Model building and phenomenology with leptoquarks

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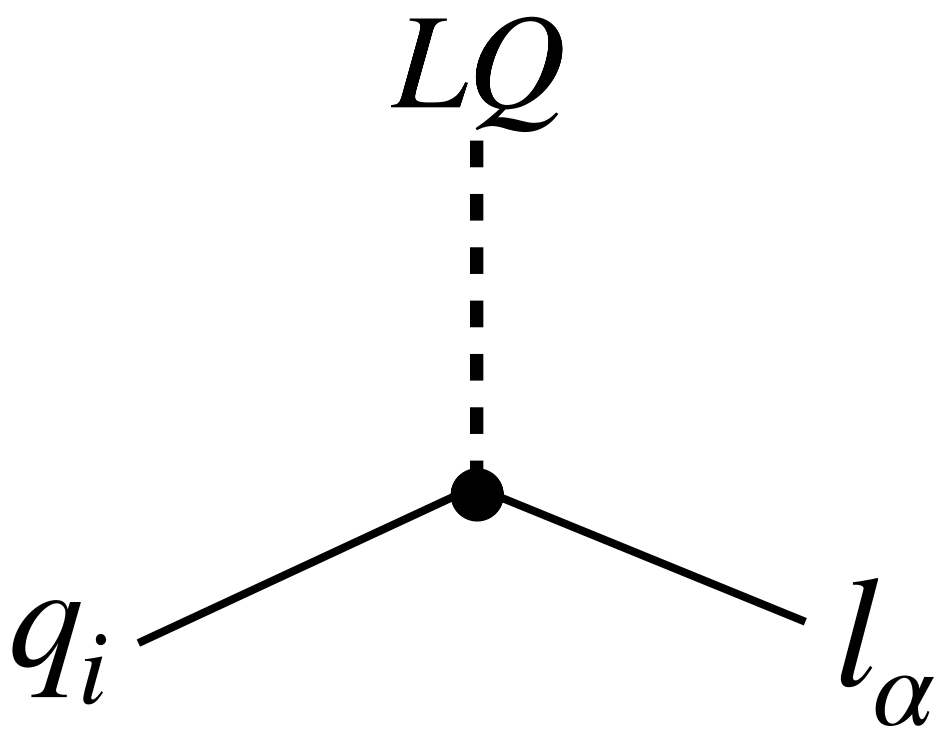
Leptoquarks at the TeV scale?

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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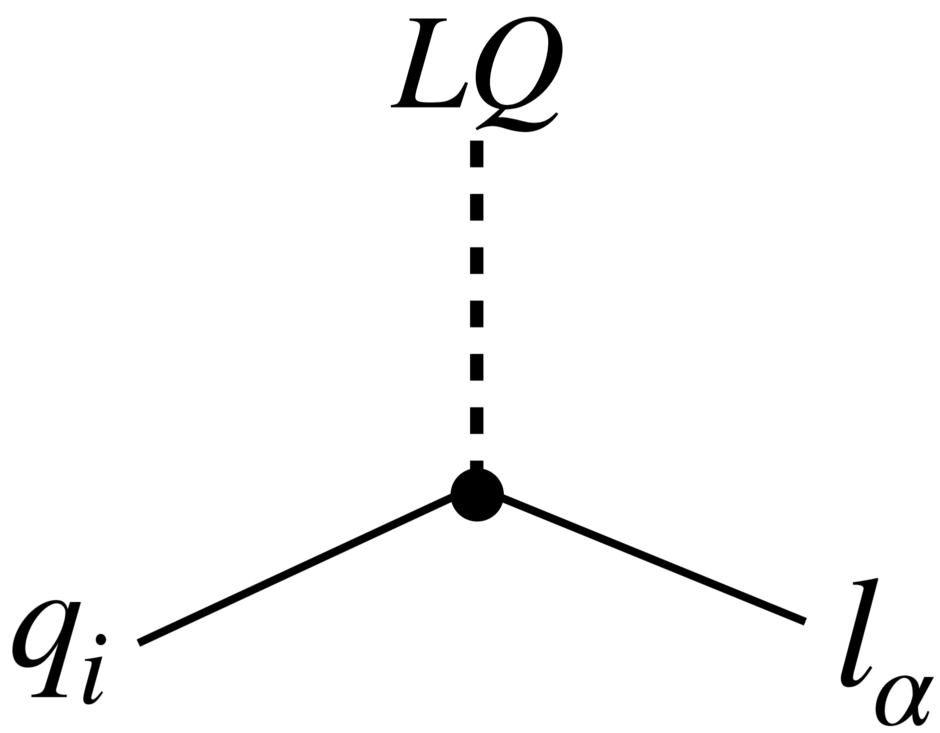

Wanted:

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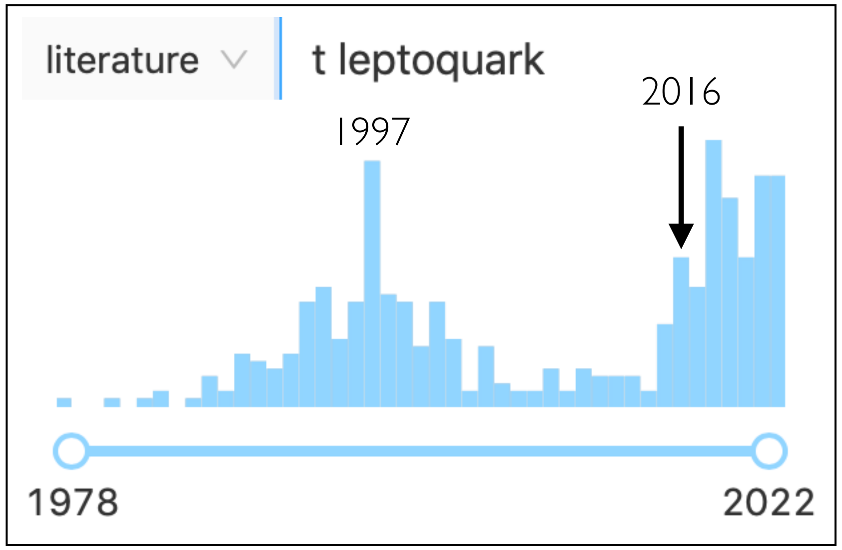
Why?

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

Theory

- A model building direction: Gauged flavour

PART II

Phenomenology

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

PART III

Phenomenology

- Future colliders: FCC-hh versus Muon Collider

Accidental Symmetries in the SM

$$q_i, \ell_i, U_i, D_i, E_i \quad \textit{flavour } i = 1,2,3$$

$\mathscr{L}_{\rm SM}$ 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 $\Delta B = \Delta L = 0 \,(\mathrm{mod}\, 3)$

TeV-scale BSM?

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

- Not a generic case!

Example: Leptoquarks

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

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

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

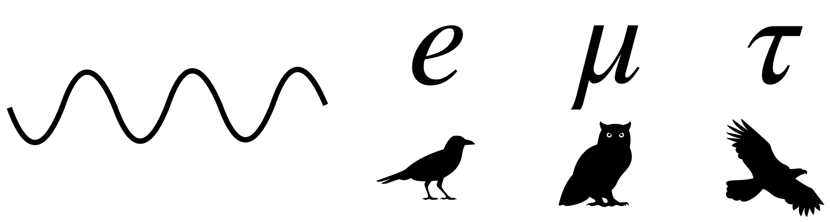
~~$U(1)_B$~~ Proton decay $[z \cdot y]$ $\quad \tau_p \gtrsim 10^{34}$ years

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

- Generic TeV-scale LQs are dead!

Gauged $U(1)_X$

+ leptoquarks



<u>The storyline</u>

- 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
$(\bar{\mathbf{3}},\mathbf{3}/\mathbf{1})_{1/3}$ — Leptoquarks	$S_3,\ S_1$	$2m+2n$
Scalars (SM singlets)	$\phi_{e\tau}$	$6m-2n$
	ϕ_μ	$6m+n$

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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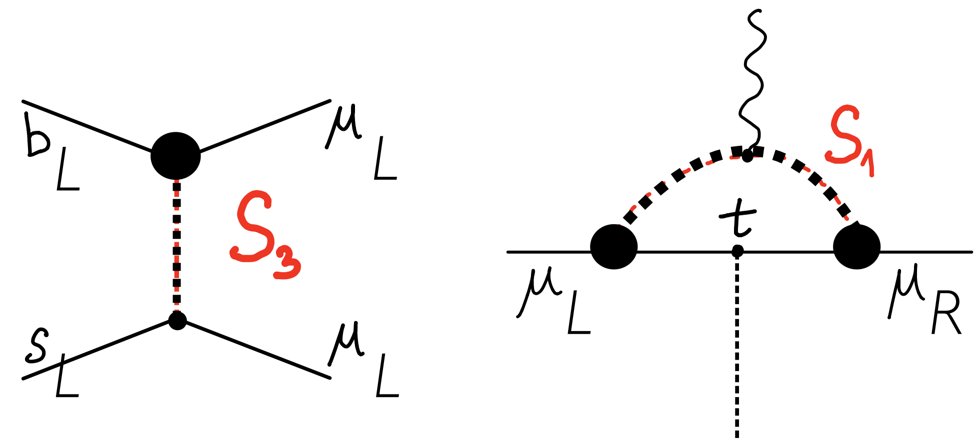

- $b \to s\mu\mu$ & $(g-2)_\mu$

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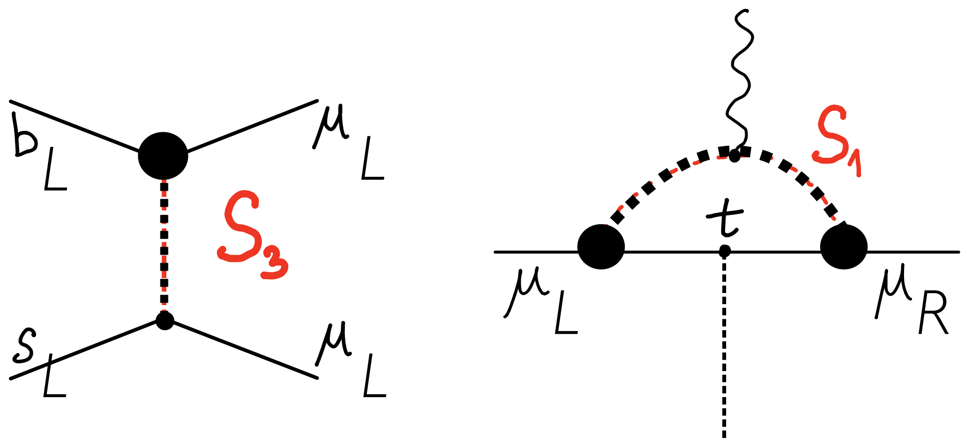
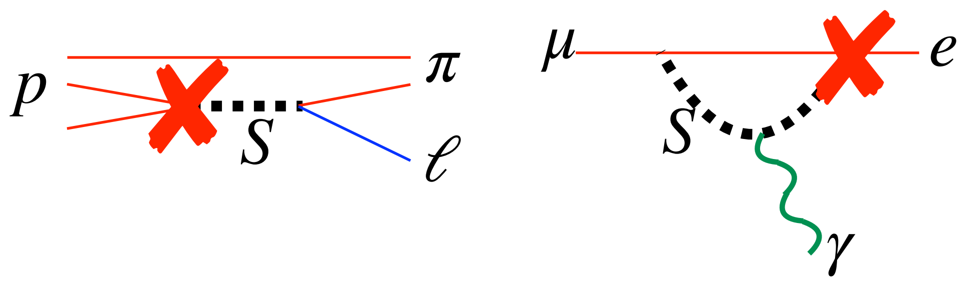


- $b \to s\mu\mu$ & $(g-2)_\mu$

- No proton decay & cLFV

$\tau_p \gtrsim 10^{34}$ years

$BR(\mu \to e\gamma) \lesssim 10^{-13}$



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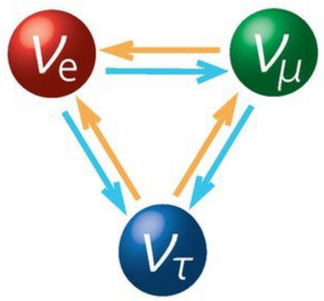
Neutrino Masses



- 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

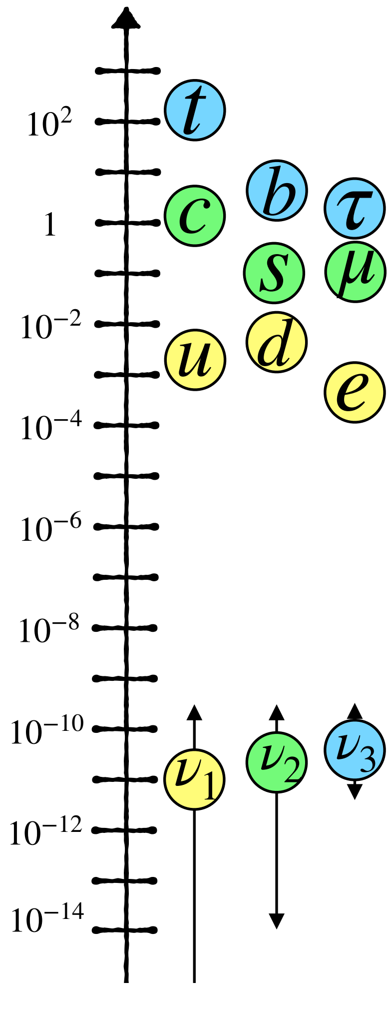
Type-I seesaw mechanism

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

- 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



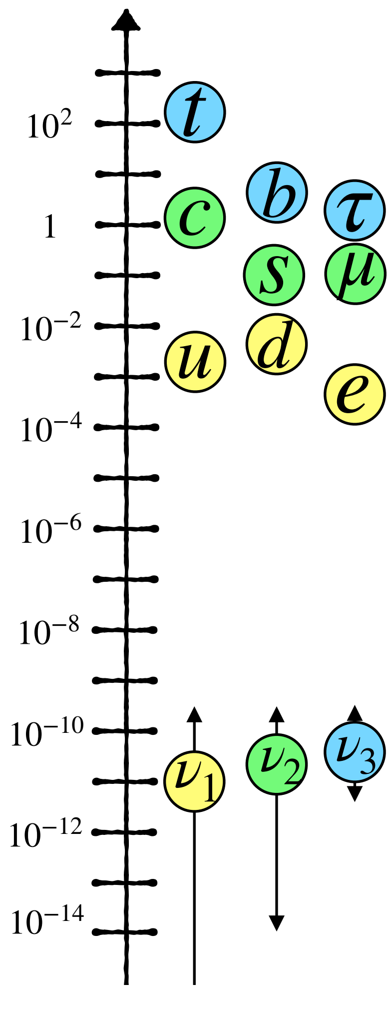
$U(1)_X$ breaking at the high scale?

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



$U(1)_X$ 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

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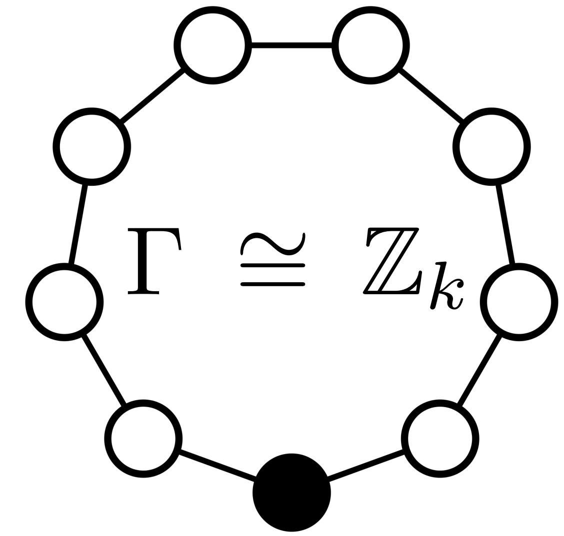
$$k = \mathrm{gcd}\big([\phi_{e\tau}]_X,\ [\phi_\mu]_X\big)$$

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



- 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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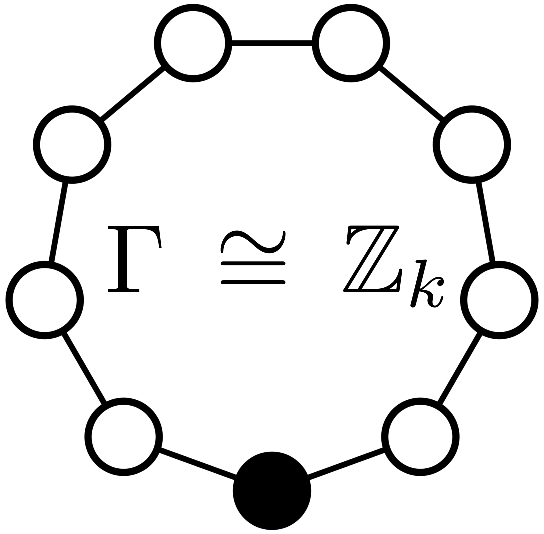

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- The diquark operators qqS^* are banned by Γ when:

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

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

Davighi, AG, Thomsen; 2202.05275

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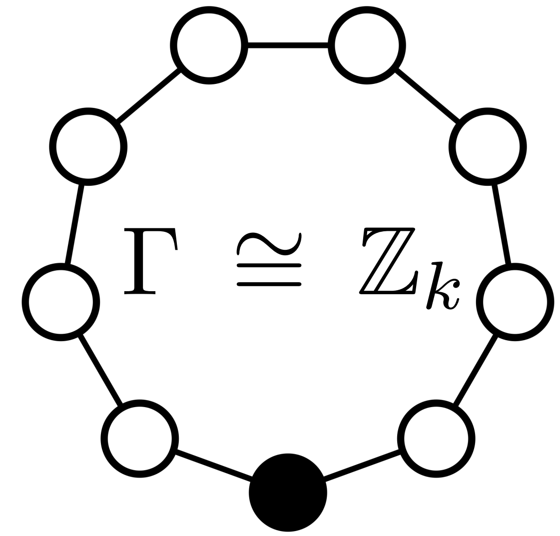

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- No proton decay!

- 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:

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

Exact proton stability to all orders in the SMEFT!

✗ $qqq\ell$ and so on

Davighi, AG, Thomsen; 2202.05275

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✗ $qqq\ell$ and so on

- 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:

$$\frac{1}{\Lambda^2}\phi_{e\tau}\phi_\mu^*\, qS_{1/3}\ell_{1,3} \qquad\qquad \frac{1}{\Lambda^2}\phi_{e\tau}\phi_\mu^*\, uS_1 e_{1,3}$$

- 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

All 3 families of fermions fit into:

$\Psi_L \sim (\mathbf{12}, \mathbf{2}, \mathbf{1}) \qquad \Psi_R \sim (\mathbf{12}, \mathbf{1}, \mathbf{2})$

UV

$SU(12) \times SU(2)_L \times SU(2)_R$

$SU(9) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_\ell$

$SU(3) \times SU(2)_L \times U(1)_Y \times U(1)_X$

v_X — Right-handed neutrinos

TeV — Muoquarks

$SU(3) \times SU(2)_L \times U(1)_Y \times \mathbb{Z}_{9(18)}$

IR

Tentative gauge–flavour unification scenario.

Davighi, AG, Thomsen; 2202.05275

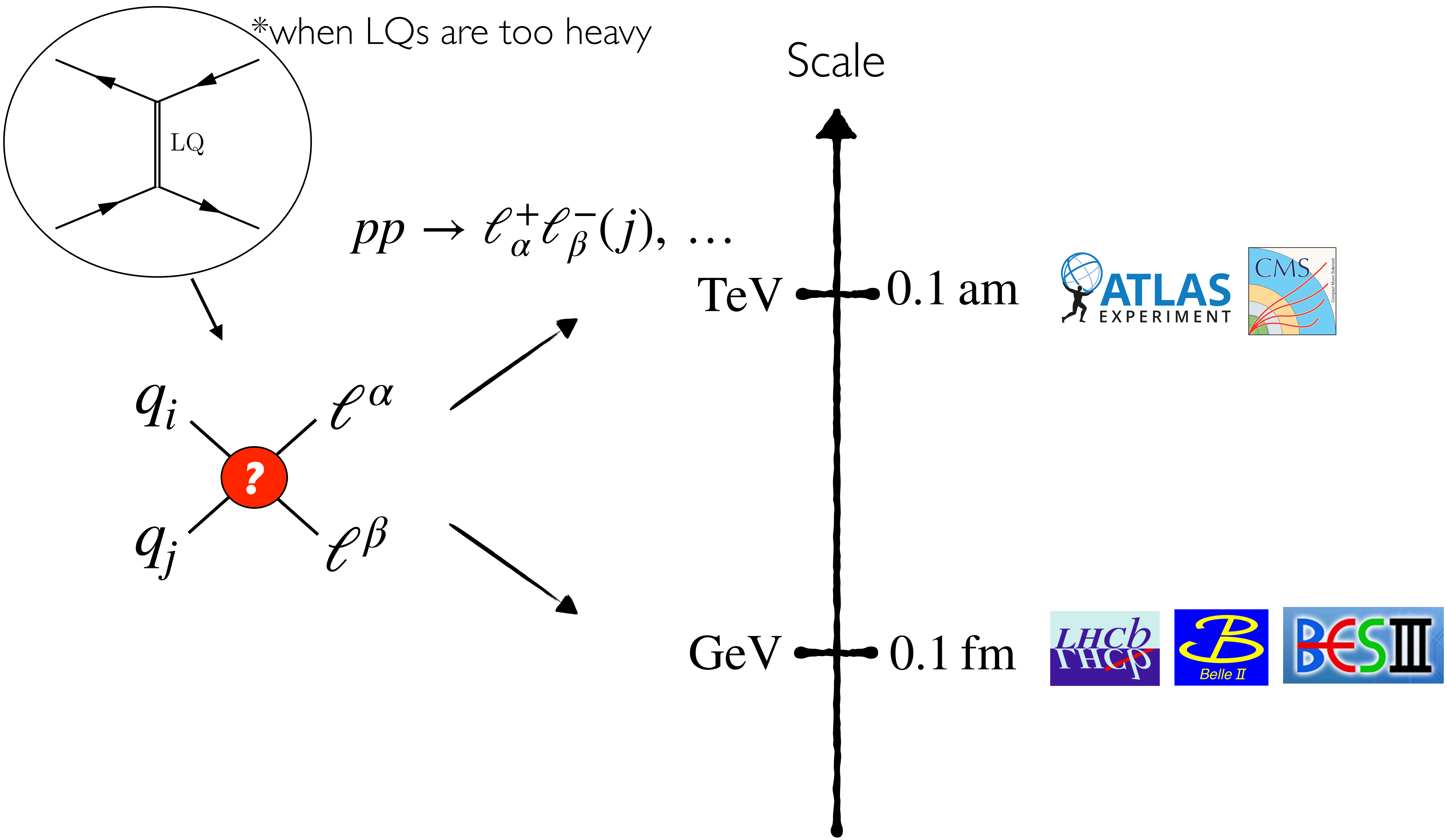
PART II

Comments on $\mathrm{R}_{\mathrm{K}^{(*)}}$

The storyline

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

Drell-Yan versus B-decays



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

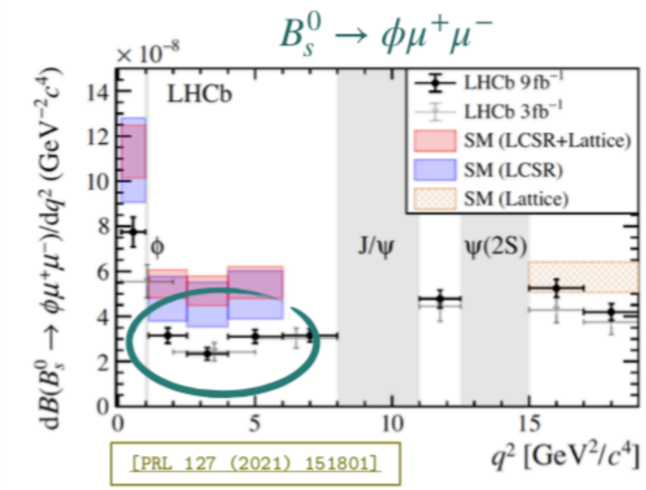
Systematic SMEFT study using `flavio`
AG, Salko, Smolkovic, Stangl; 2212.10497

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

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

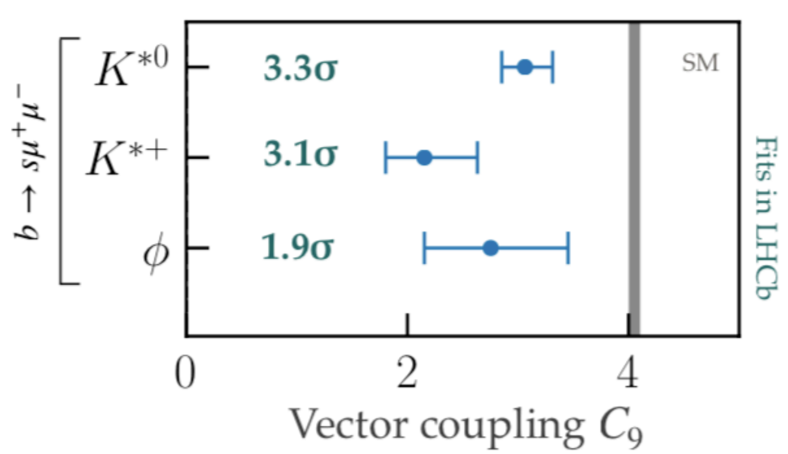
cf. Renato Quagliani, CERN seminar 20.12.2022.

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



+ ...

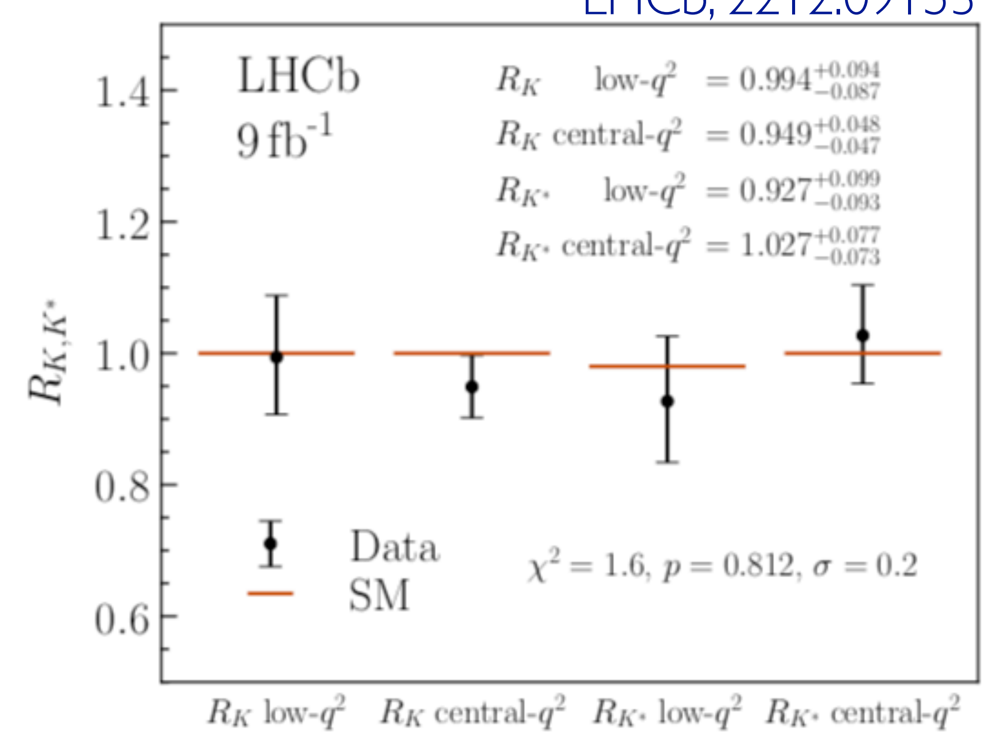
$b \to s\mu^+\mu^-$ angular analyses



- ✦ Intriguing coherent and consistent pattern
  - However, *charm-loops* can mimic shift in C_9

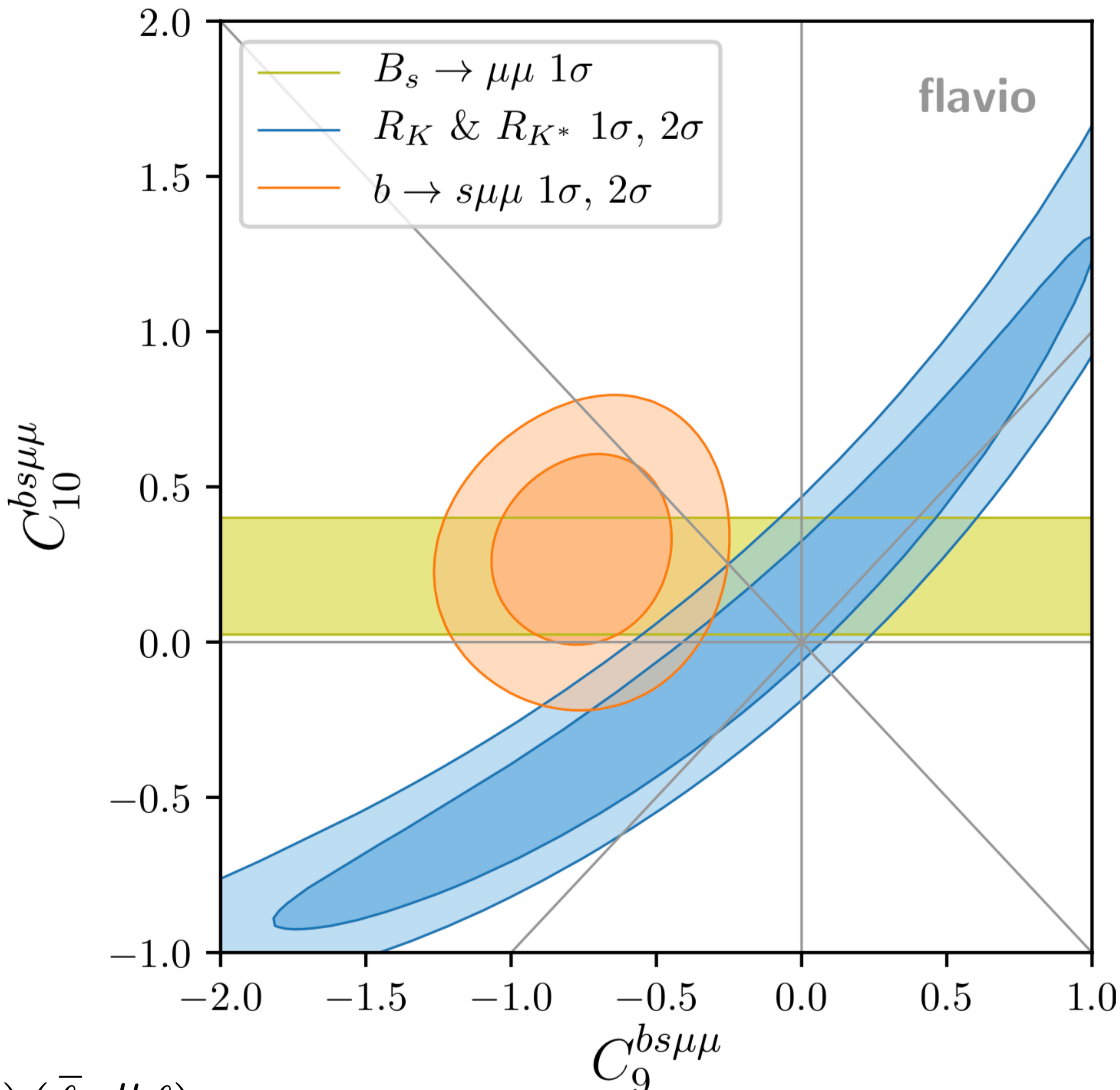
- But **L**epton **F**lavor **U**niversality ratios are SM-like

LHCb, 2212.09153



The EFT fit

AG, Salko, Smolkovic, Stangl; 2212.10497



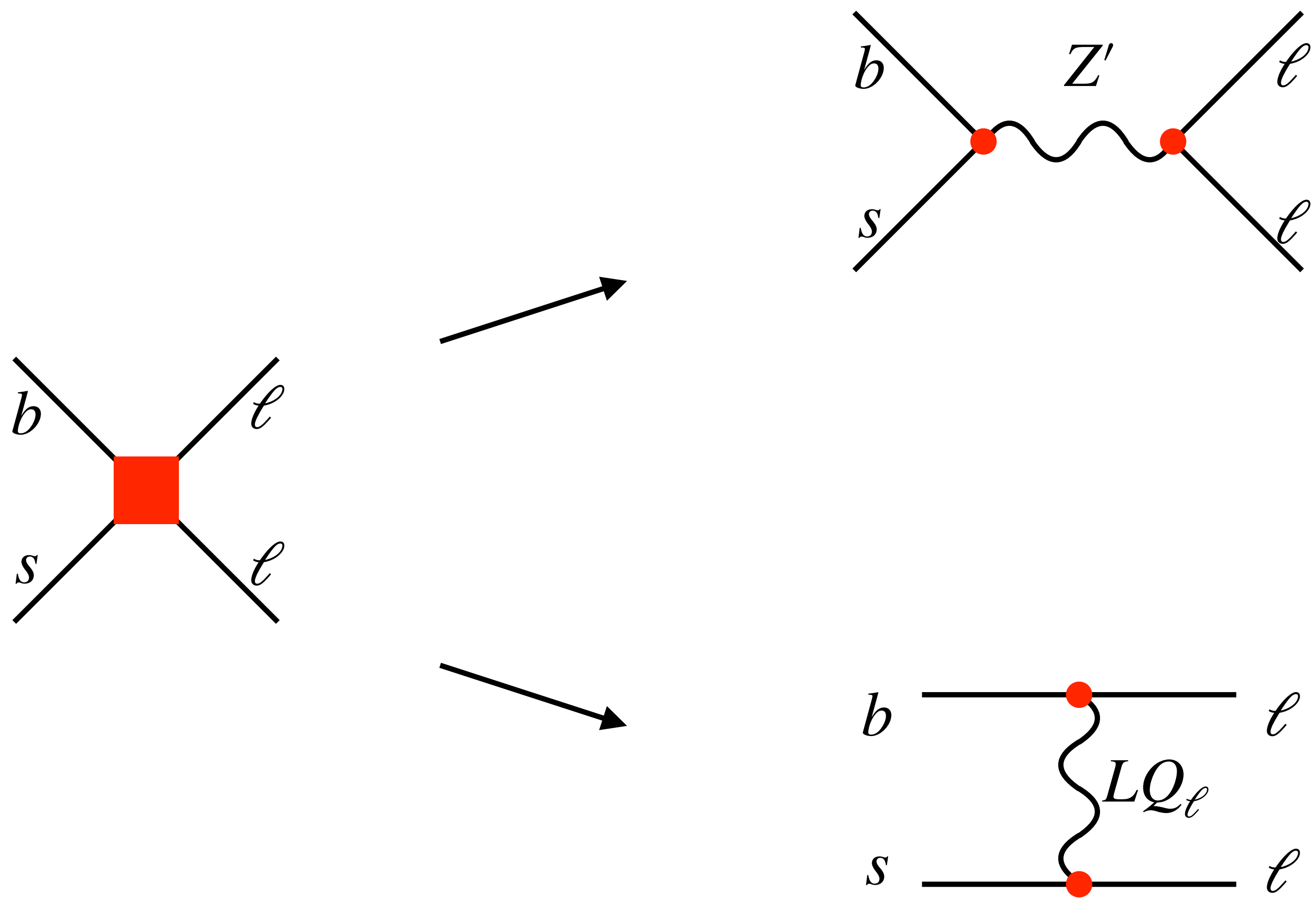
Tension!

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

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

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

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

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

  $\downarrow$

  $LQ_e \leftrightarrow LQ_\mu$

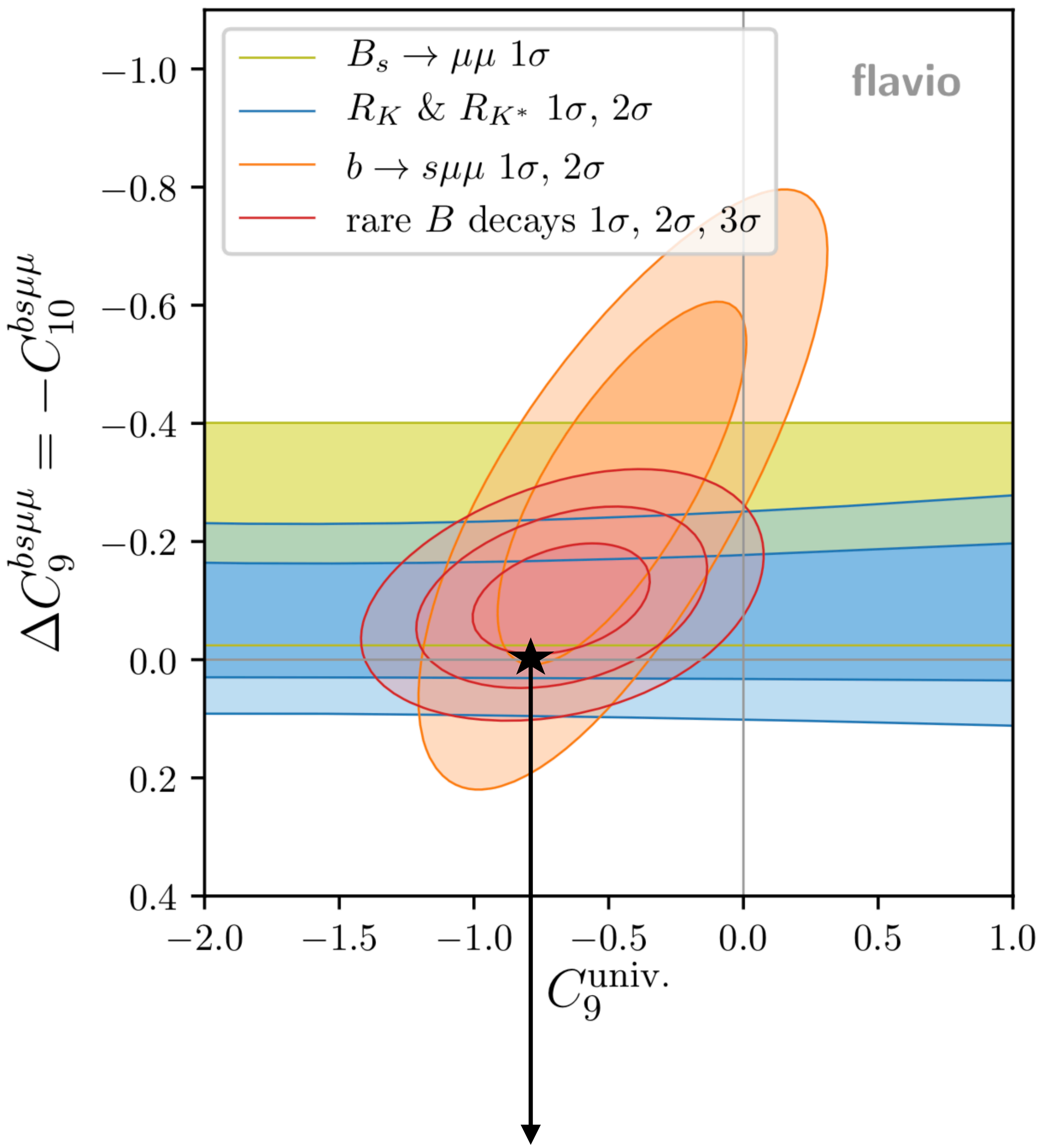
  $e \leftrightarrow \mu$

Mass/Coupling degeneracy

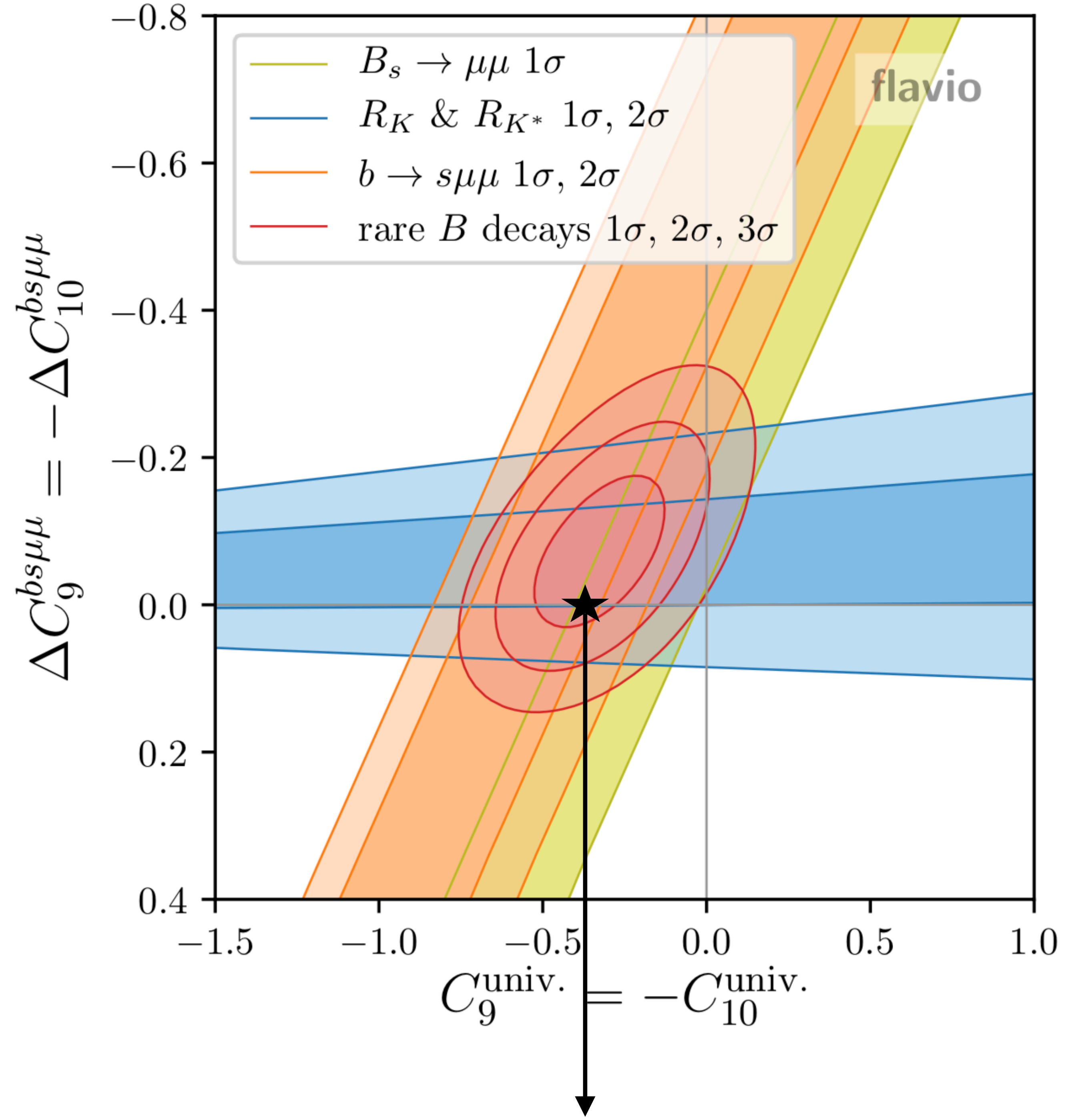
Gauged flavour (Part I) ?

The EFT fit

AG, Salko, Smolkovic, Stangl: 2212.10497



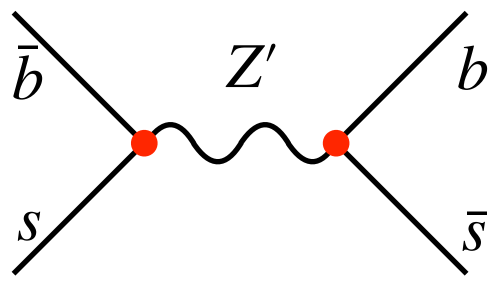
- LFU Z'



- LFU LQ

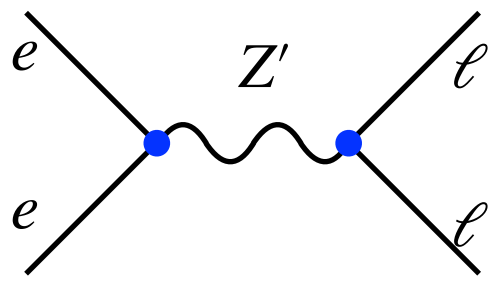
LFU models: Z'

- The bounds from



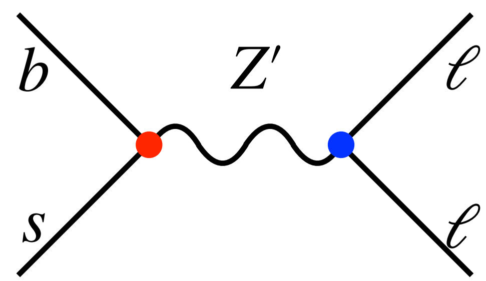
Meson mixing

+



LEP II

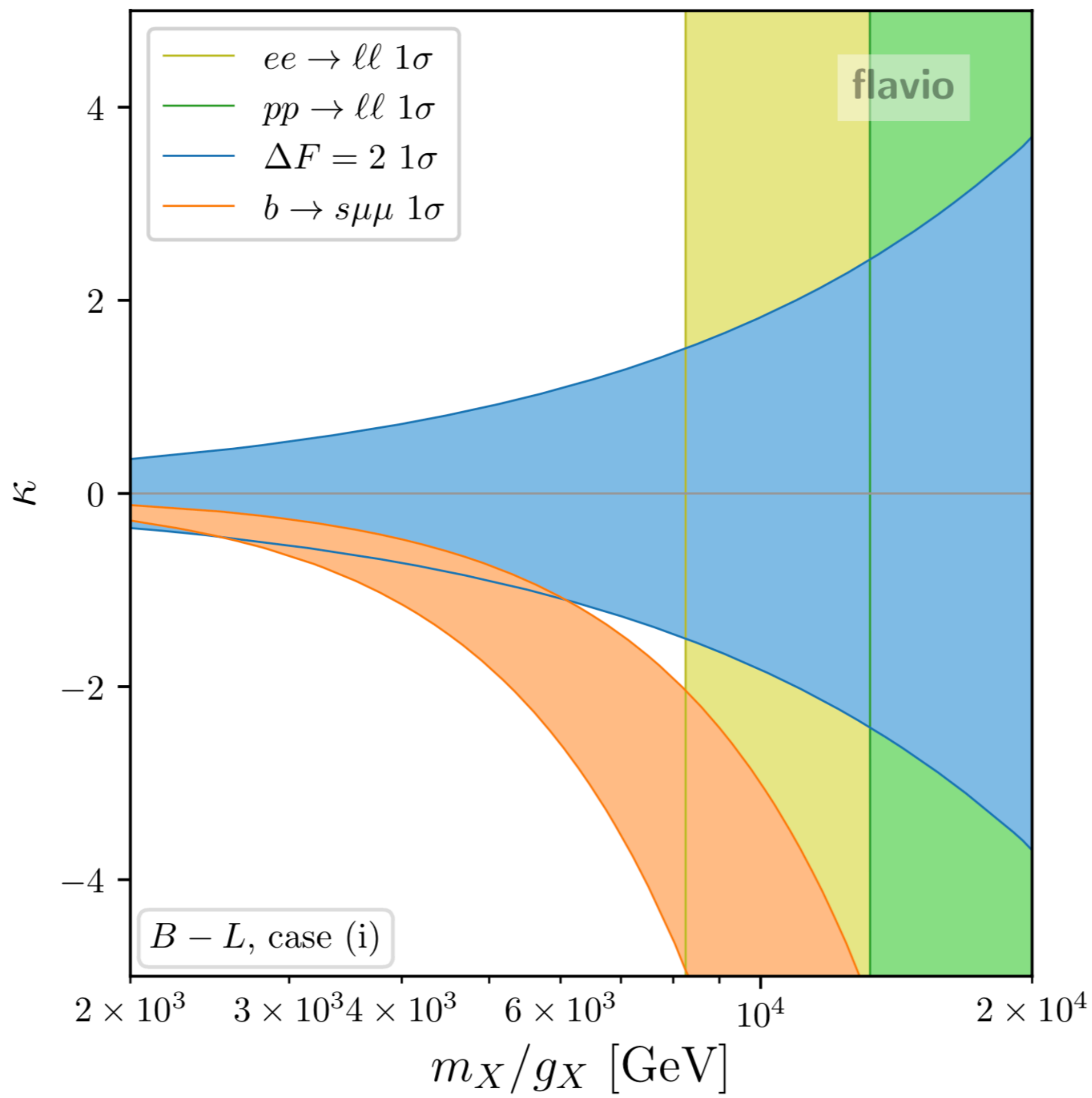
are constraining



!

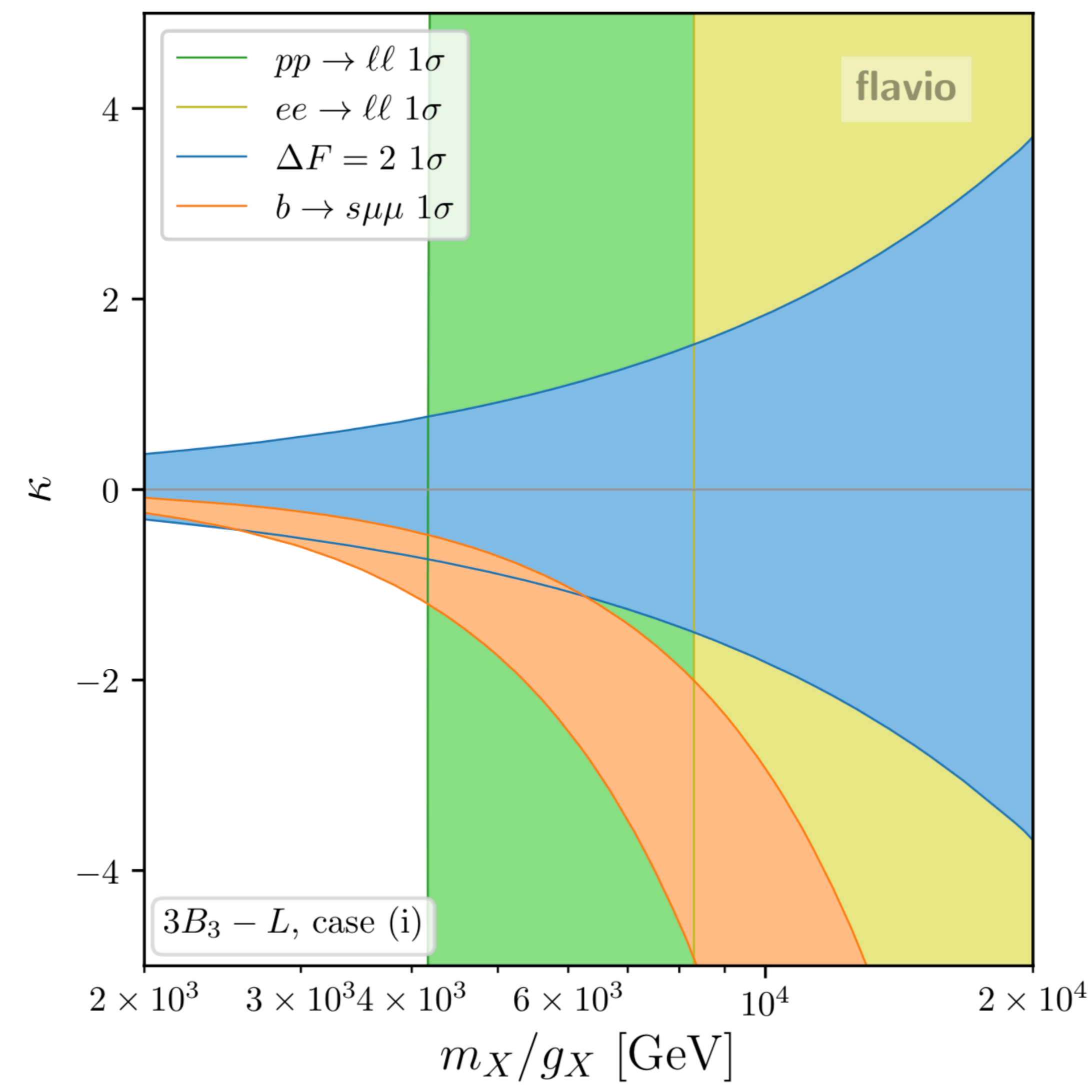
LFU models: Z'

$B-L$



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

$3B_3 - L$



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

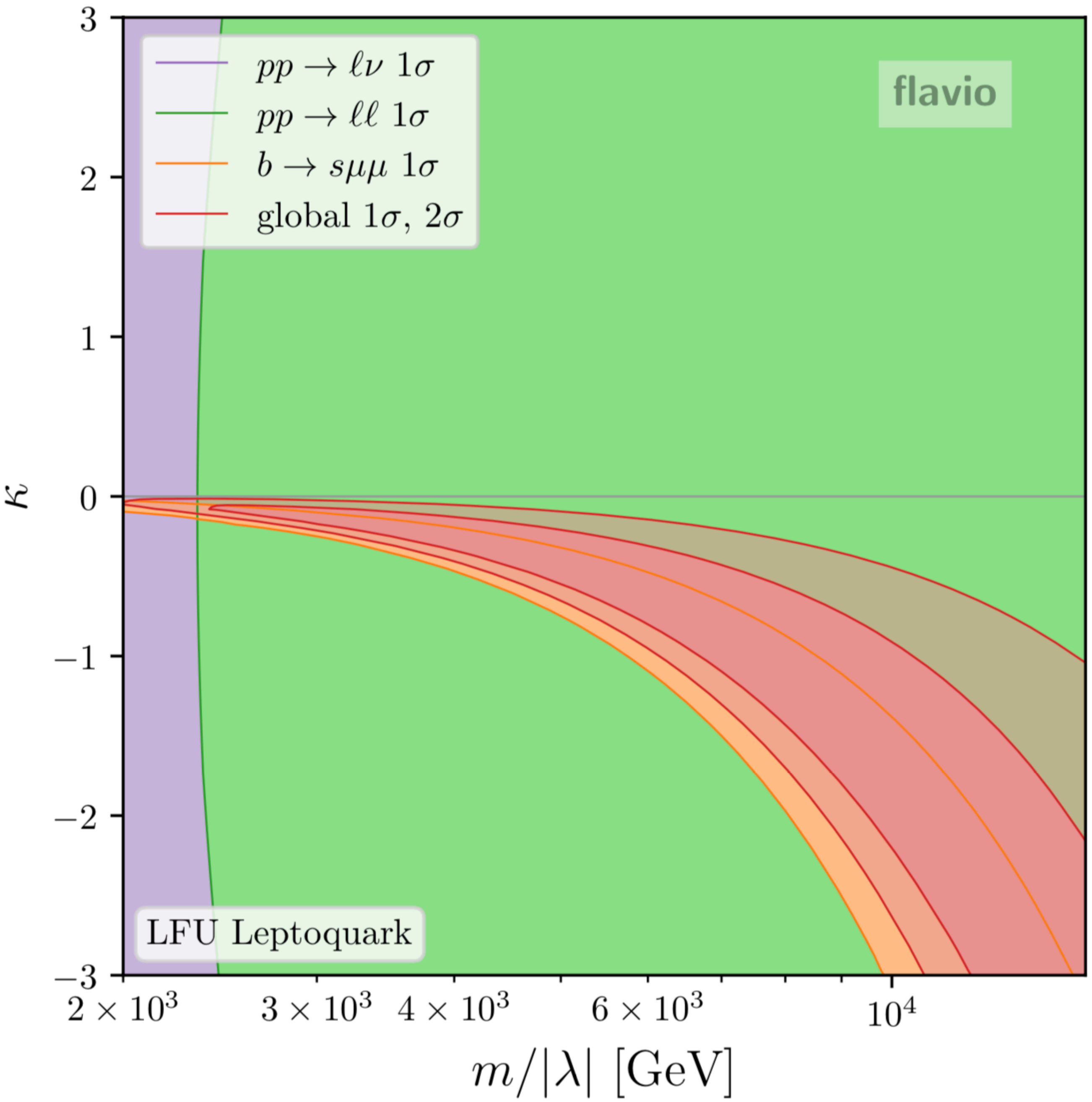
$$\epsilon_{ij} = -\kappa\,|V_{ts}|(\delta_{i2}\delta_{j3} + \delta_{i3}\delta_{j2})$$

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

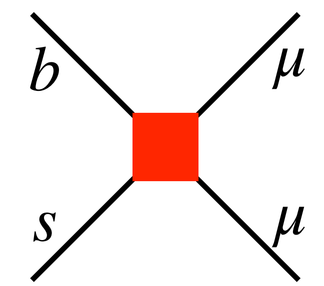
Collider	C.o.m. Energy	Luminosity	Label
LHC Run-2	13 TeV	140 fb^{-1}	LHC
HL-LHC	14 TeV	6 ab^{-1}	HL-LHC
FCC-hh	100 TeV	30 ab^{-1}	FCC-hh
Muon Collider	3 TeV	1 ab^{-1}	MuC3
Muon Collider	10 TeV	10 ab^{-1}	MuC10
Muon Collider	14 TeV	20 ab^{-1}	MuC14

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

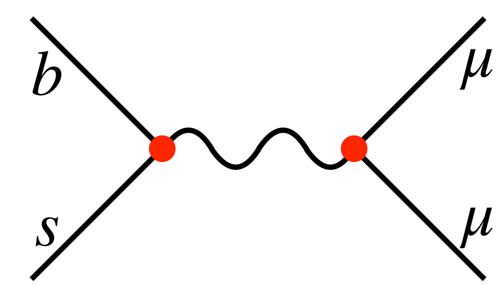
The scope

- New Physics benchmarks:

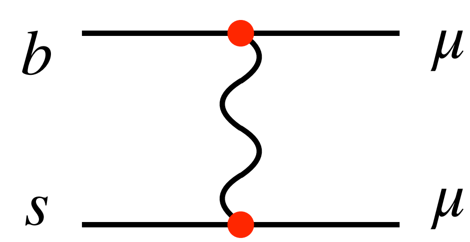
1. Semileptonic 4F interactions



2. Z'



3. LQ



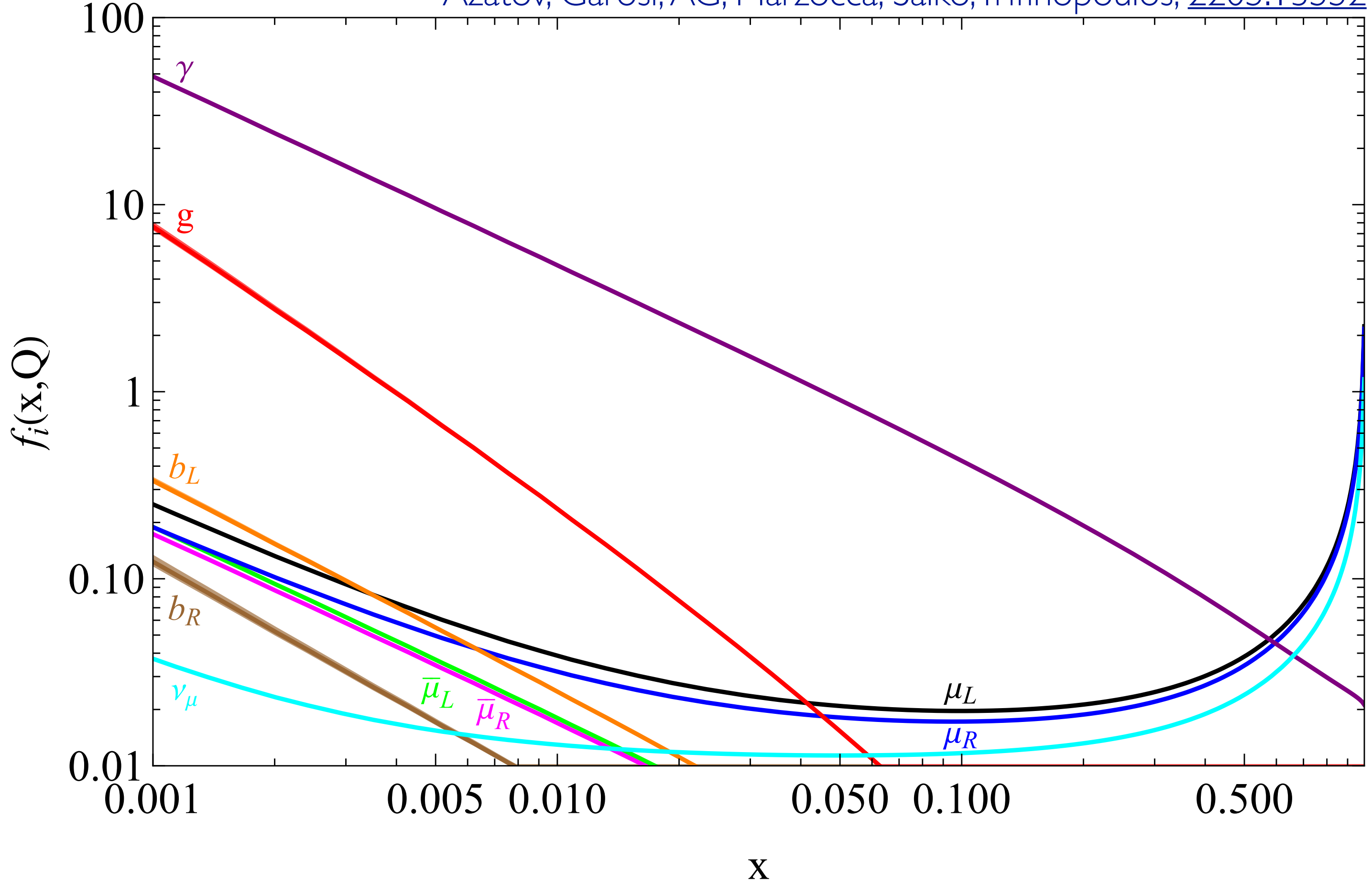
[See backup slides]

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

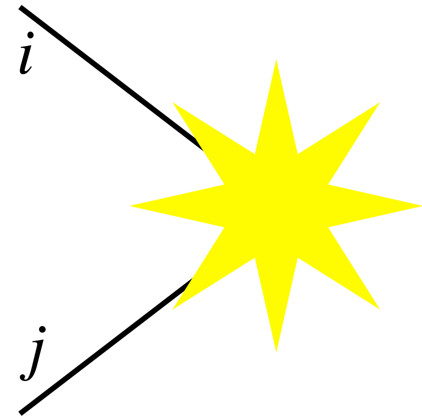
Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; 2205.13552



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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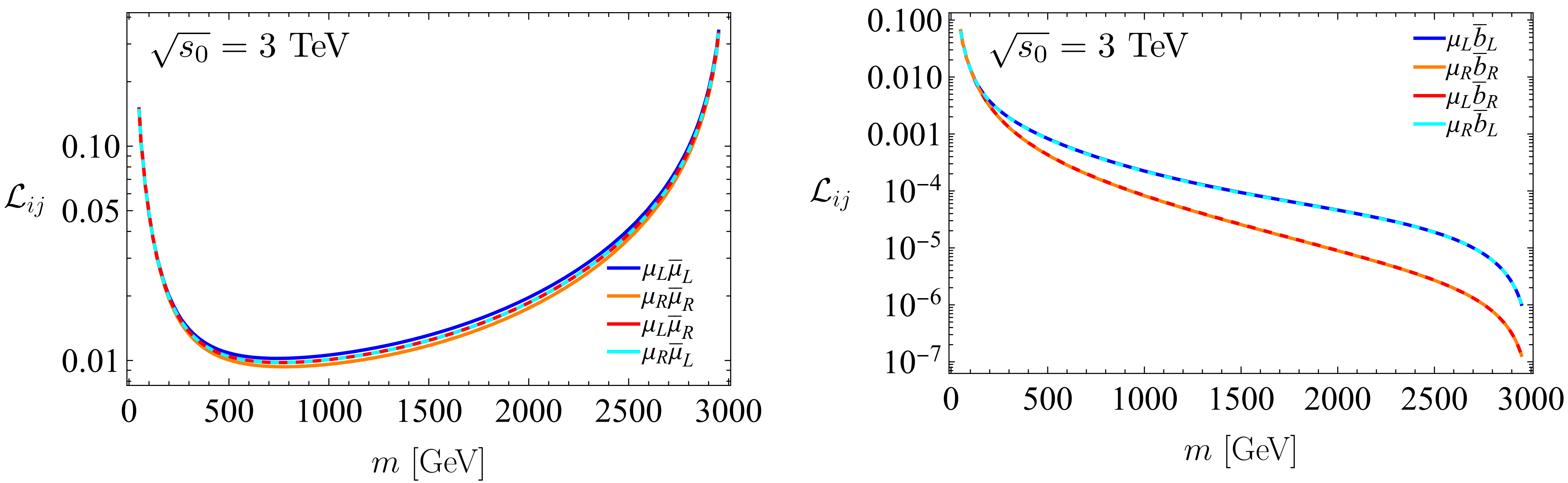
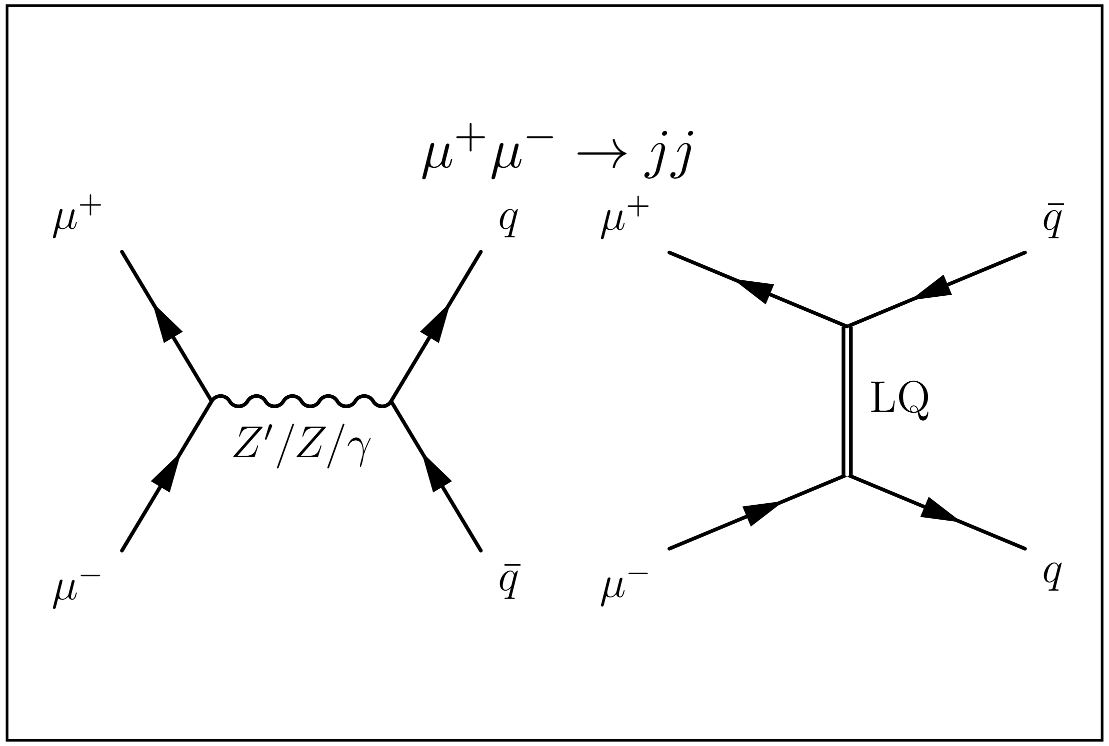
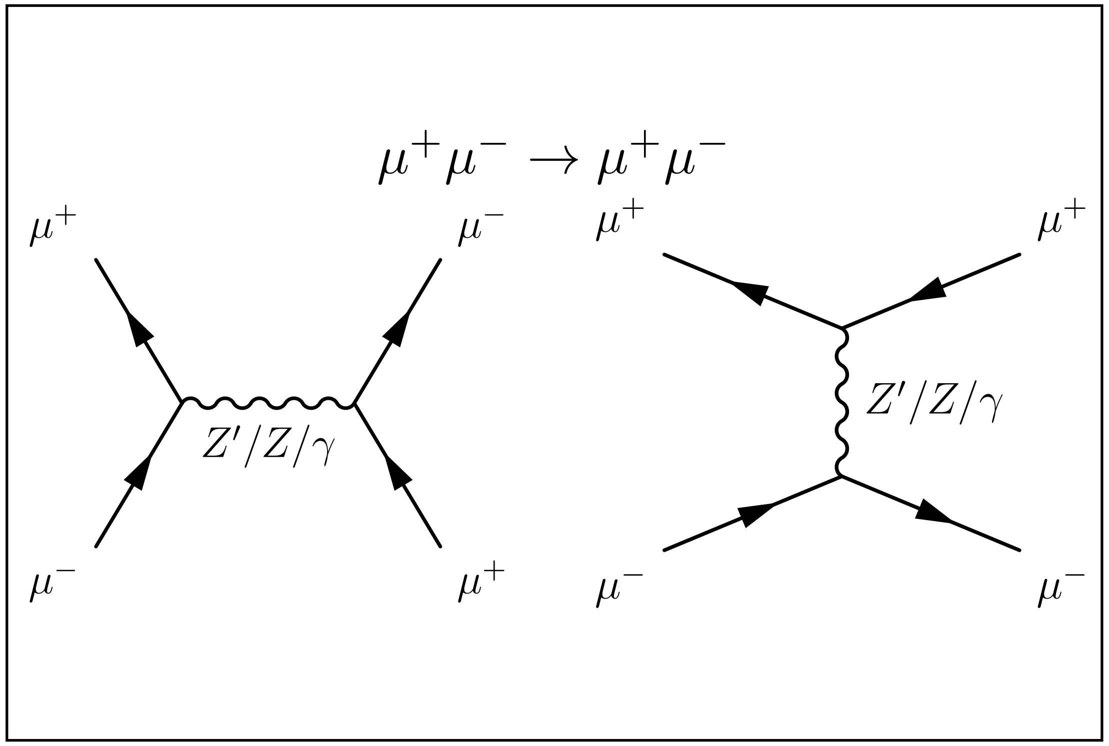
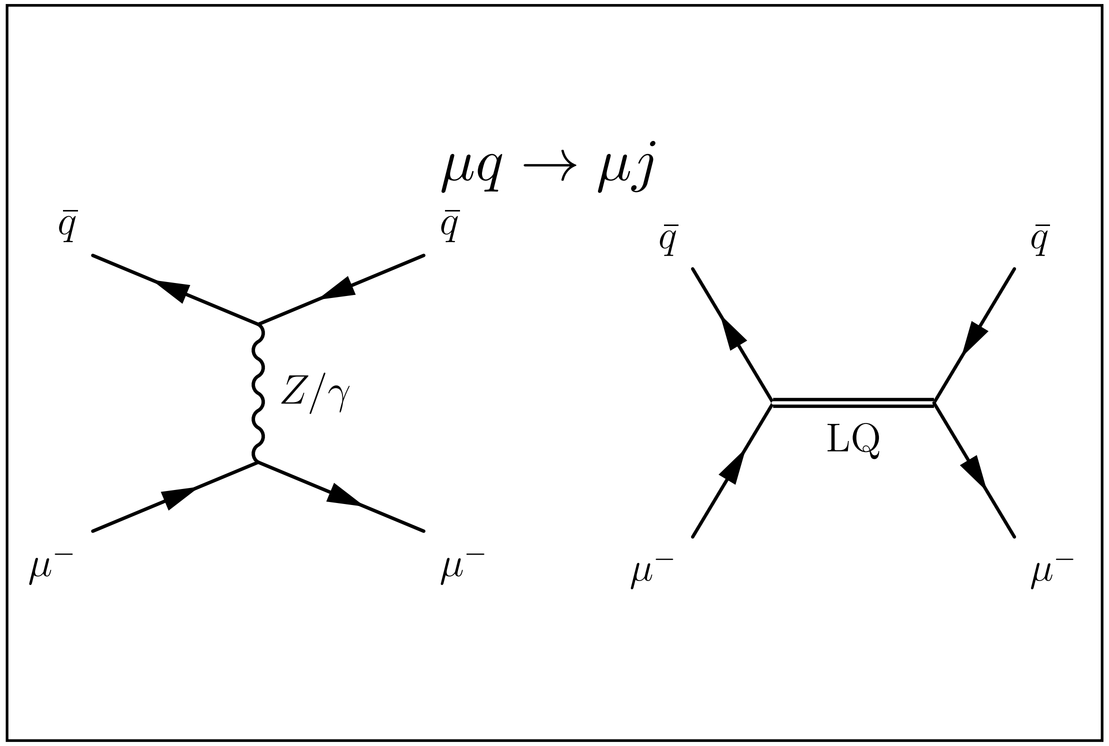
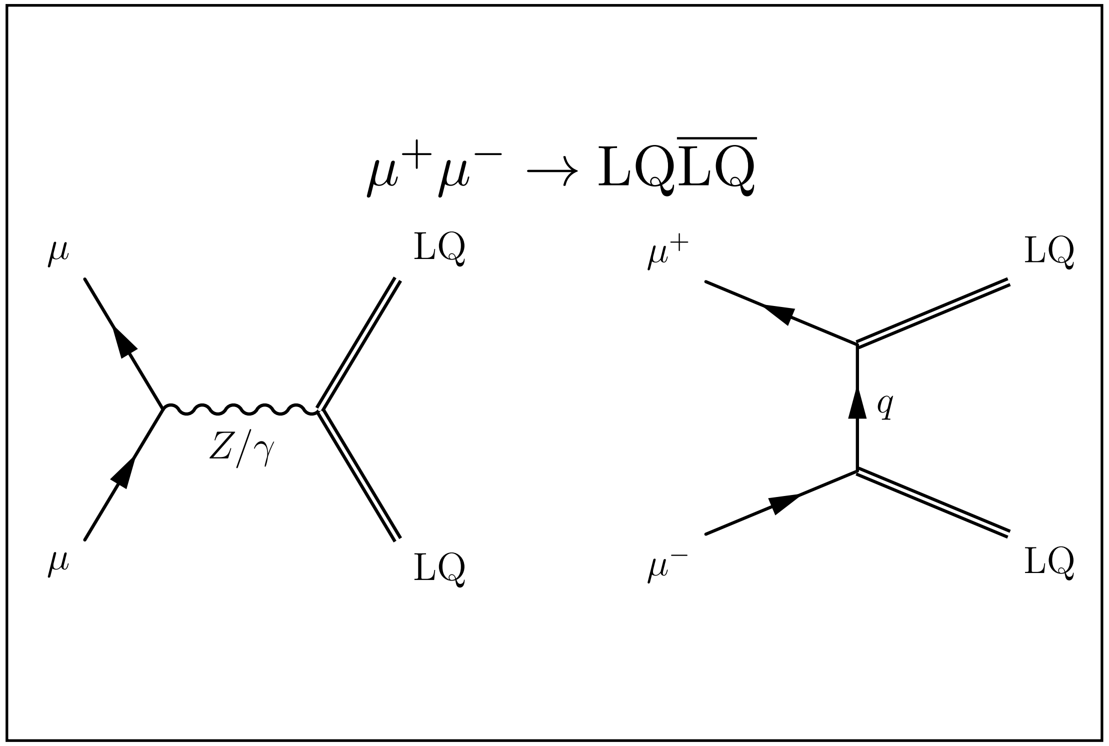


The signatures at MuC









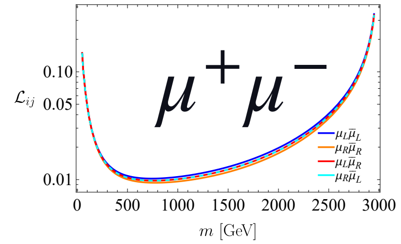
The signatures at MuC

$m_X < \sqrt{s_0}$

- 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

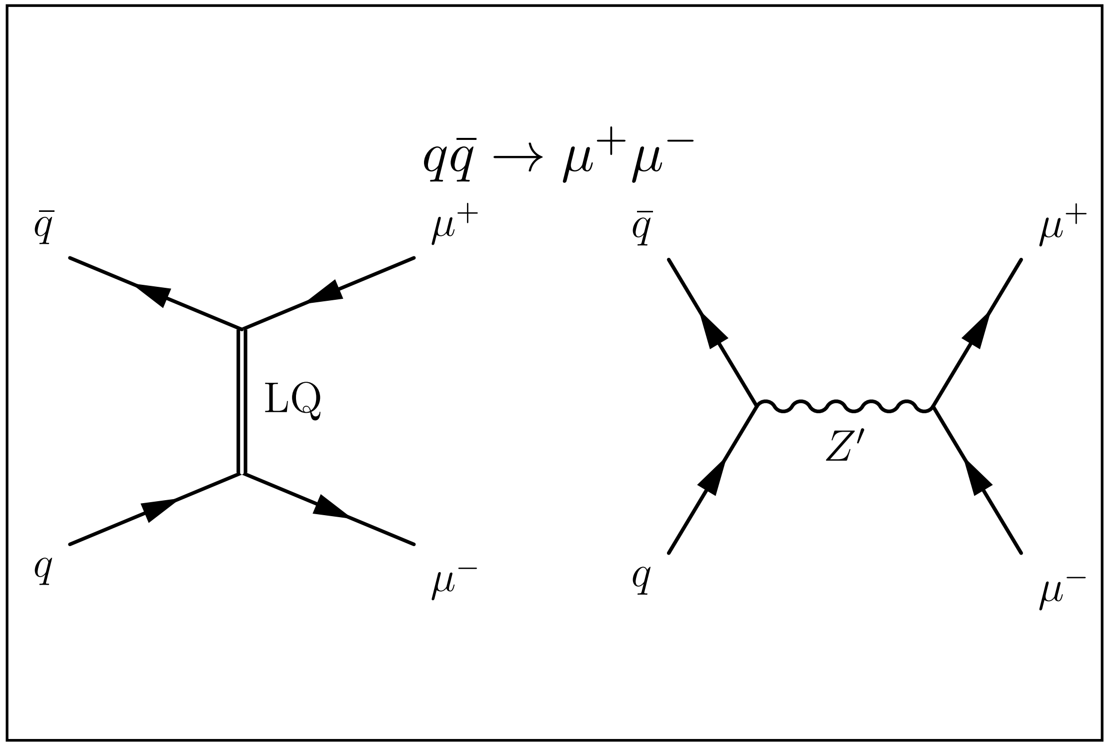


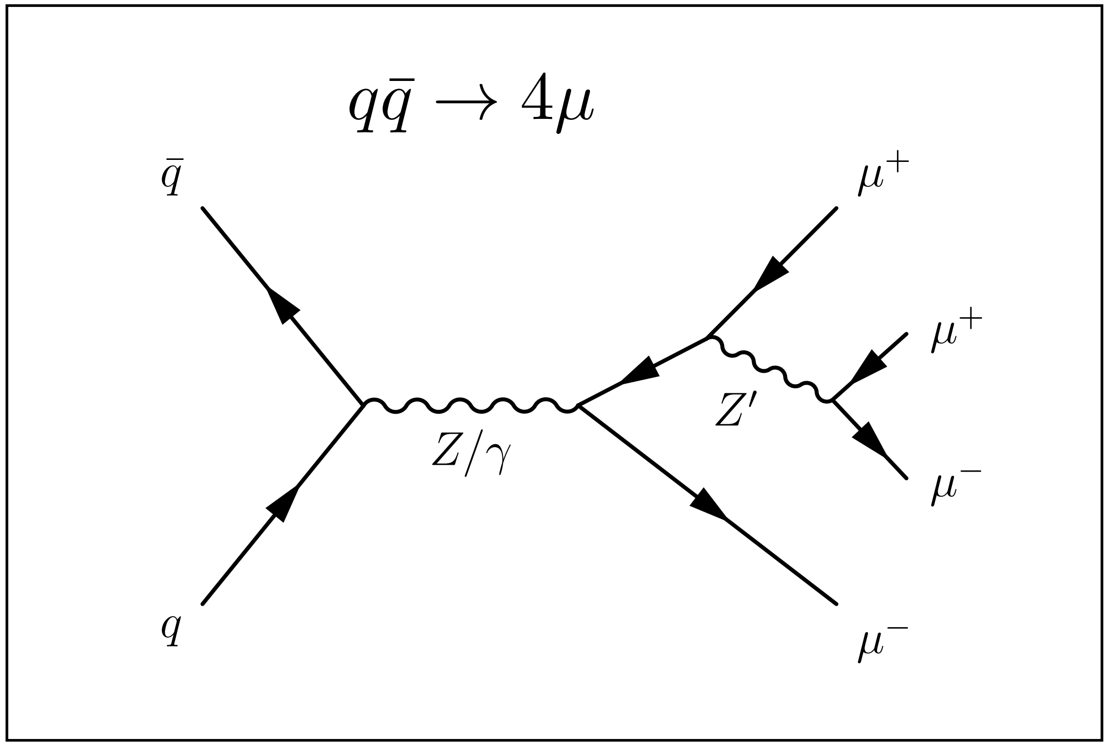
- Monotonously decreasing luminosities in proton colliders

$m_X > \sqrt{s_0}$

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

The signatures at hadron colliders

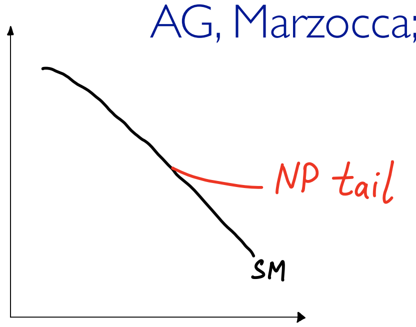


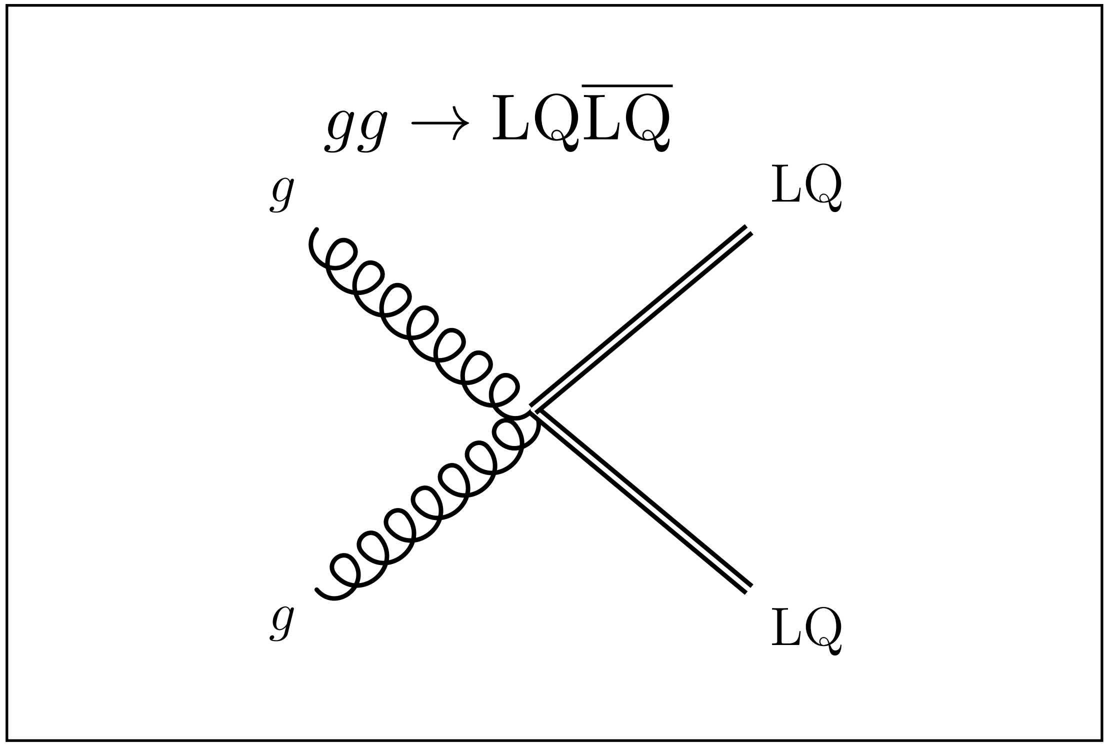


- Corrections to the high-mass Drell-Yan
- LHC data already useful to constrain models for $b \to s\mu\mu$

AG, Marzocca; 1704.09015

EFT limit





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 → $\lambda_{b\mu}$

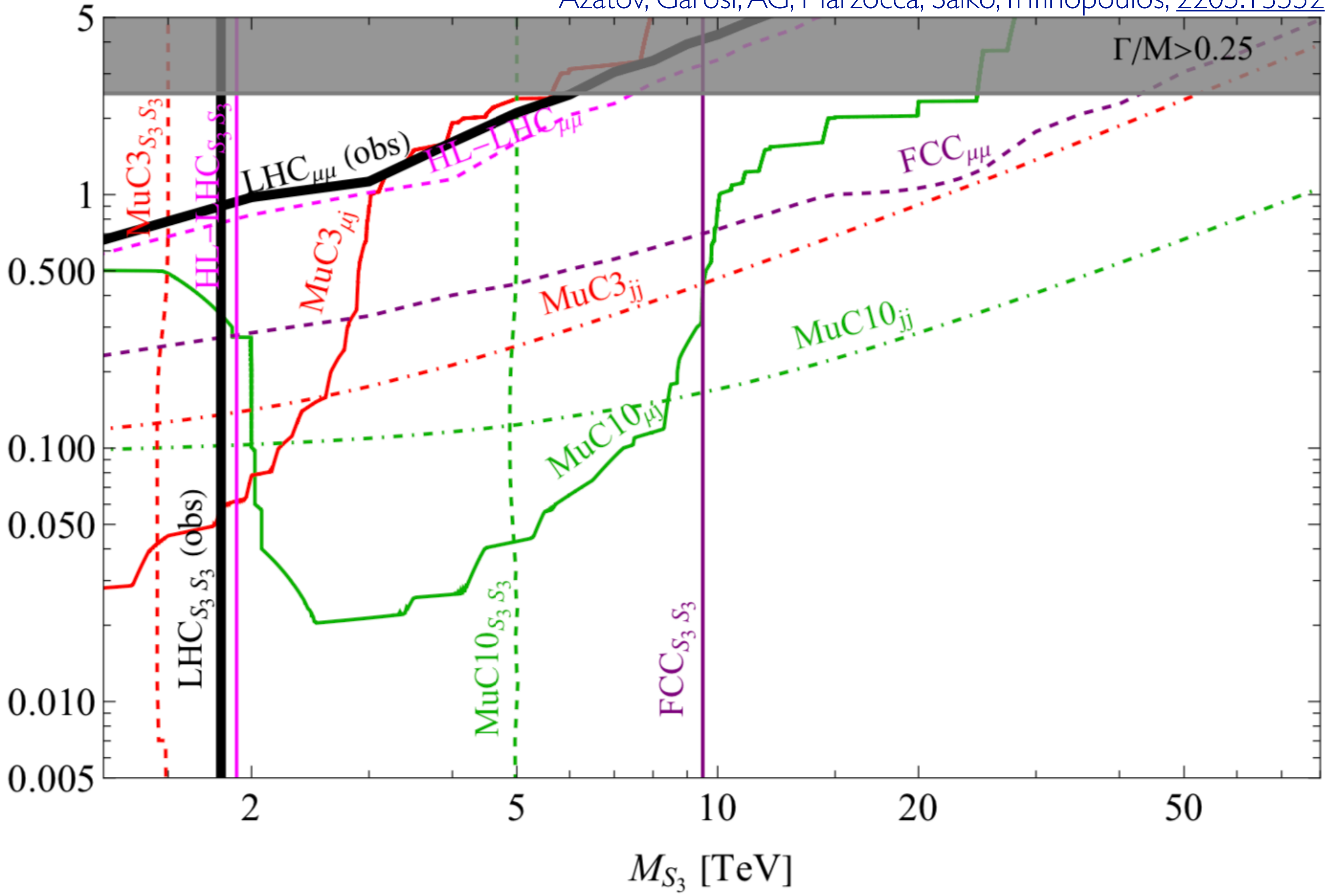
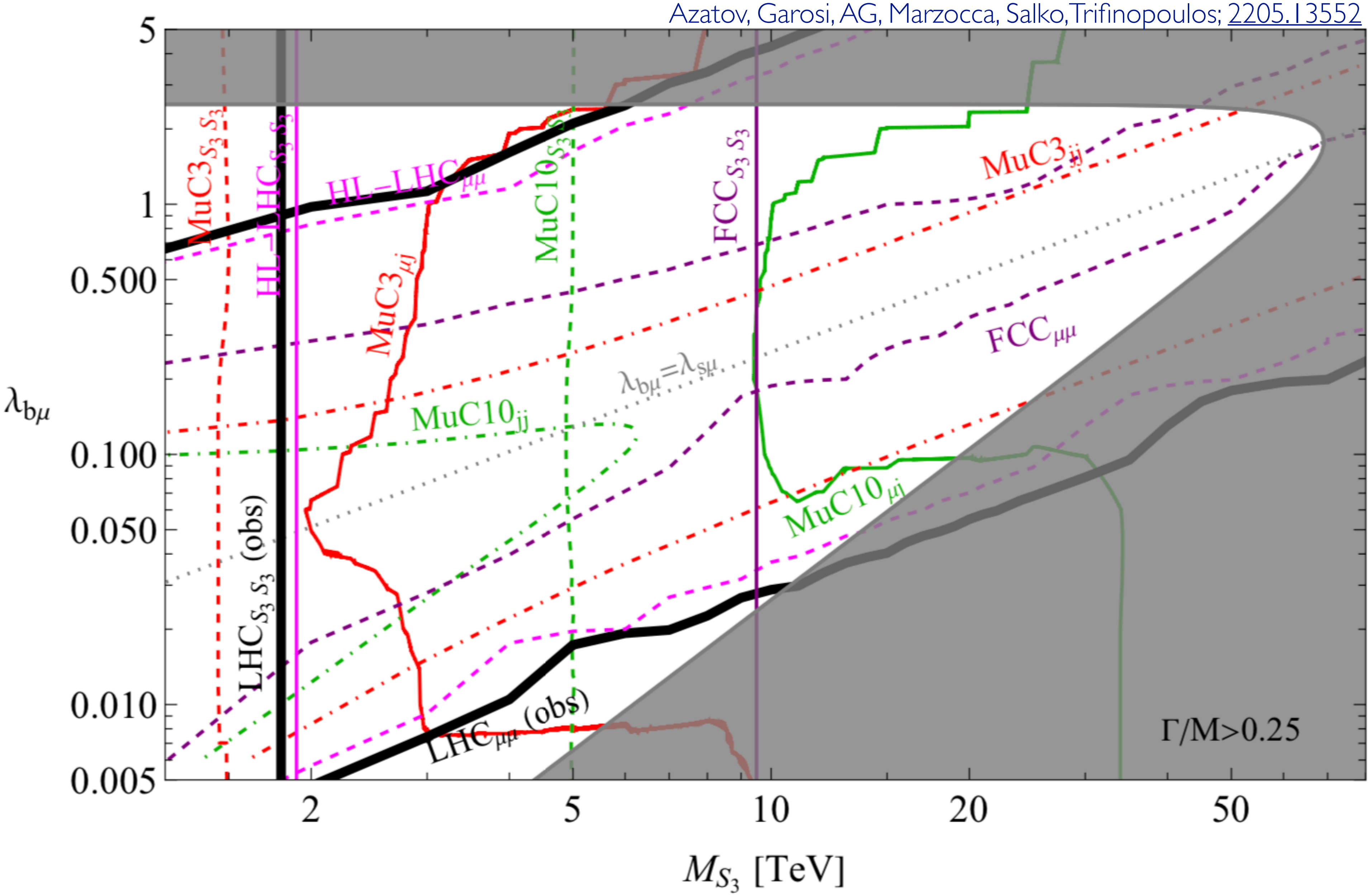


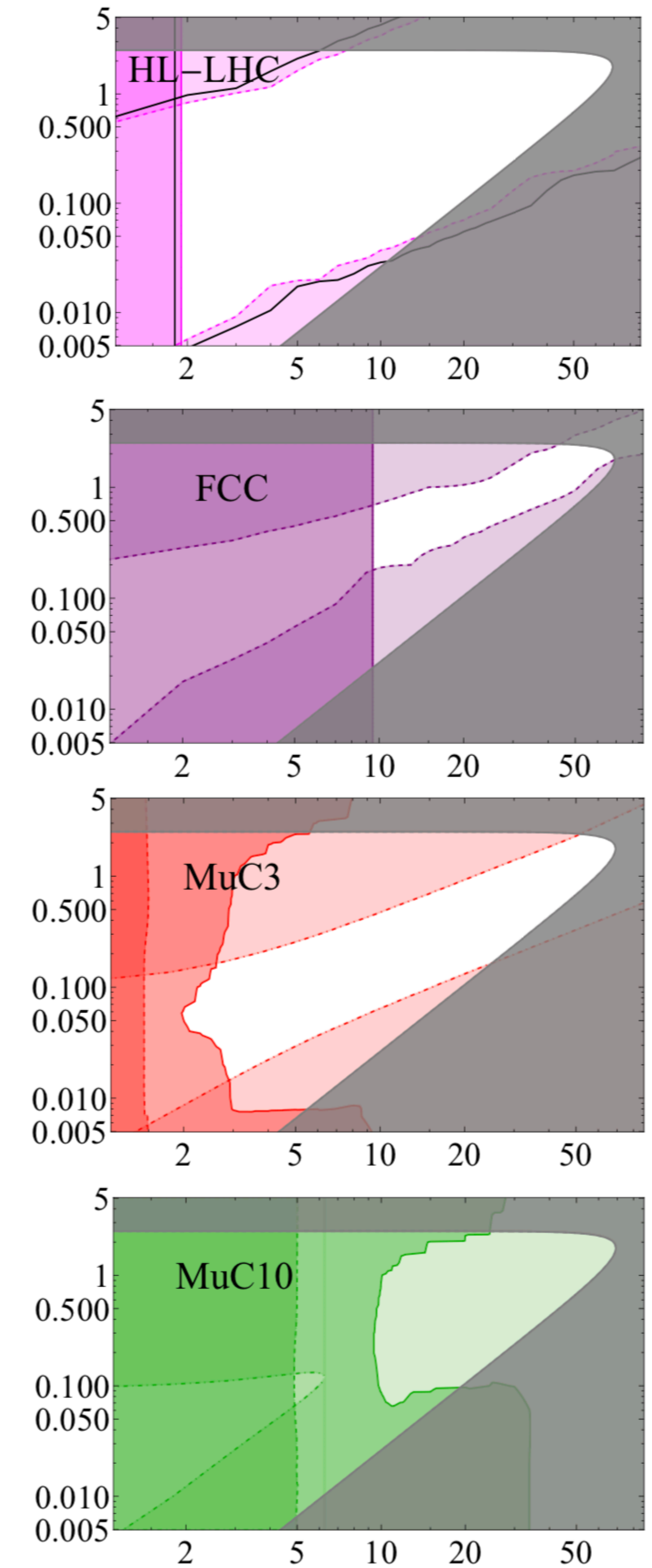
Figure 13. The 5σ discovery prospects at future colliders for the S_3 leptoquark assuming the $U(2)^3$ quark flavour symmetry and the exclusive leptoquark coupling to muons (see Section 6.1).

Scalar Leptoquark

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

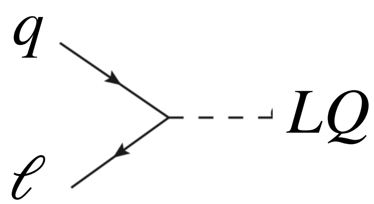
Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; 2205.13552





Resonant Leptoquark production

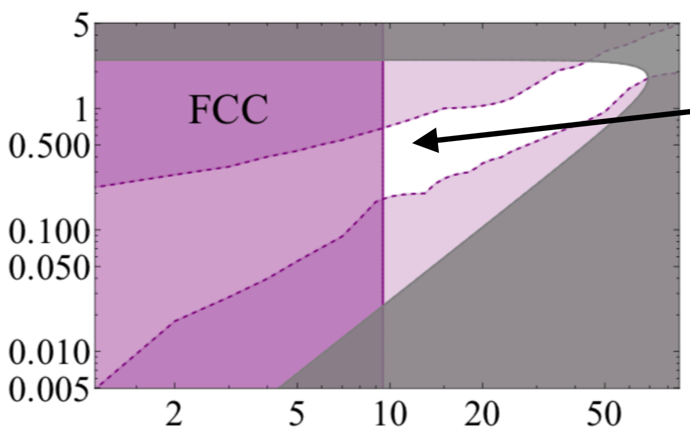
- From the lepton PDF inside the proton



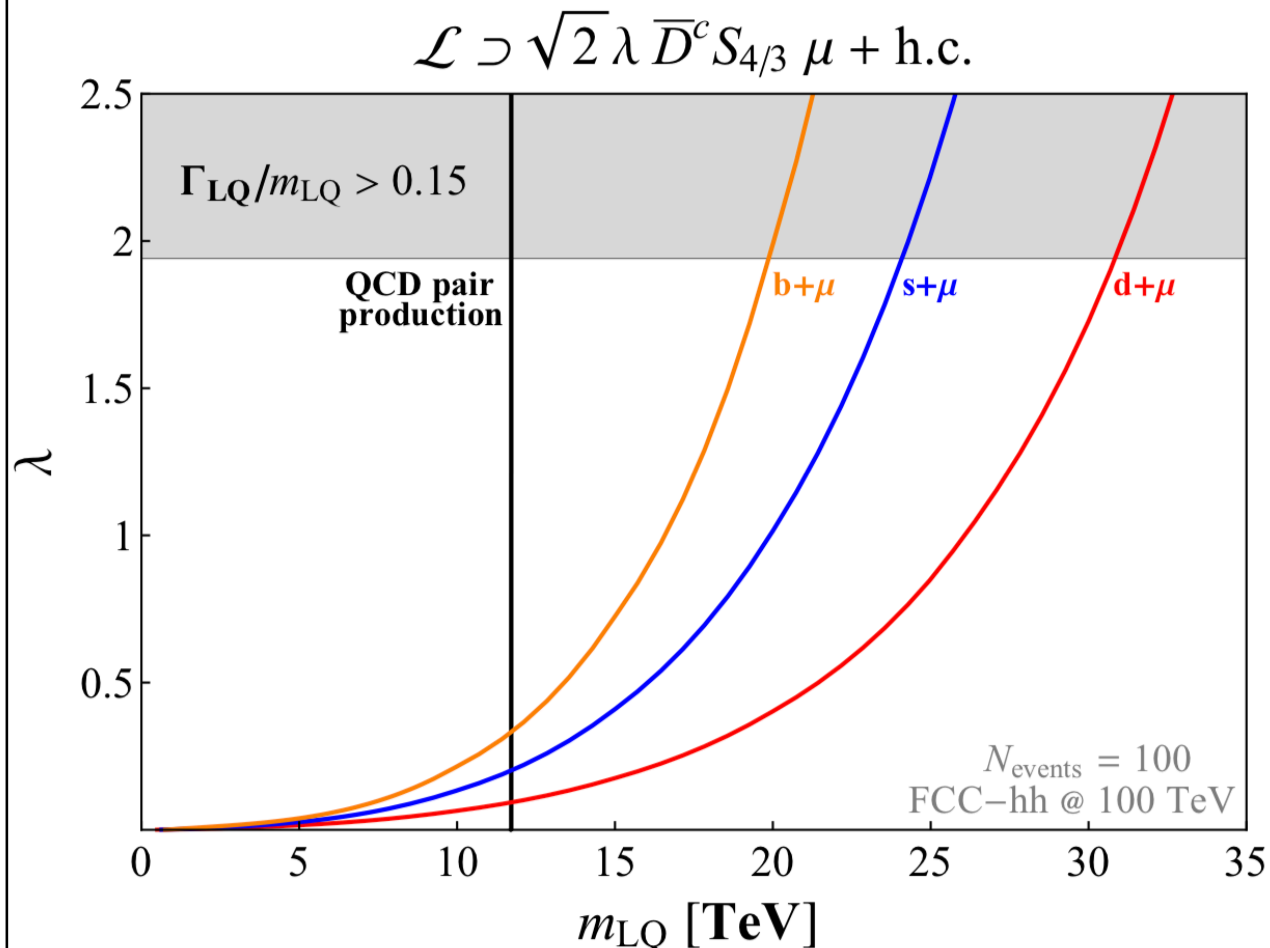
Buonocore, Haisch, Nason, Tramontano, Zanderighi; 2005.06475
AG, Selimovic; 2012.02092
Haisch, Polesello; 2012.11474

- 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



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
- Complementarity between high-mass Drell-Yan tails and B decays
- Status of $b \to s\ell\ell$ anomalies after the $R_{K^{(*)}}$ update
- A 3 TeV MuC ~ FCC-hh if NP shows up in $b \to s\mu\mu$

Backup

The $U(1)_X$ atlas

- 18 chiral fermions

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

- Six anomaly cancelation conditions:

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

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

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

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]
- Muoquark requirement

  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]

AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

Contact interactions

The pessimistic case

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

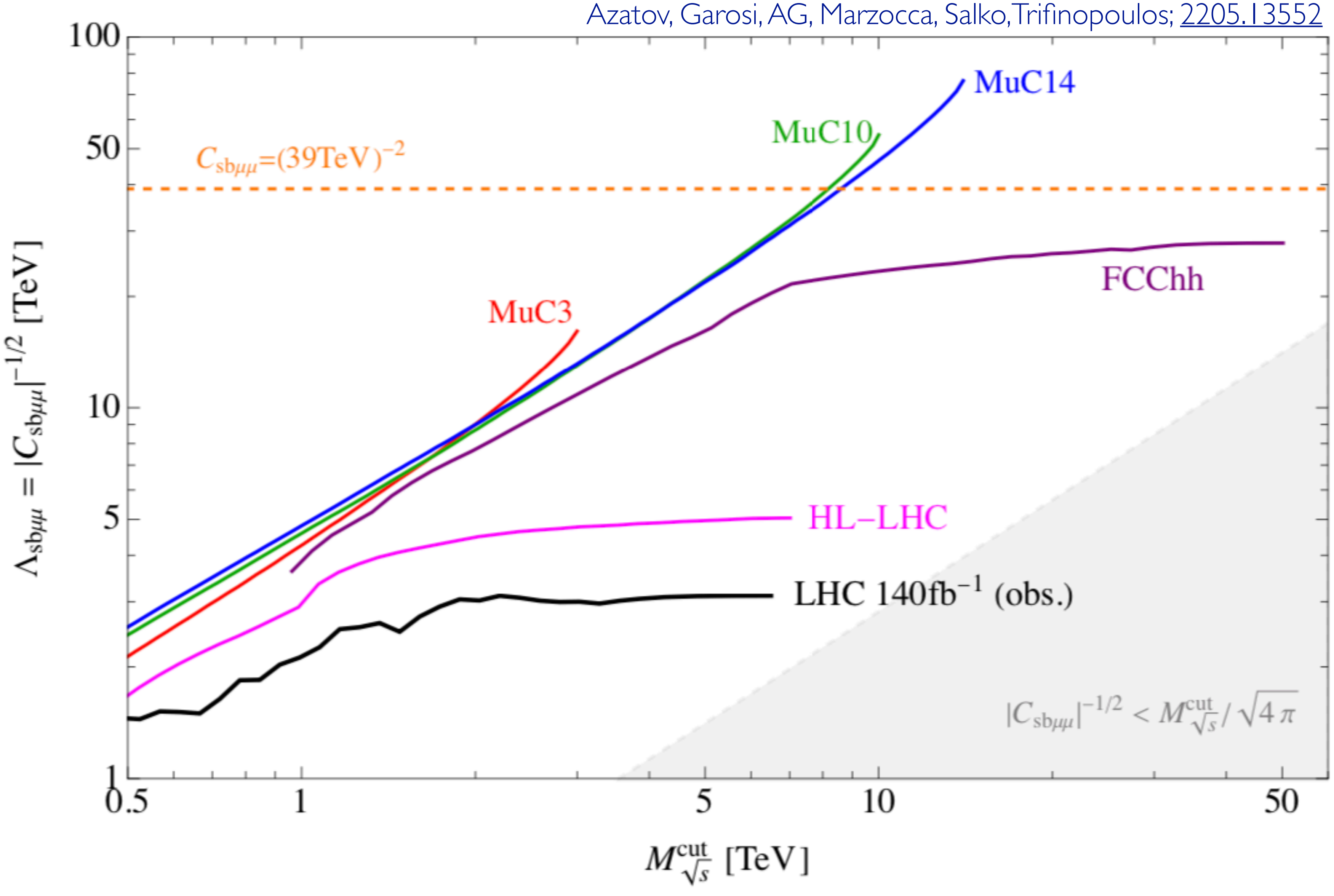


Figure 7. Sensitivity reach (95%CL) for the $(\bar{s}_L\gamma_\alpha b_L)(\bar{\mu}_L\gamma^\alpha\mu_L)$ contact interaction as function of the upper cut on the final-state invariant mass, compared to the value required to fit $bs\mu\mu$ anomalies (dashed orange line).

Contact interactions

The realistic case ★

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

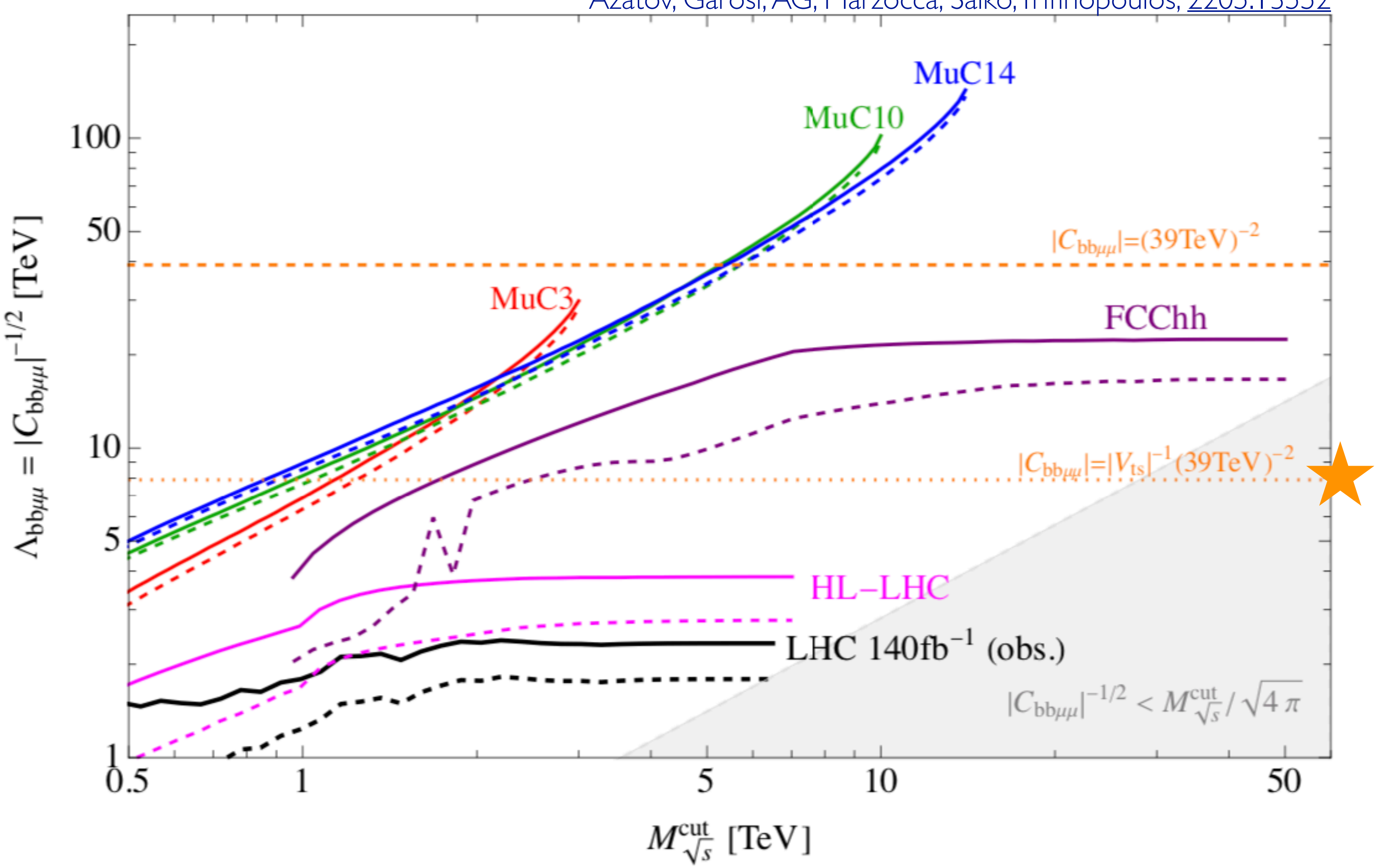


Figure 8. Sensitivity reach (95%CL) for the $(\bar{b}_L\gamma_\alpha b_L)(\bar{\mu}_L\gamma^\alpha\mu_L)$ contact interaction as function of the upper cut on the final-state invariant mass. Solid (dashed) lines represent the limit for positive (negative) values of $C_{bb\mu\mu}$. The orange dotted and 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

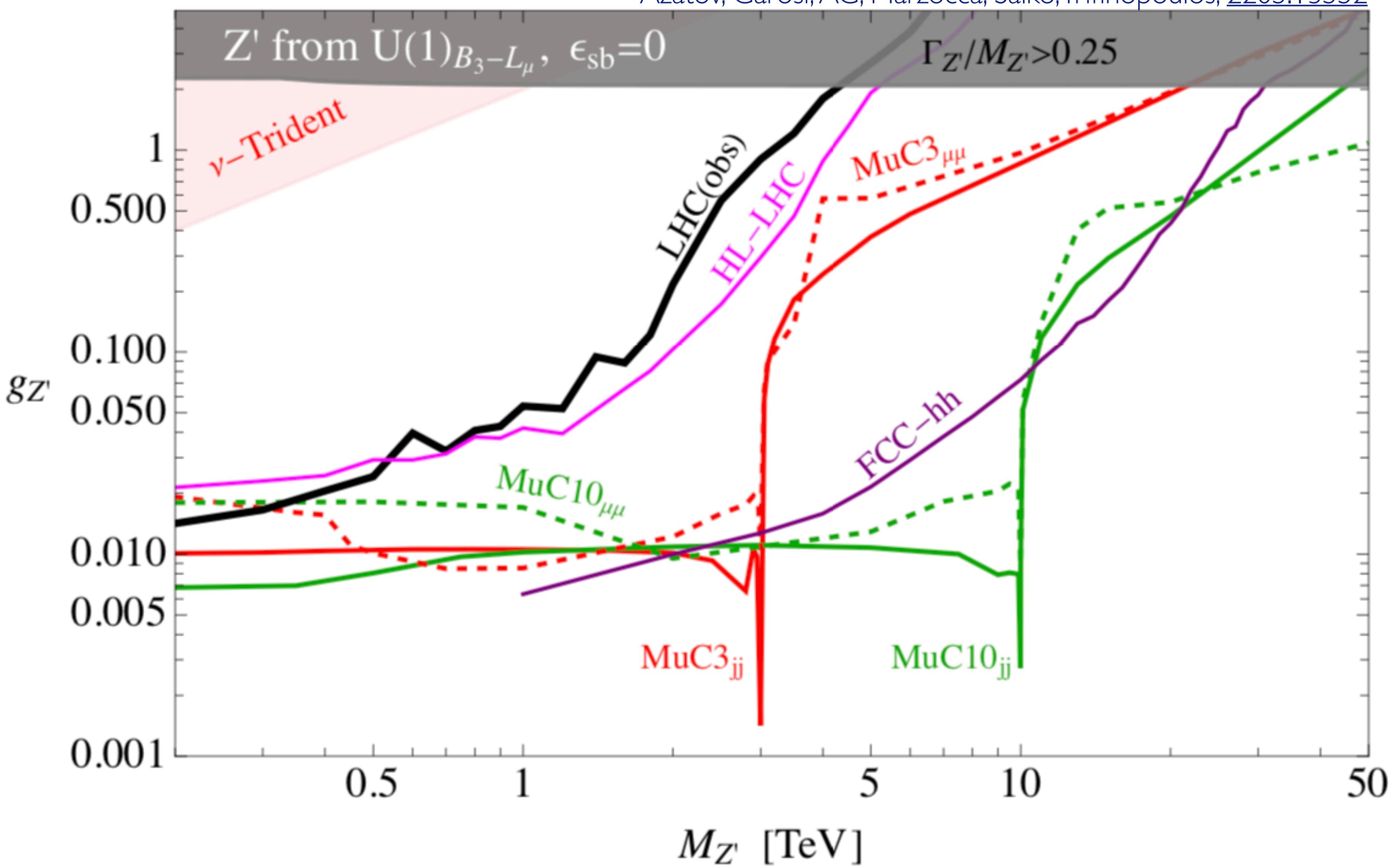
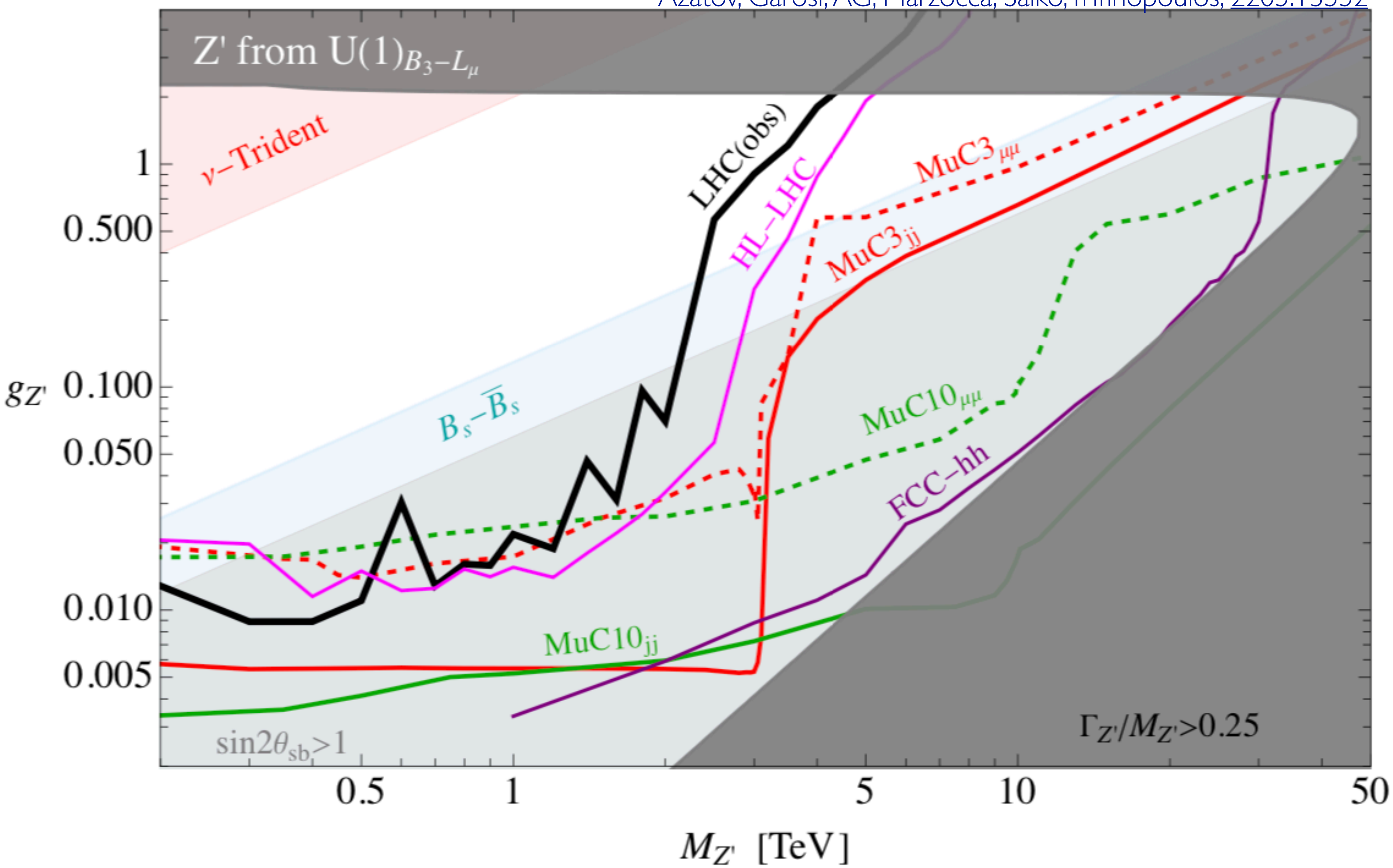


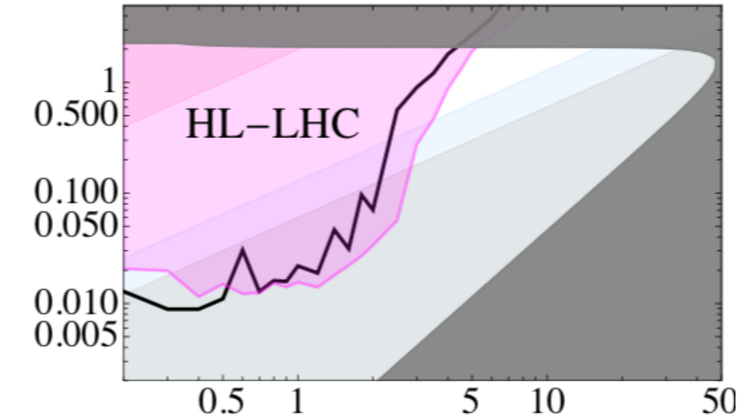
Figure 9. Discovery reach at 5σ for the $B_3 - L_\mu$ model with $\epsilon_{sb} = 0$, for different final states at each collider (as indicated by the labels). The region excluded at 95% CL by LHC [111] is above the black line while in the dark gray region the Z' has a large width, signaling a loss of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

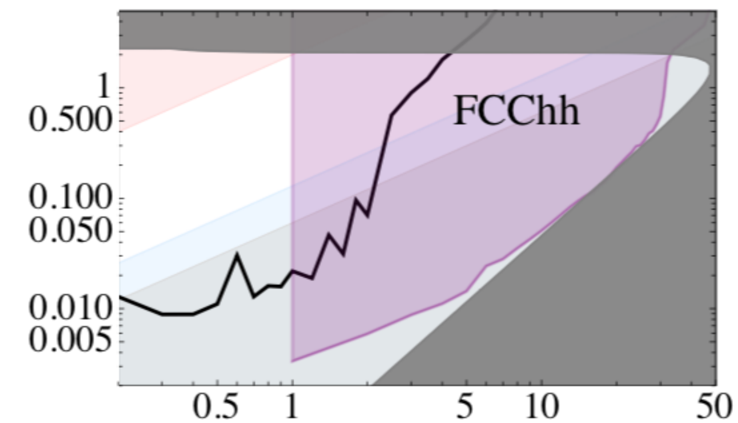
Z' models: $B_3 - L_\mu$

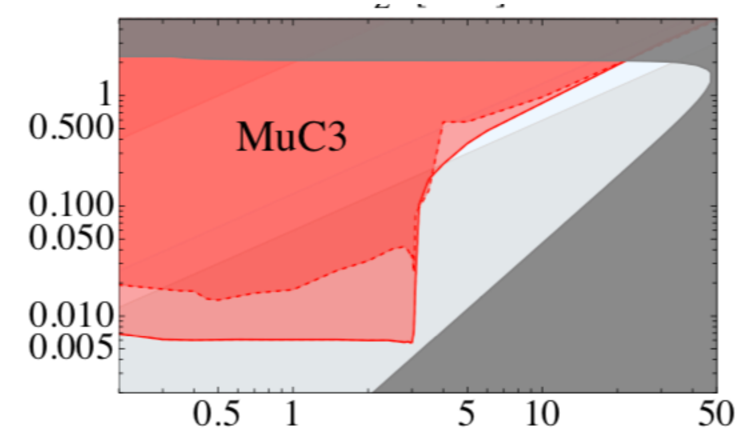
$bs\mu\mu:\quad \epsilon_{sb} = -1.7\times 10^{-3}\left(\frac{M_{Z'}}{g_{Z'}\,\mathrm{TeV}}\right)^2$

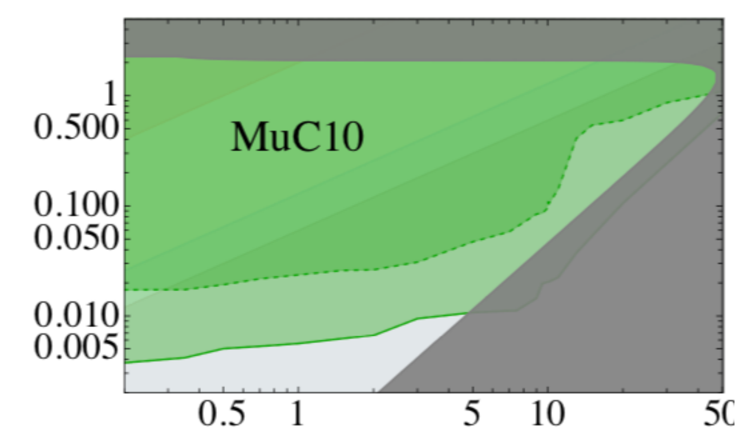
Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; 2205.13552











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

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

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

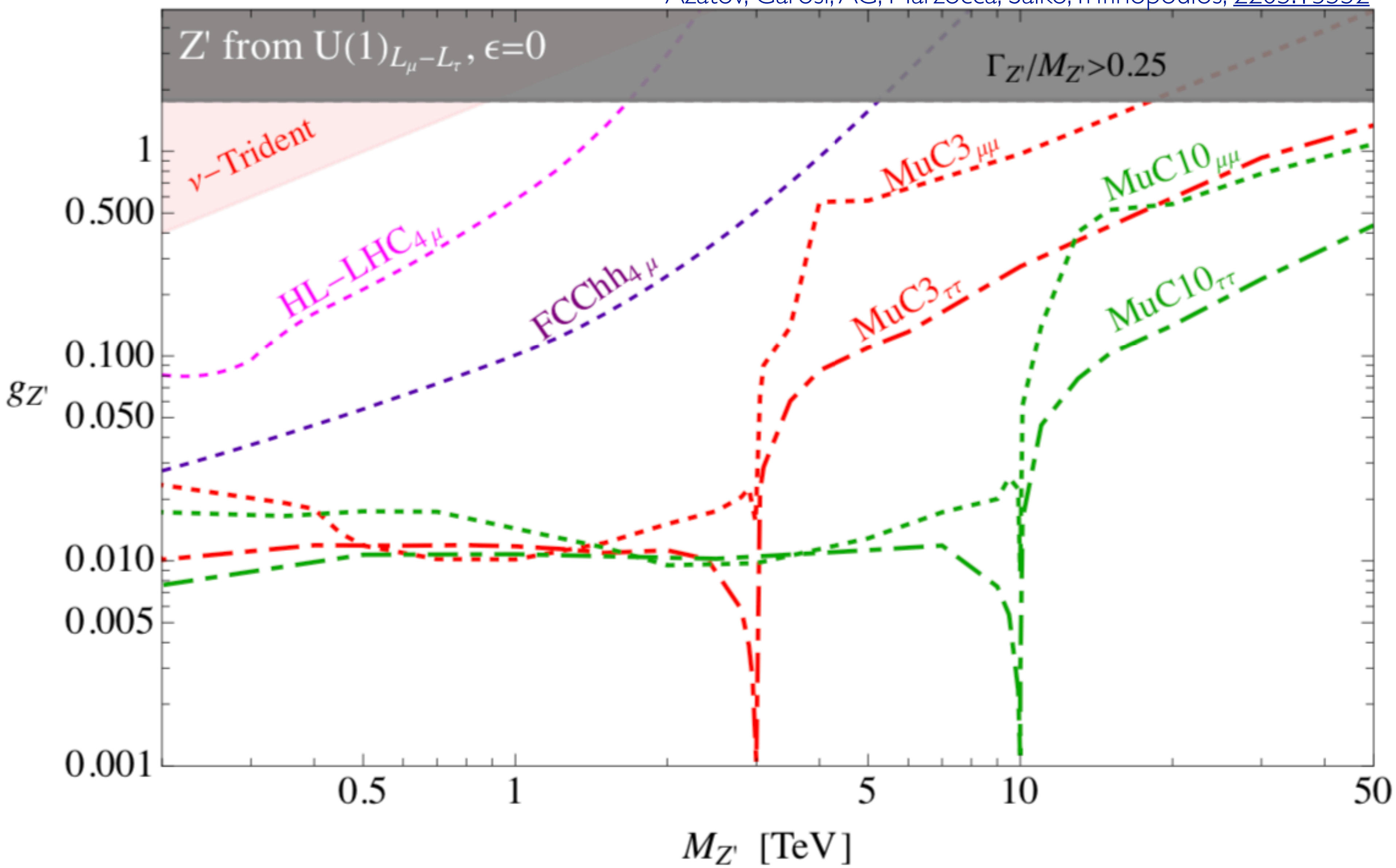


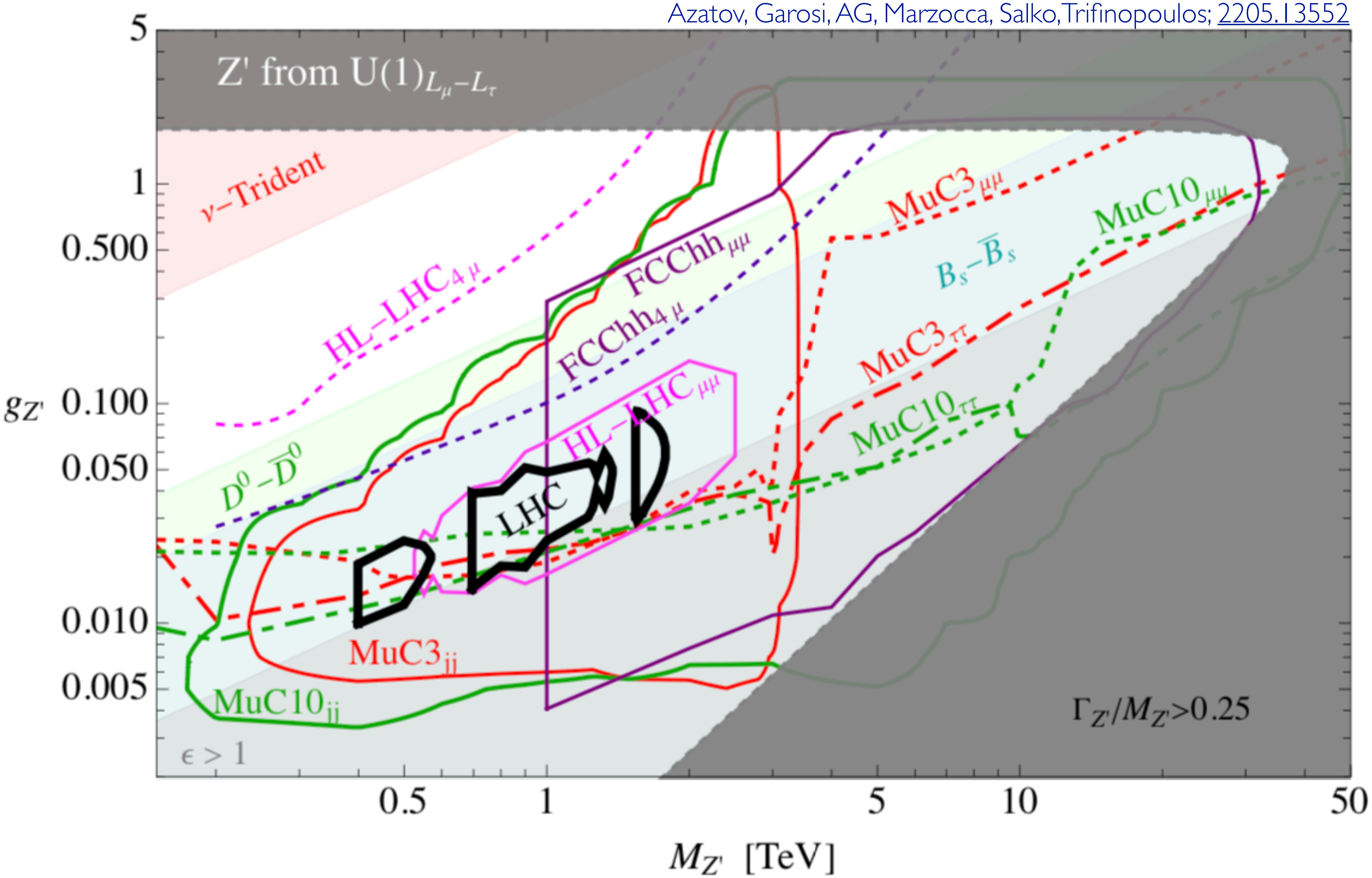
Figure 11. Discovery reach at 5σ for the $L_\mu - L_\tau$ model with $\epsilon_s = \epsilon_b = 0$ in Eq. (5.6). In the dark gray region the Z' has a large width, signaling a loss of perturbativity.

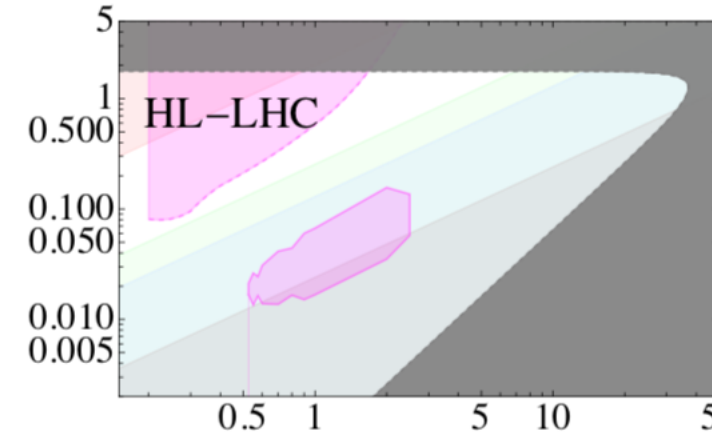
Z' models: $L_\mu - L_\tau$

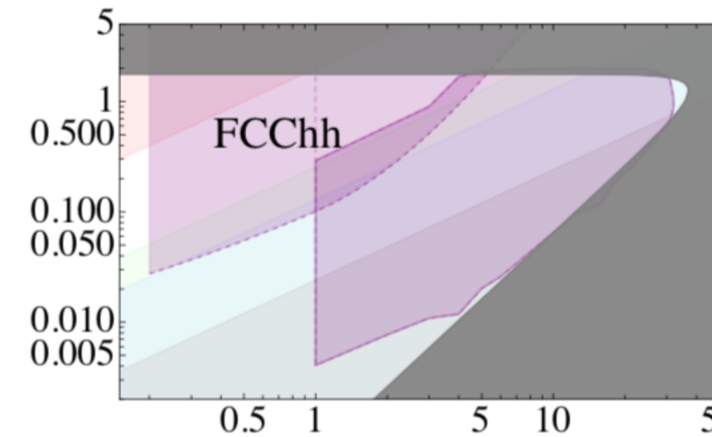
$$bs\mu\mu: \quad \epsilon_b \epsilon_s^* = -5.7 \times 10^{-4} \left(\frac{M_{Z'}}{g_{Z'}\,\text{TeV}} \right)^2$$

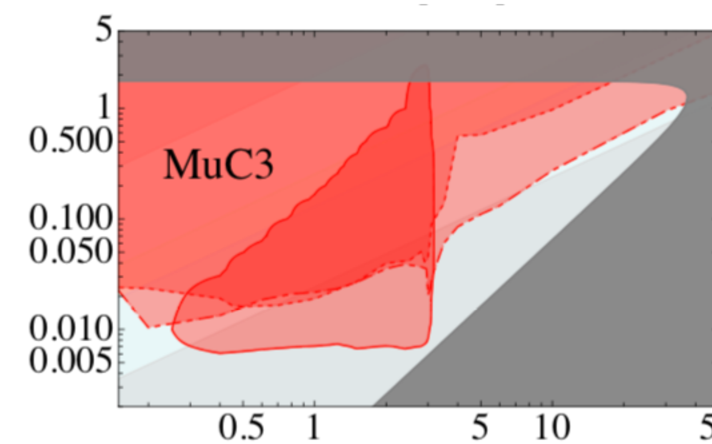
e.g. $\epsilon_b = -\epsilon_s$

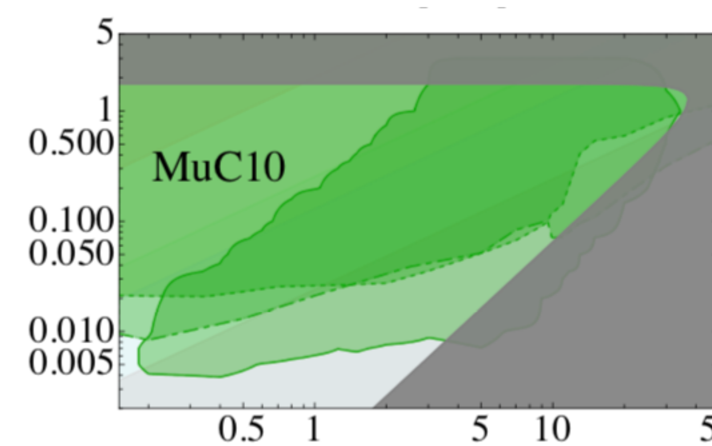
Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; 2205.13552











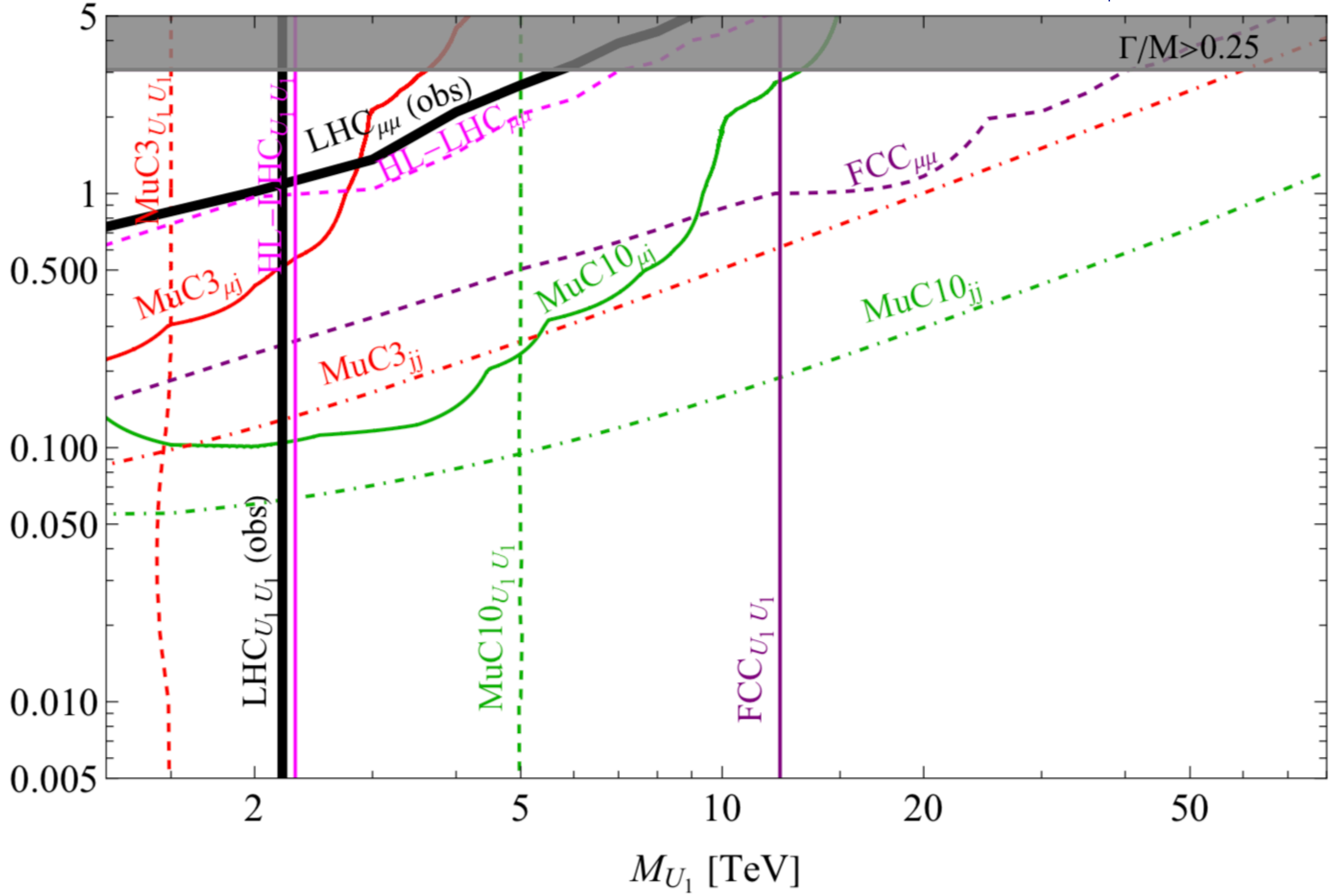
Vector Leptoquark

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

$$\mathcal{L}^{\text{int}}_{U_1} = \lambda_{i\mu} \overline{Q_L}^i \gamma_\alpha L^2_L U^\alpha_1 + \text{h.c.} = \lambda_{i\mu} U^\alpha_1 \left(V_{ji} \bar{u}^j_L \gamma_\alpha \nu_\mu + \bar{d}^i_L \gamma_\alpha \mu_L \right) + \text{h.c.}$$

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