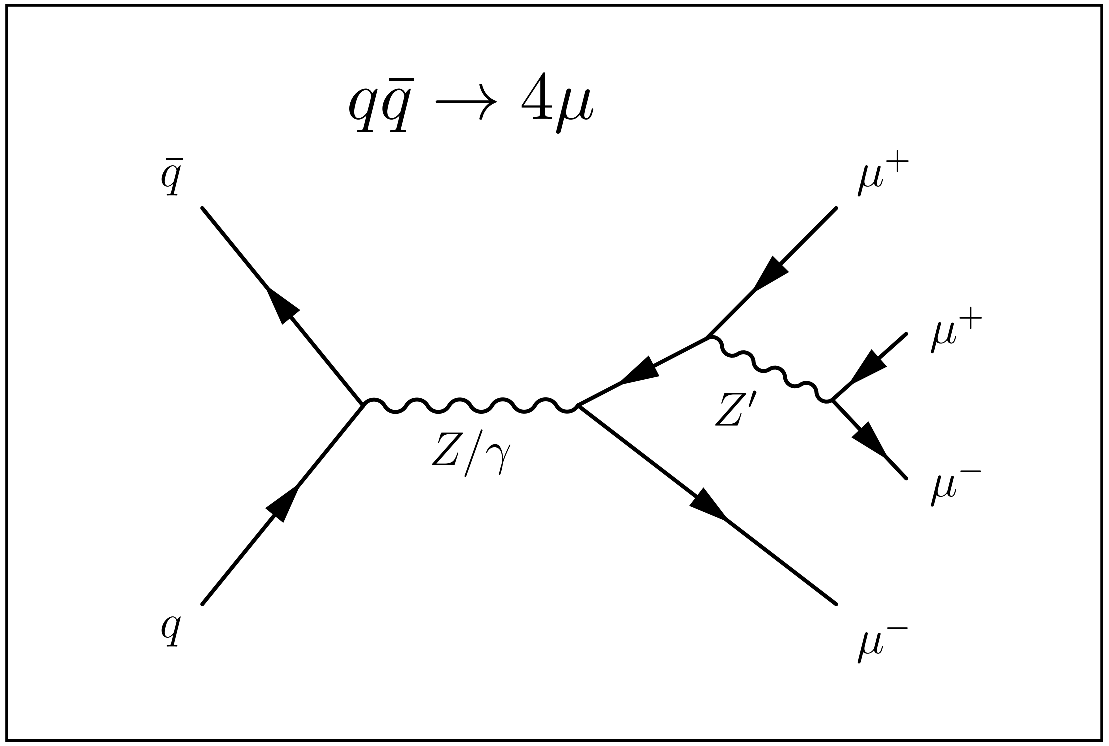
- Monotonously decreasing luminosities in proton colliders

$m_X > \sqrt{s_0}$

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

The signatures at hadron colliders

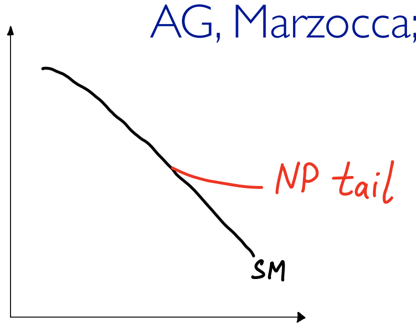


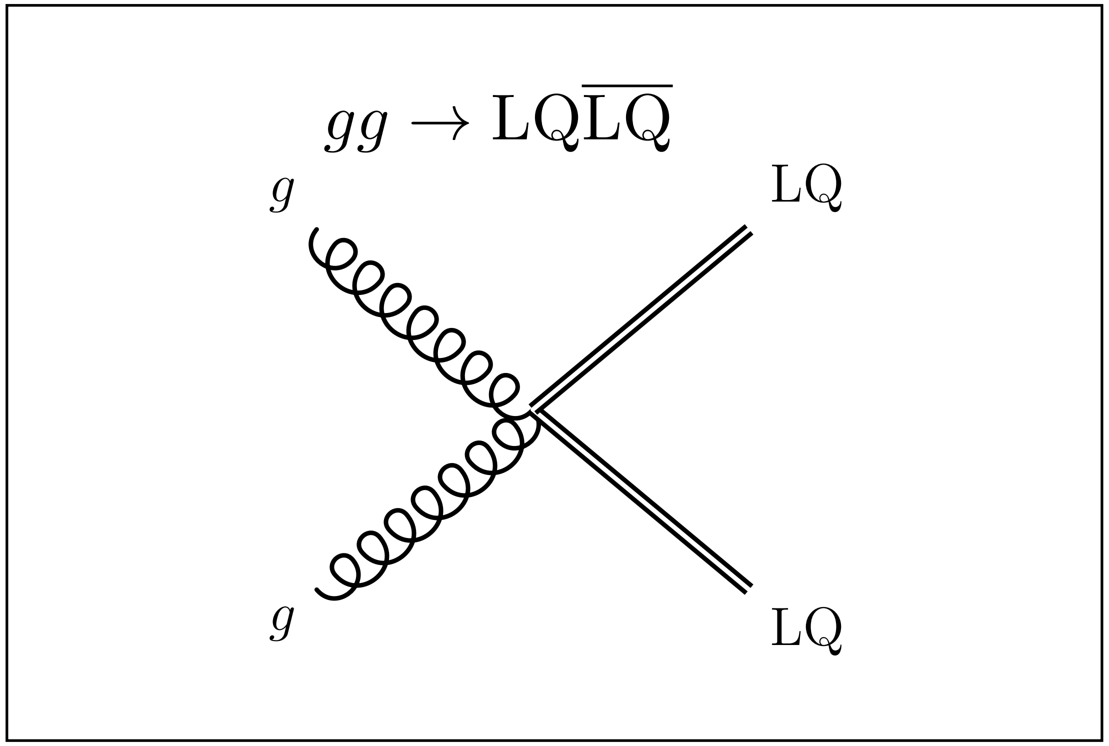


- Corrections to the high-mass Drell-Yan
- LHC data already useful to constrain models for $b \to s\mu\mu$

AG, Marzocca; 1704.09015

EFT limit





Contact interactions

The pessimistic case

Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; 2205.13552

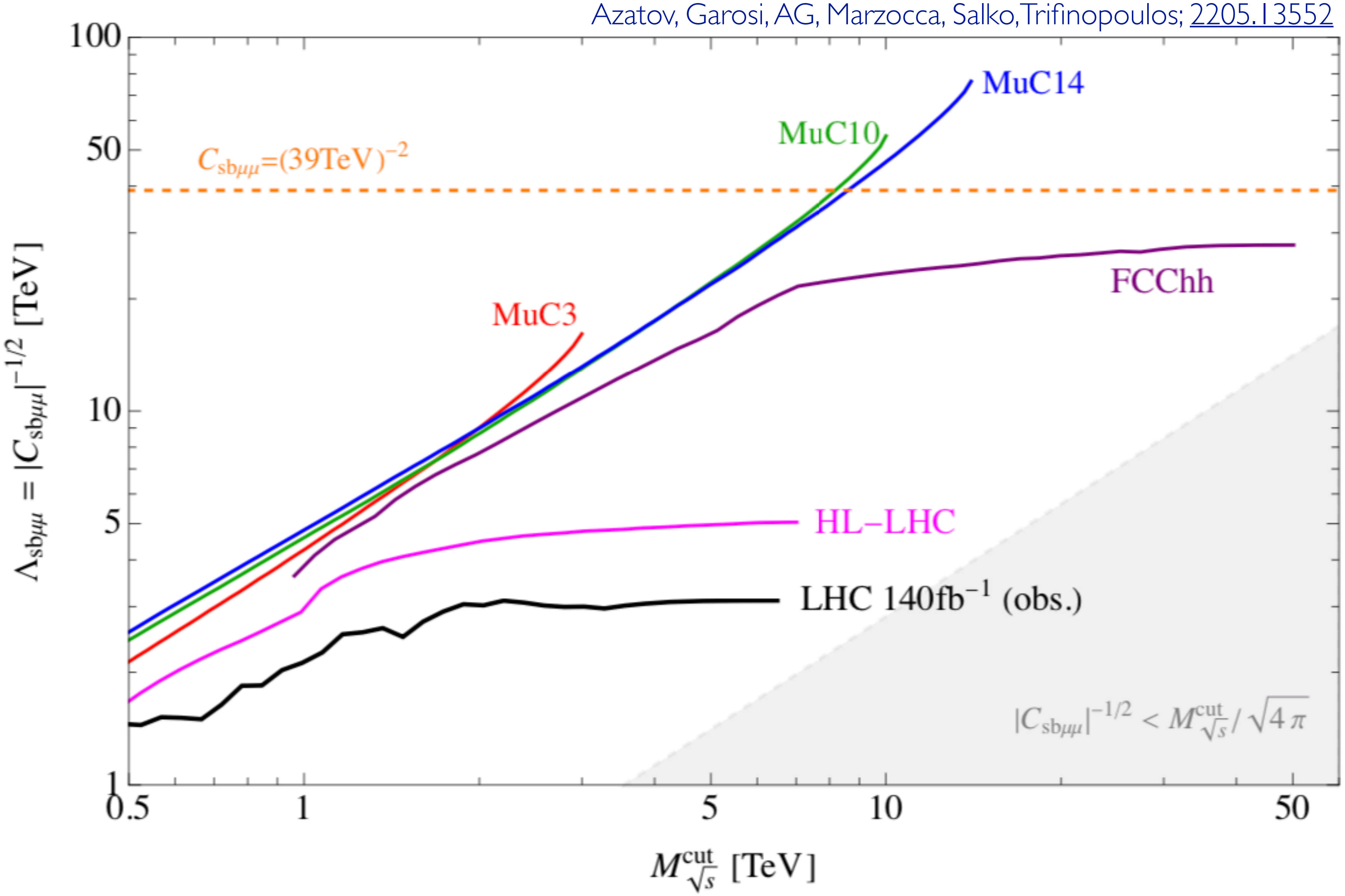


Figure 7. Sensitivity reach (95%CL) for the $(\bar{s}_L\gamma_\alpha b_L)(\bar{\mu}_L\gamma^\alpha\mu_L)$ contact interaction as function of the upper cut on the final-state invariant mass, compared to the value required to fit $bs\mu\mu$ anomalies (dashed orange line).

Contact interactions

The realistic case ★

Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; 2205.13552

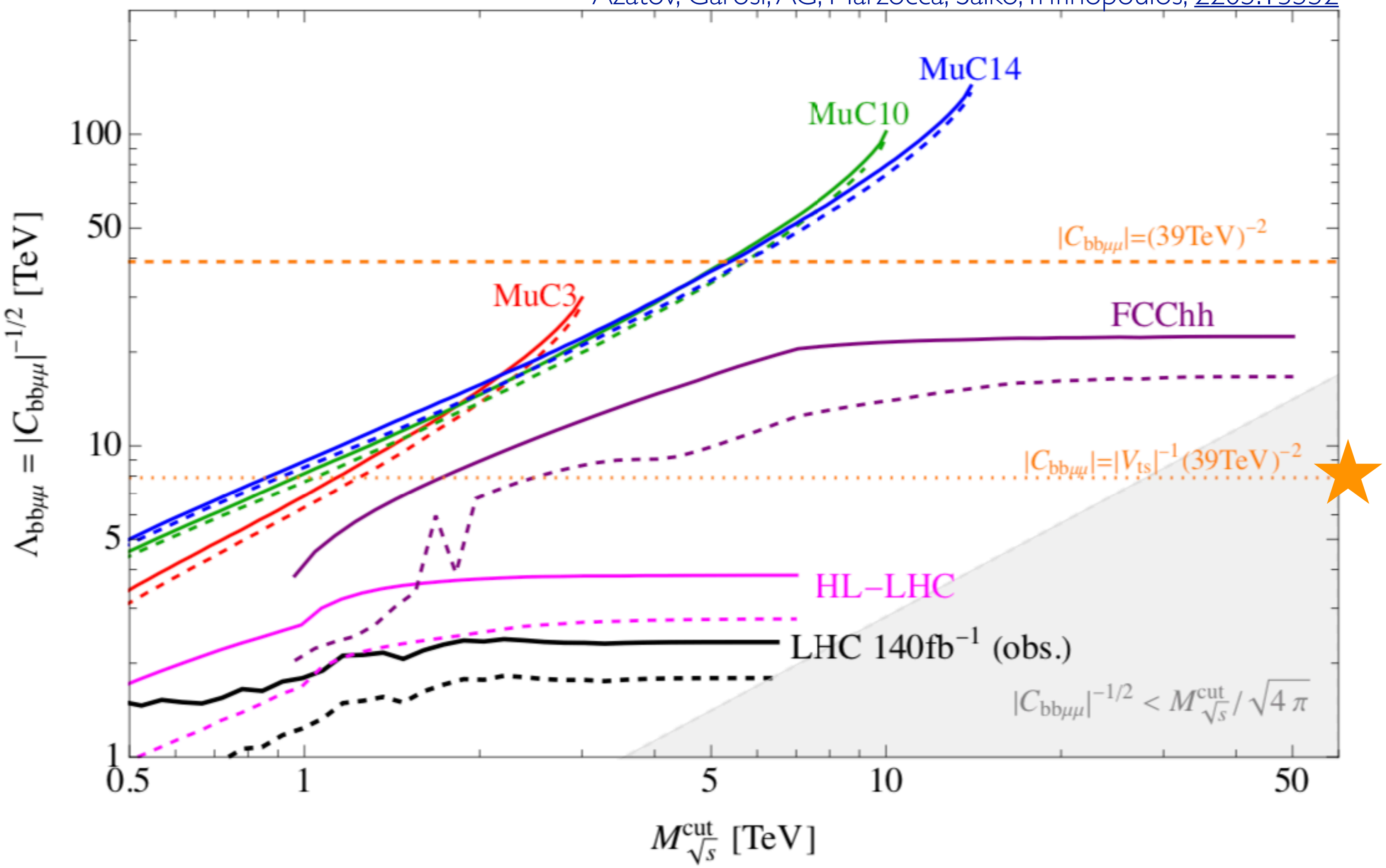


Figure 8. Sensitivity reach (95%CL) for the $(\bar{b}_L\gamma_\alpha b_L)(\bar{\mu}_L\gamma^\alpha\mu_L)$ contact interaction as function of the upper cut on the final-state invariant mass. Solid (dashed) lines represent the limit for positive (negative) values of $C_{bb\mu\mu}$. The orange dotted and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

Z' models: $B_3 - L_\mu$

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

Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; 2205.13552

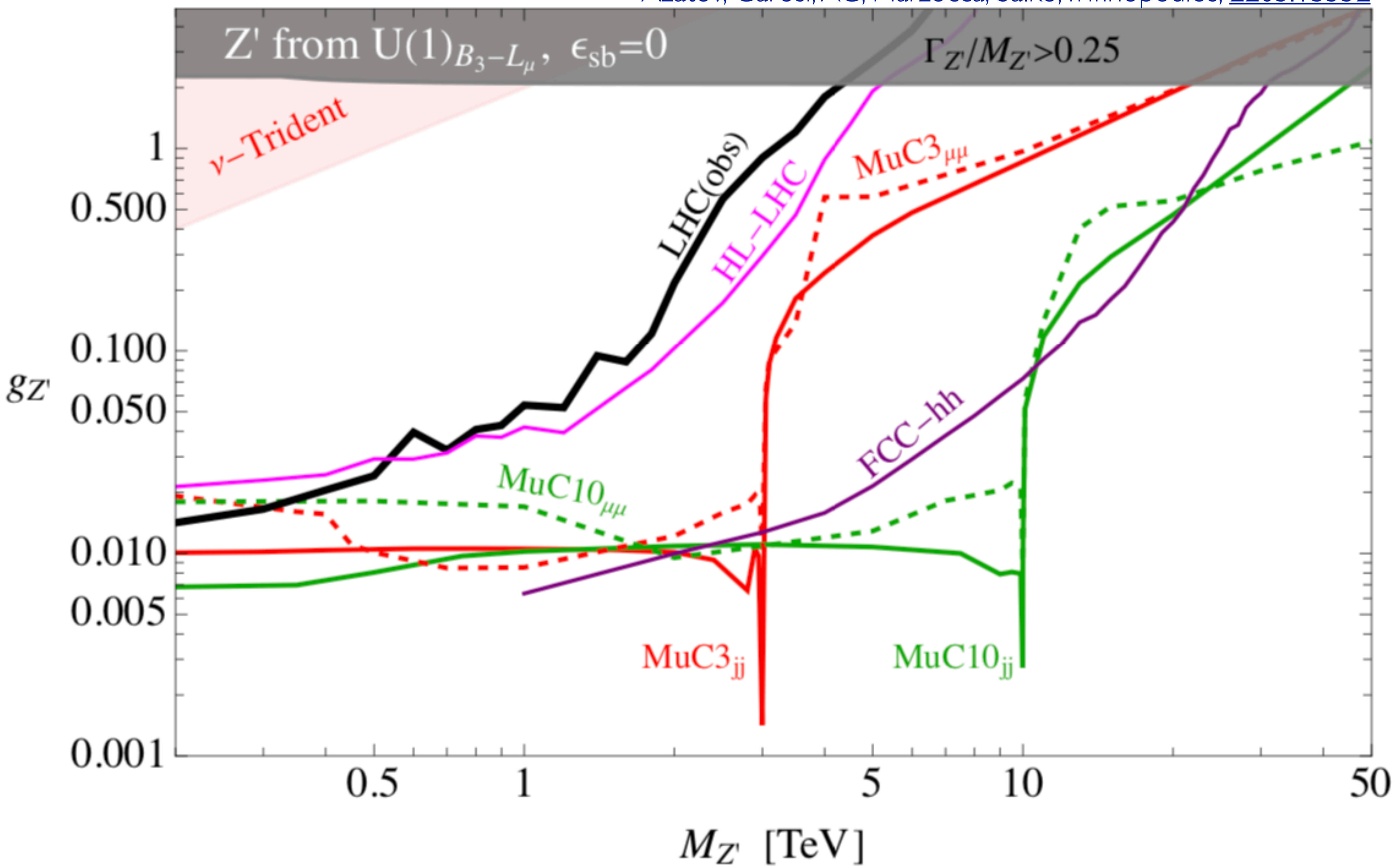
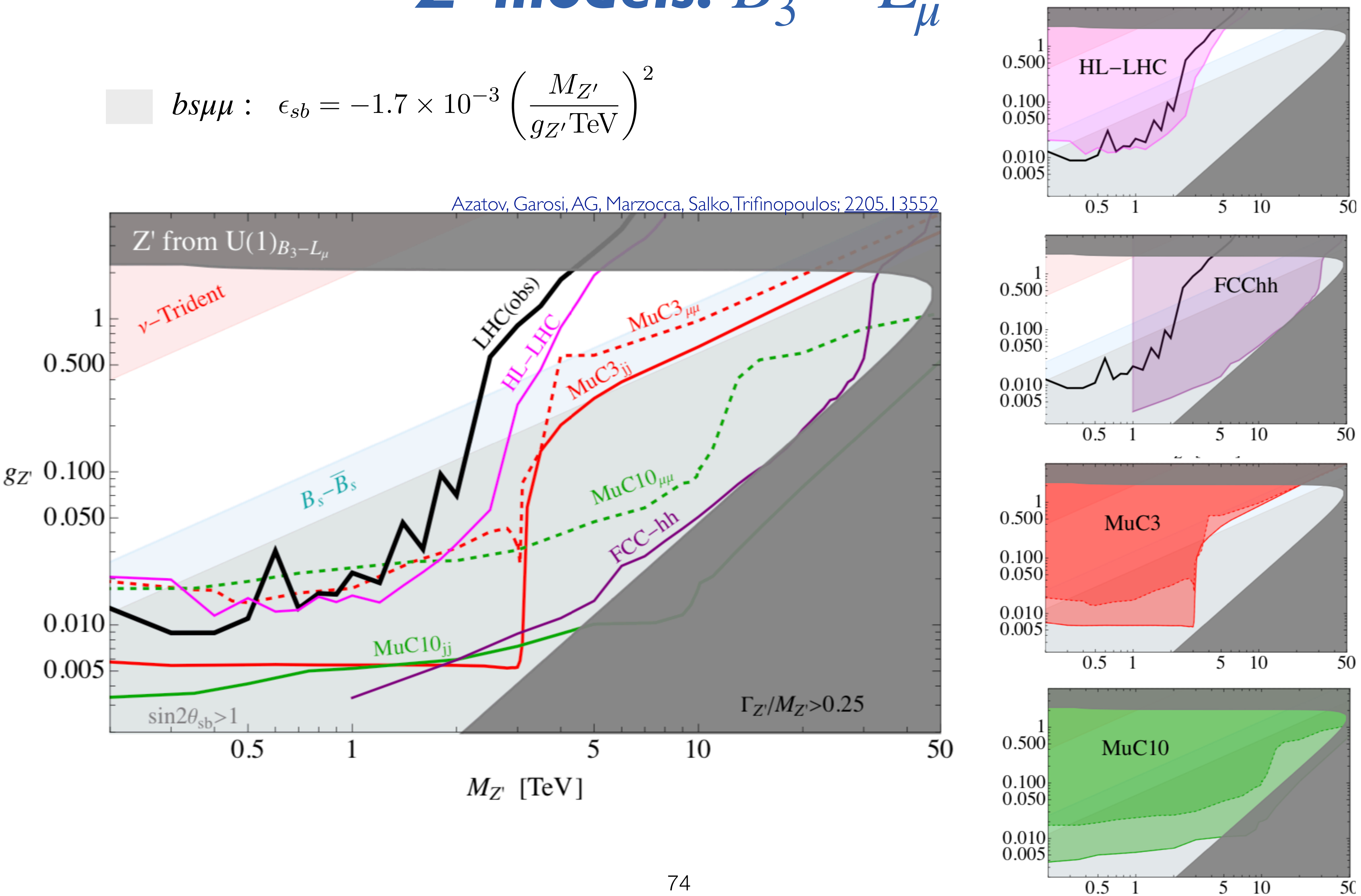


Figure 9. Discovery reach at 5σ for the $B_3 - L_\mu$ model with $\epsilon_{sb} = 0$, for different final states at each collider (as indicated by the labels). The region excluded at 95% CL by LHC [111] is above the black line while in the dark gray region the Z' has a large width, signaling a loss of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

Z' models: $B_3 - L_\mu$

$bs\mu\mu: \quad \epsilon_{sb} = -1.7 \times 10^{-3} \left(\frac{M_{Z'}}{g_{Z'}\,\mathrm{TeV}}\right)^2$

Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; 2205.13552



Z' models: $L_\mu - L_\tau$

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

Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; 2205.13552

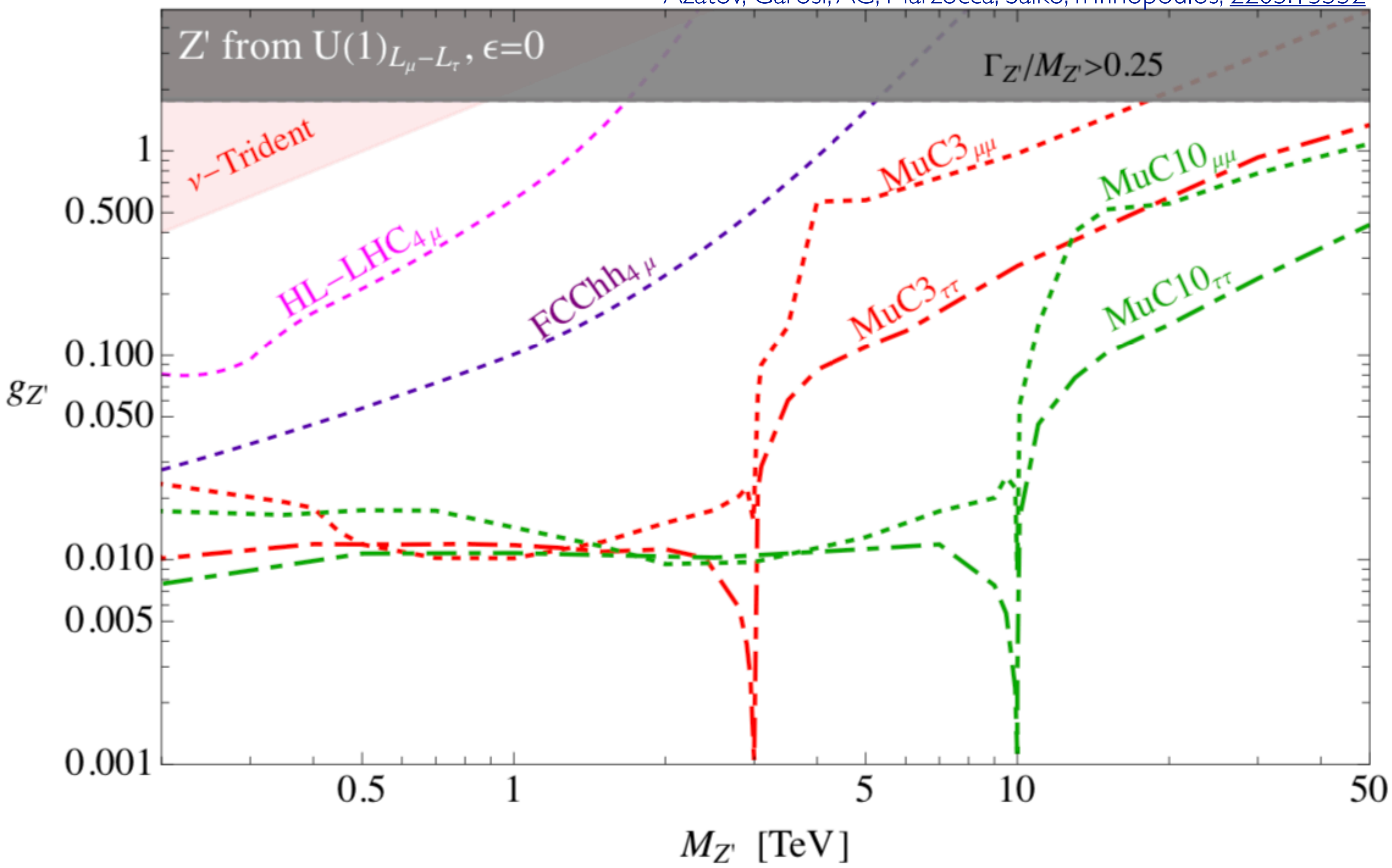


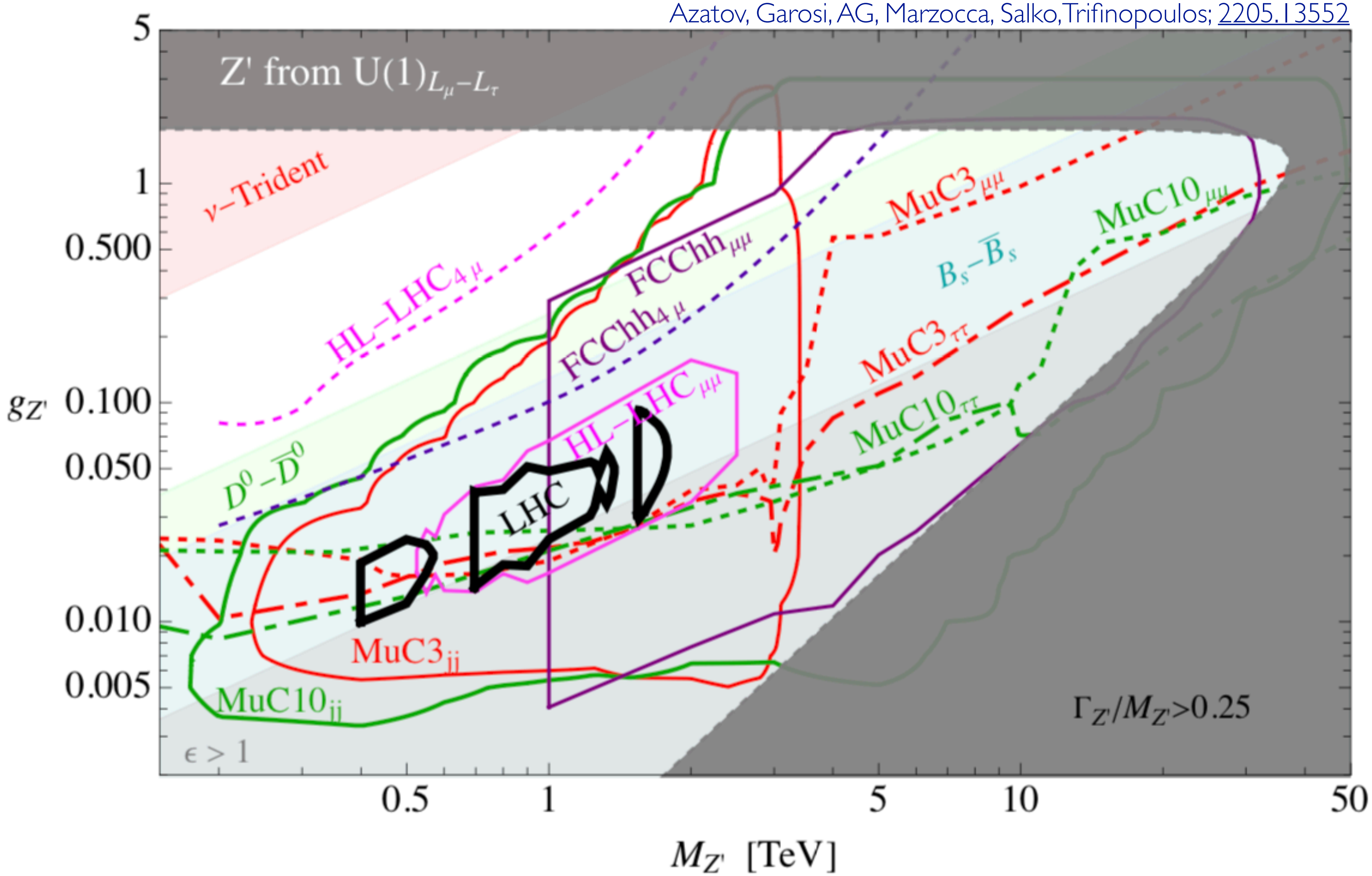
Figure 11. Discovery reach at 5σ for the $L_\mu - L_\tau$ model with $\epsilon_s = \epsilon_b = 0$ in Eq. (5.6). In the dark gray region the Z' has a large width, signaling a loss of perturbativity.

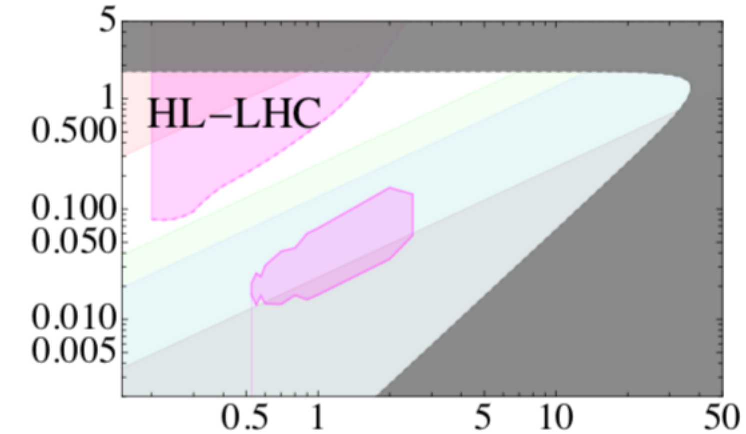
Z' models: $L_\mu - L_\tau$

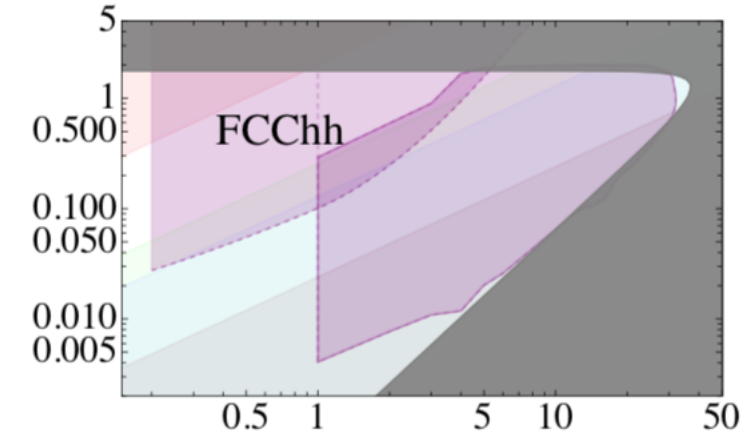
$$bs\mu\mu: \quad \epsilon_b \epsilon_s^* = -5.7 \times 10^{-4} \left(\frac{M_{Z'}}{g_{Z'}\,\text{TeV}} \right)^2$$

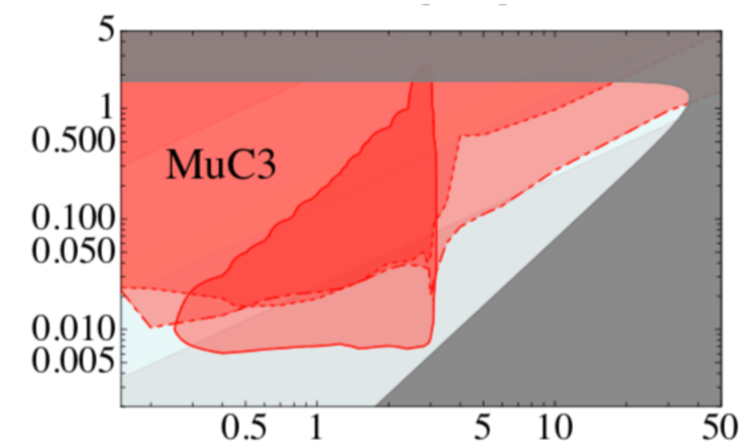
e.g. $\epsilon_b = -\epsilon_s$

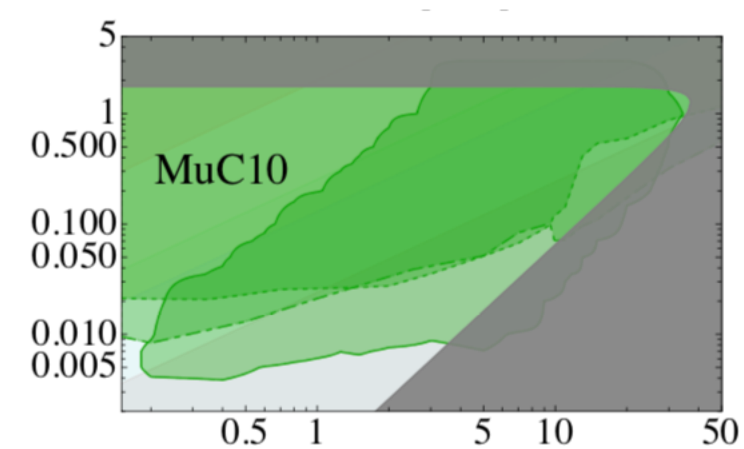
Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; 2205.13552











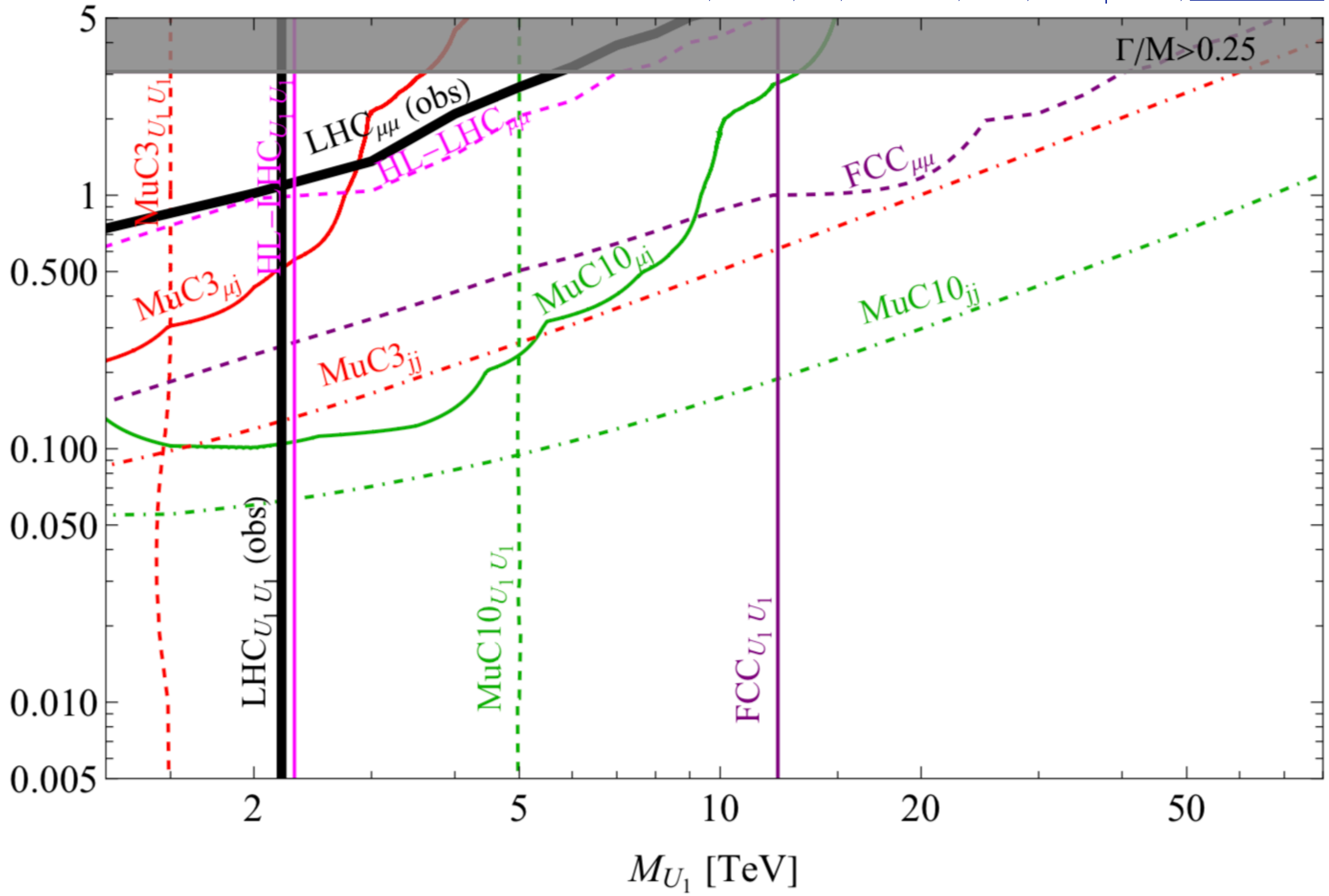
Vector Leptoquark

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

$$\mathcal{L}^{\rm int}_{U_1} = \lambda_{i\mu} \overline{Q_L}^i \gamma_\alpha L_L^2 U_1^\alpha + \text{h.c.} = \lambda_{i\mu} U_1^\alpha \left(V_{ji} \bar{u}_L^j \gamma_\alpha \nu_\mu + \bar{d}_L^i \gamma_\alpha \mu_L \right) + \text{h.c.}$$

Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; 2205.13552

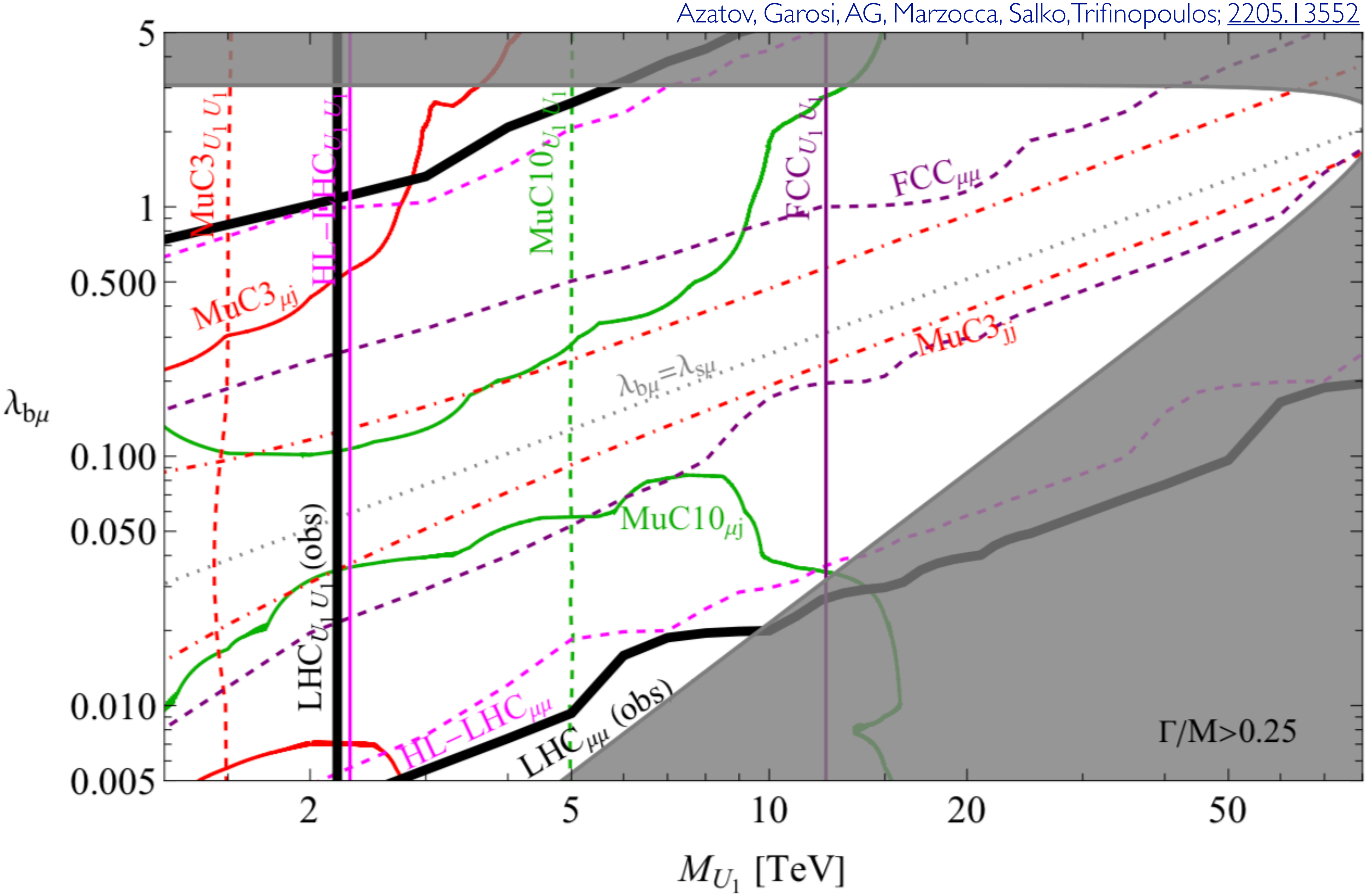
The only coupling → $\lambda_{b\mu}$

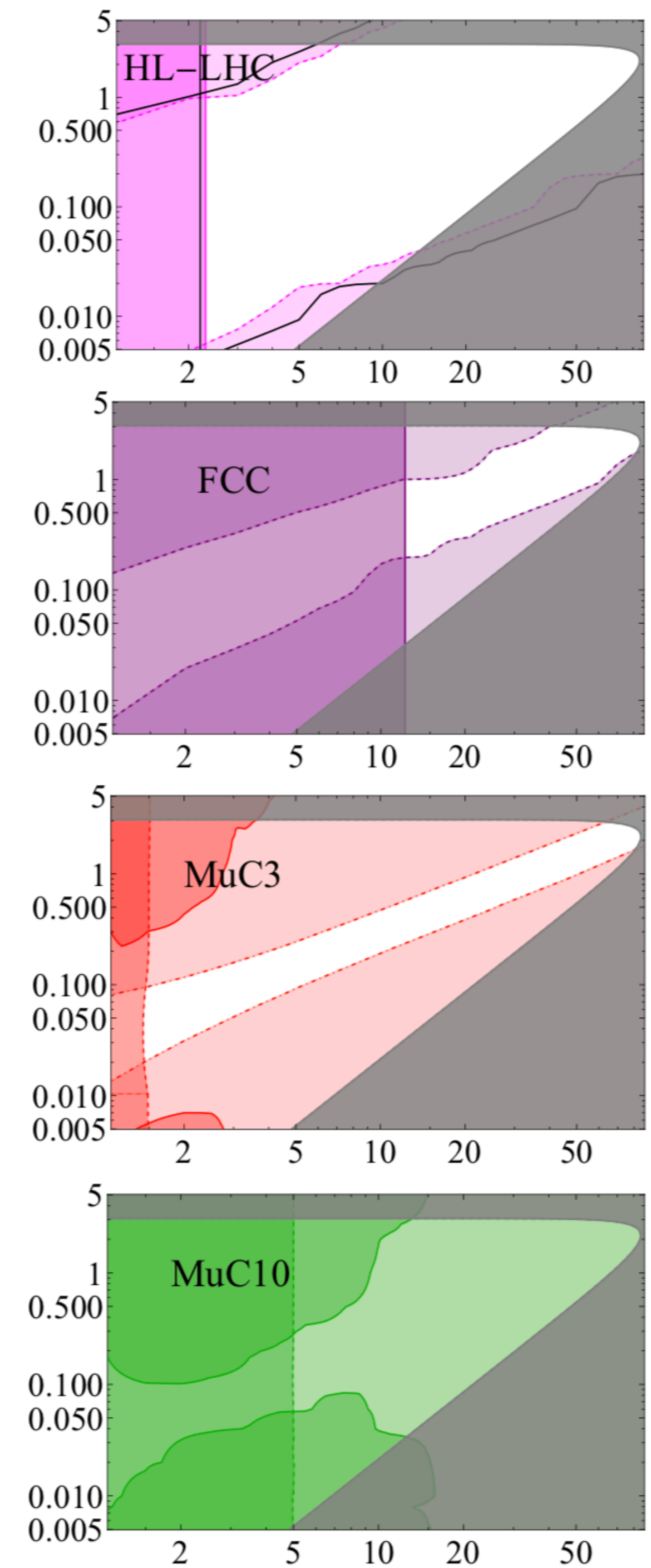


Vector Leptoquark

$$bs\mu\mu: \quad \lambda_{b\mu}\lambda_{s\mu} = -8.4\times 10^{-4}\left(\frac{M_{U_1}}{\text{TeV}}\right)^2$$

Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; 2205.13552





Scalar Leptoquark

$$S_3 \sim (\bar{\mathbf{3}}, \mathbf{3}, 1/3) \qquad \mathcal{L}^{\rm int}_{S_3} = \lambda_{i\mu}\, \overline{Q^{i\,c}_L}\, \epsilon\, \sigma^I L^2_L S^I_3 + \text{h.c.}\ ,$$

$$= -\lambda_{i\mu} S_3^{(1/3)} (V^*_{ji} \overline{u^{j\,c}_L} \mu_L + \overline{d^{i\,c}_L} \nu_\mu) + \sqrt{2}\lambda_{i\mu} \left(V^*_{ji} S_3^{(-2/3)} \overline{u^{j\,c}_L} \nu_\mu - S_3^{(4/3)} \overline{d^{i\,c}_L} \mu_L \right) + \text{h.c.}$$

Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; 2205.13552

The only coupling → $\lambda_{b\mu}$

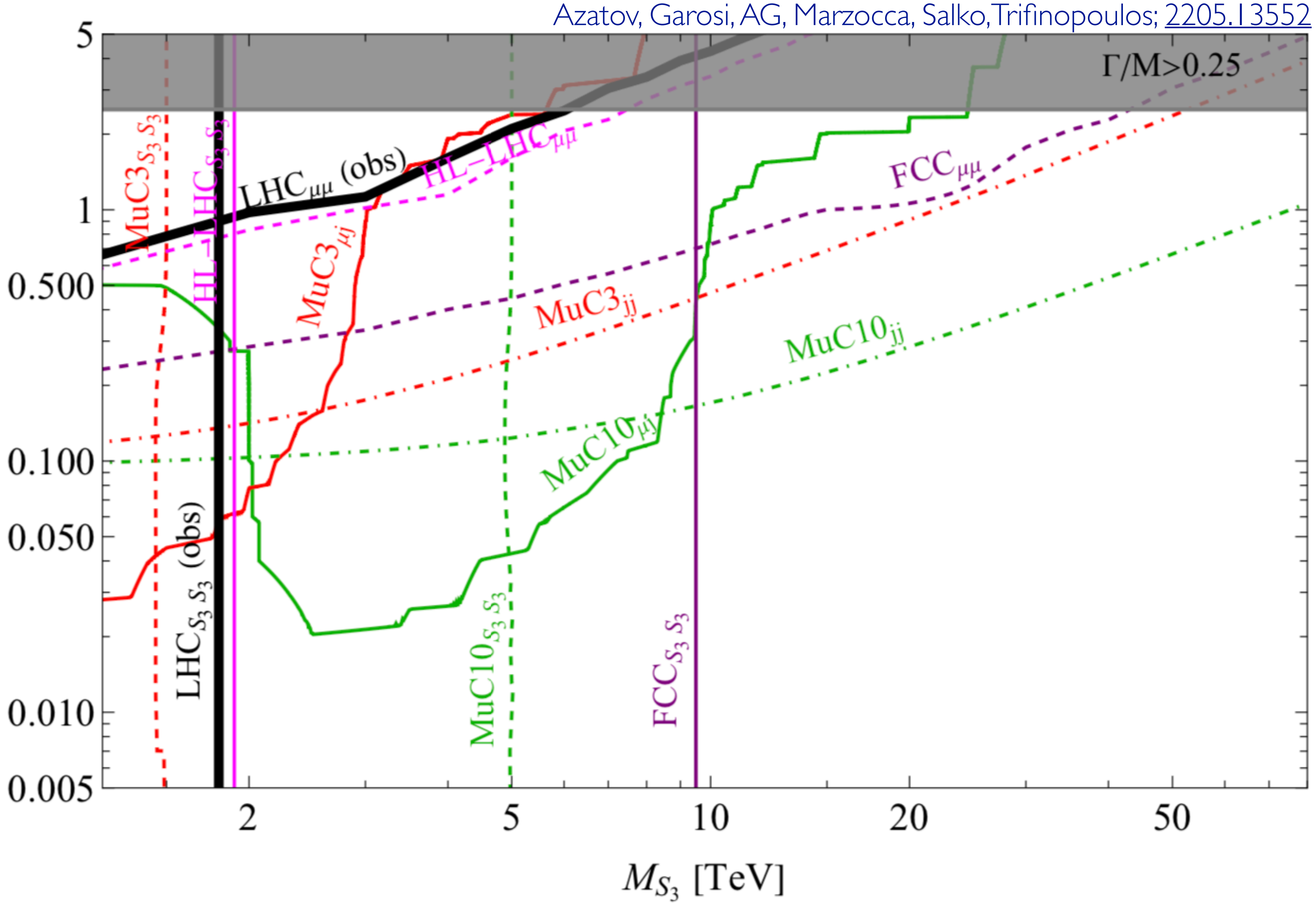
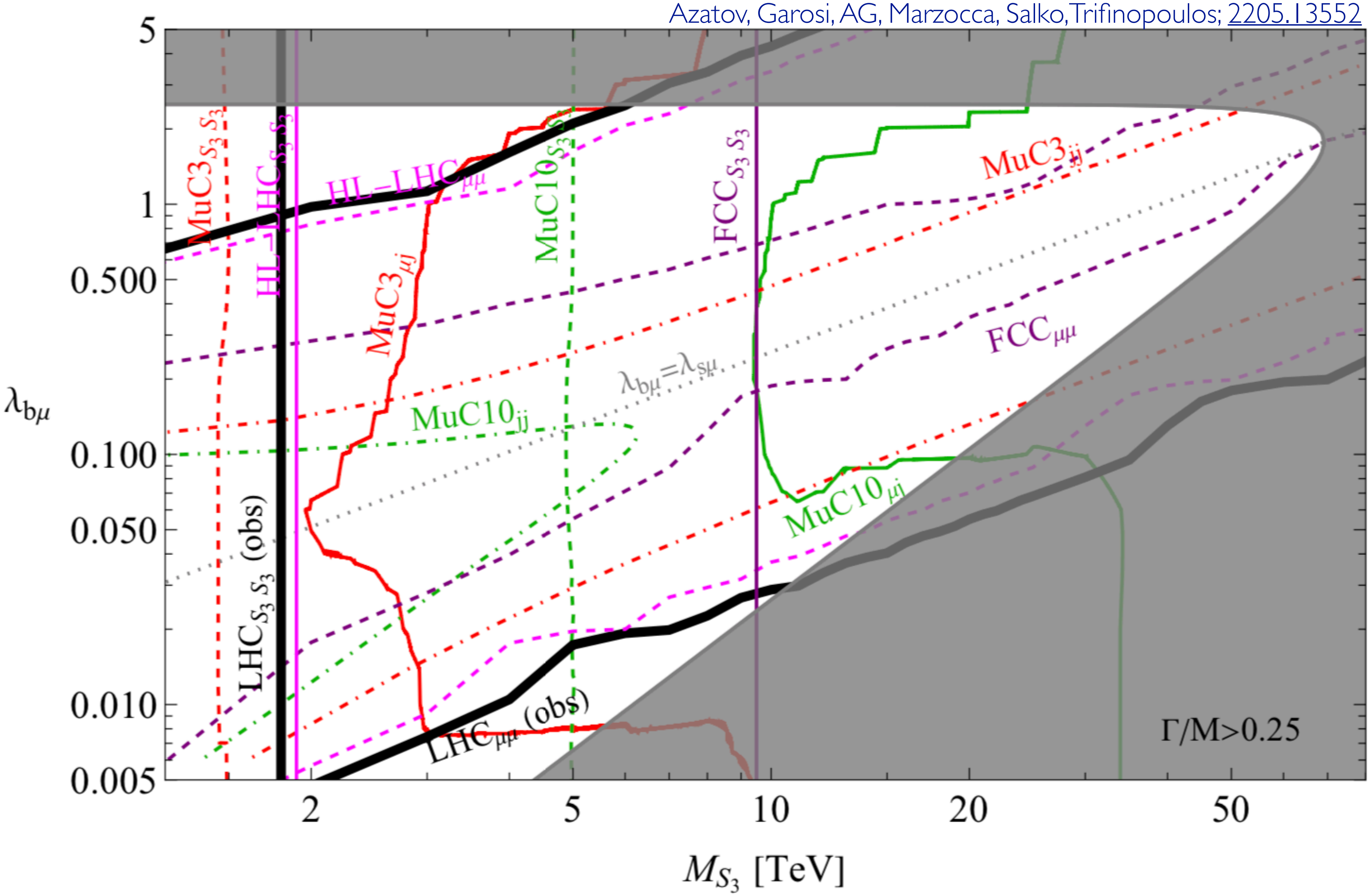


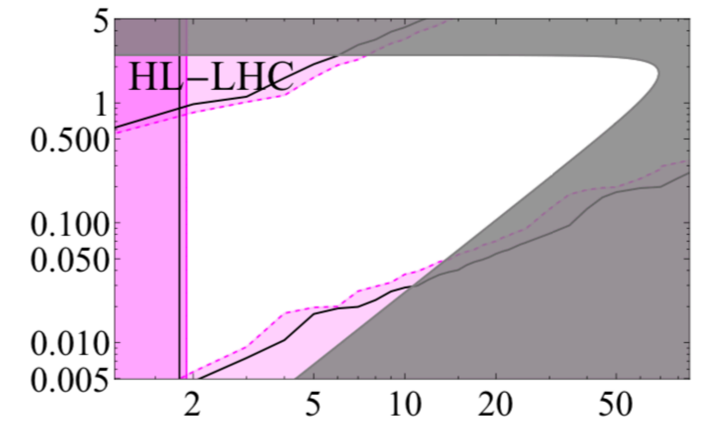
Figure 13. The 5σ discovery prospects at future colliders for the S_3 leptoquark assuming the $U(2)^3$ quark flavour symmetry and the exclusive leptoquark coupling to muons (see Section 6.1).

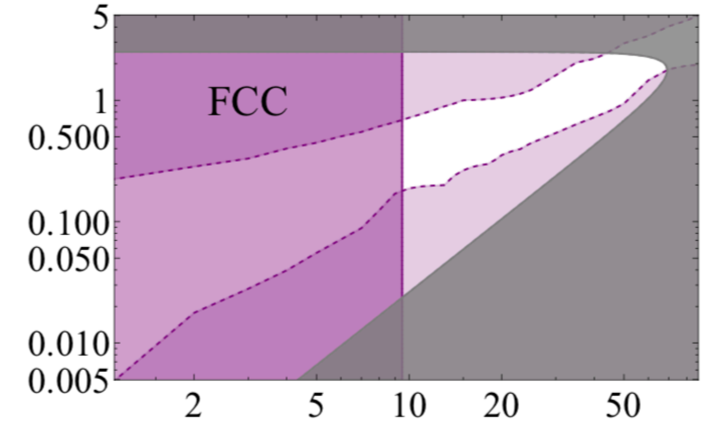
Scalar Leptoquark

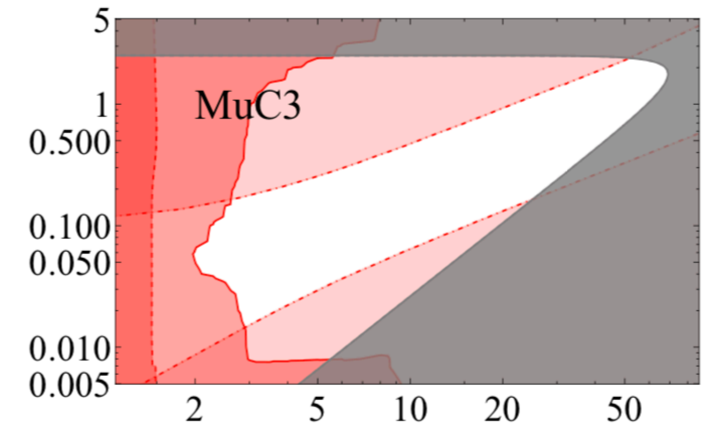
$$bs\mu\mu: \quad \lambda_{b\mu}\lambda_{s\mu} = -8.4\times 10^{-4}\left(\frac{M_{S_3}}{\text{TeV}}\right)^2$$

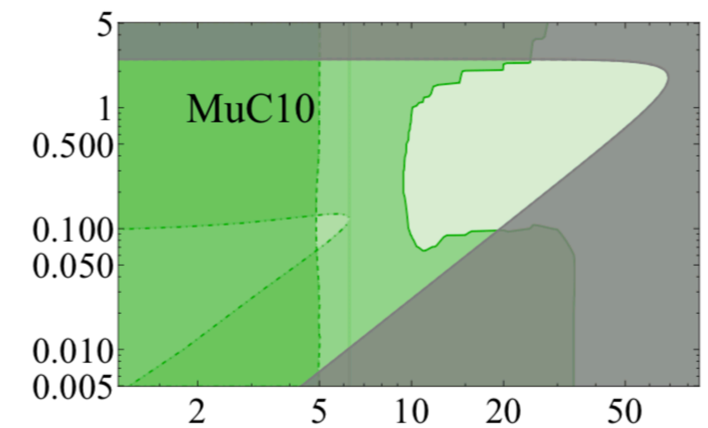
Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; 2205.13552





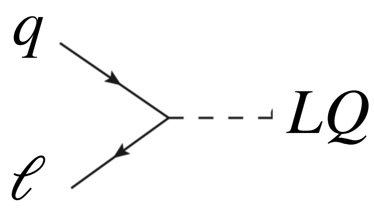






Resonant Leptoquark production

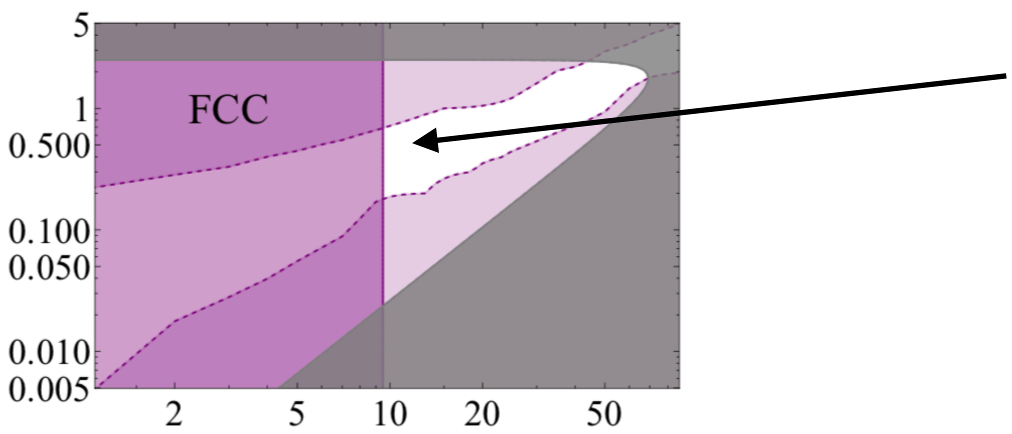
- From the lepton PDF inside the proton



Buonocore, Haisch, Nason, Tramontano, Zanderighi; 2005.06475
AG, Selimovic; 2012.02092
Haisch, Polesello; 2012.11474

- NLO QCD + QED matched to parton shower: POWHEG + HERWIG implementation

Buonocore, AG, Krack, Nason, Selimovic, Tramontano, Zanderighi; 2209.02599



Buonocore, AG, Krack, Nason, Selimovic, Tramontano, Zanderighi; 2209.02599

$$\mathcal{L} \supset \sqrt{2}\,\lambda\,\overline{D}^c S_{4/3}\,\mu + \text{h.c.}$$