LFUV at MuC

Admir Greljo

UNIVERSITÄT BERN → University of Basel

SWISS NATIONAL SCIENCE FOUNDATION
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Motivation

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

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

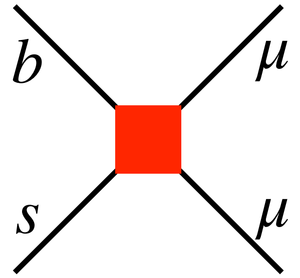
The scope

- Competitors

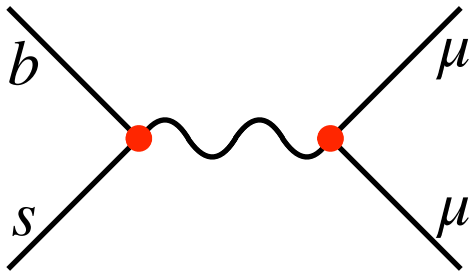
Collider	C.o.m. Energy	Luminosity	Label
LHC Run-2	13 TeV	140 fb^{-1}	LHC
HL-LHC	14 TeV	6 ab^{-1}	HL-LHC
FCC-hh	100 TeV	30 ab^{-1}	FCC-hh
Muon Collider	3 TeV	1 ab^{-1}	MuC3
Muon Collider	10 TeV	10 ab^{-1}	MuC10
Muon Collider	14 TeV	20 ab^{-1}	MuC14

- New Physics benchmarks:

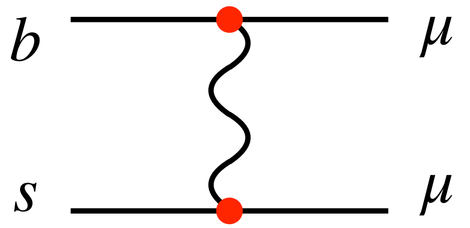
1. Semileptonic 4F interactions



2. Gauged $U(1)$ extensions



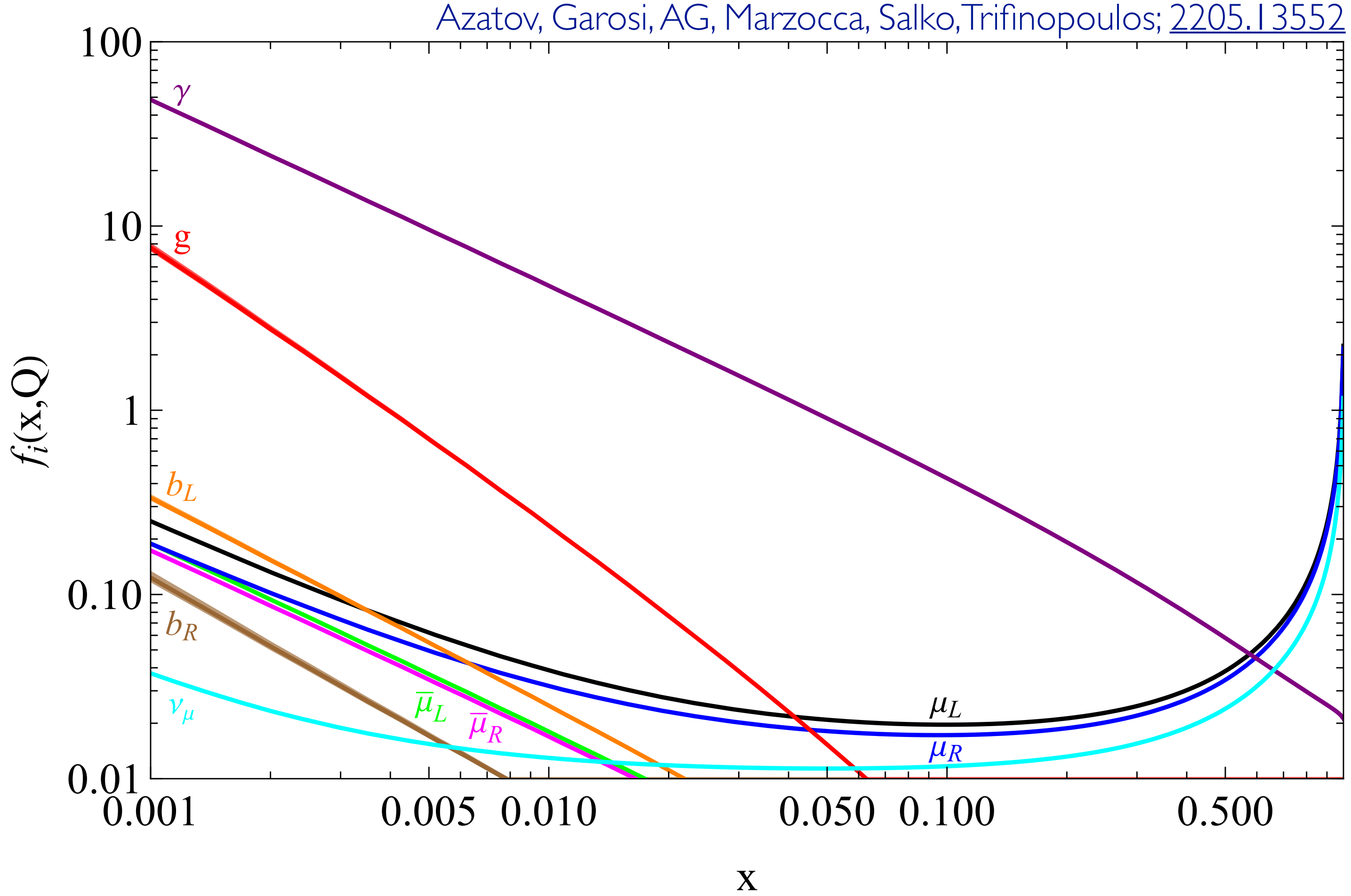
3. Leptoquarks



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

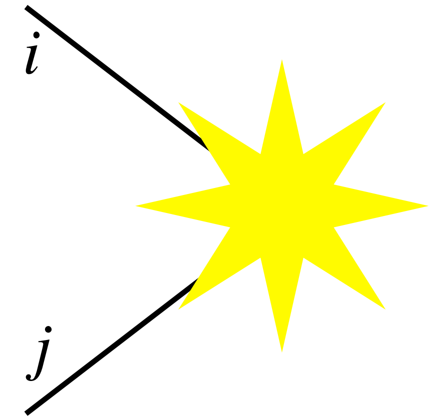
Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; 2205.13552



The Muon Beam

- Parton luminosities

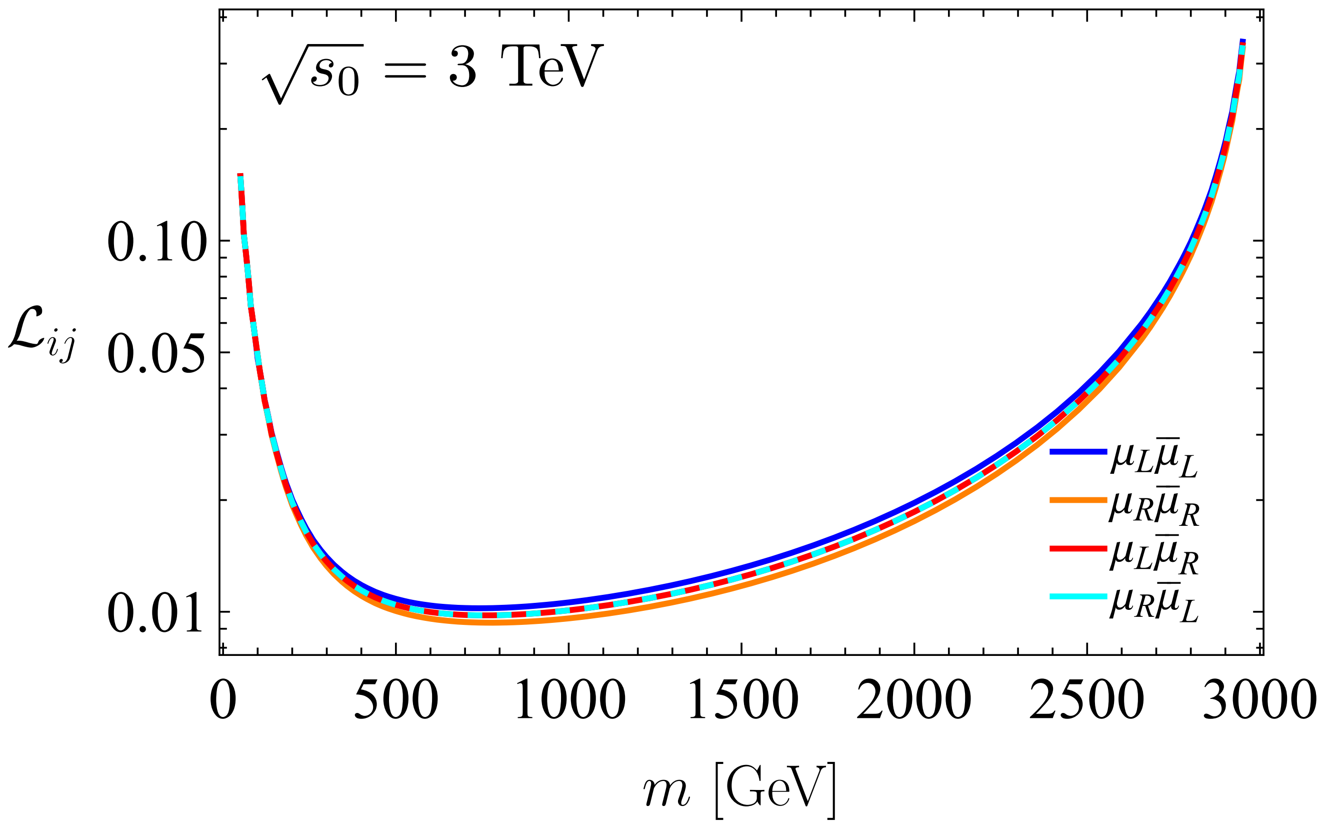
$$\mathcal{L}_{ij}(\tau) = \int_\tau^1 \frac{dx}{x} f_i(x,m) f_j\left(\frac{\tau}{x}, m\right)$$

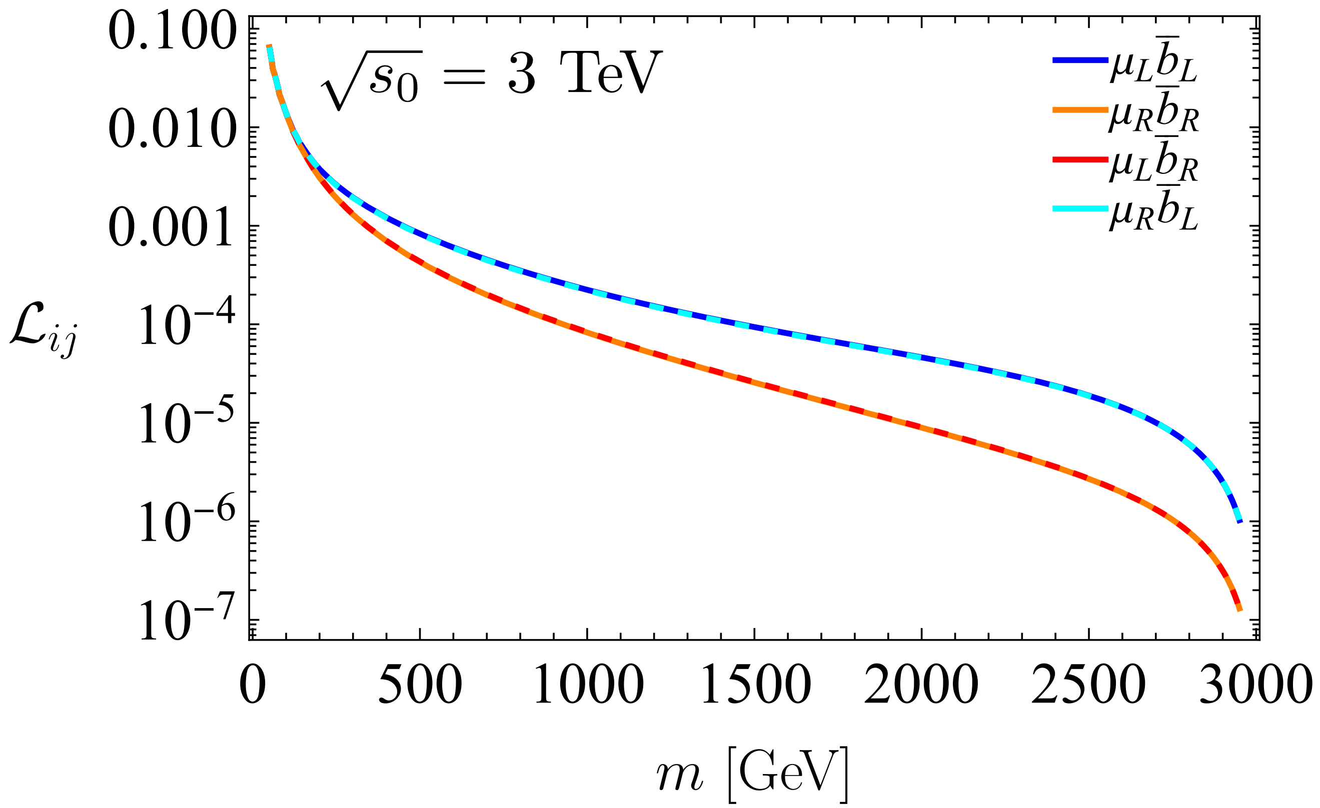


$$m^2 = (p_i + p_j)^2$$

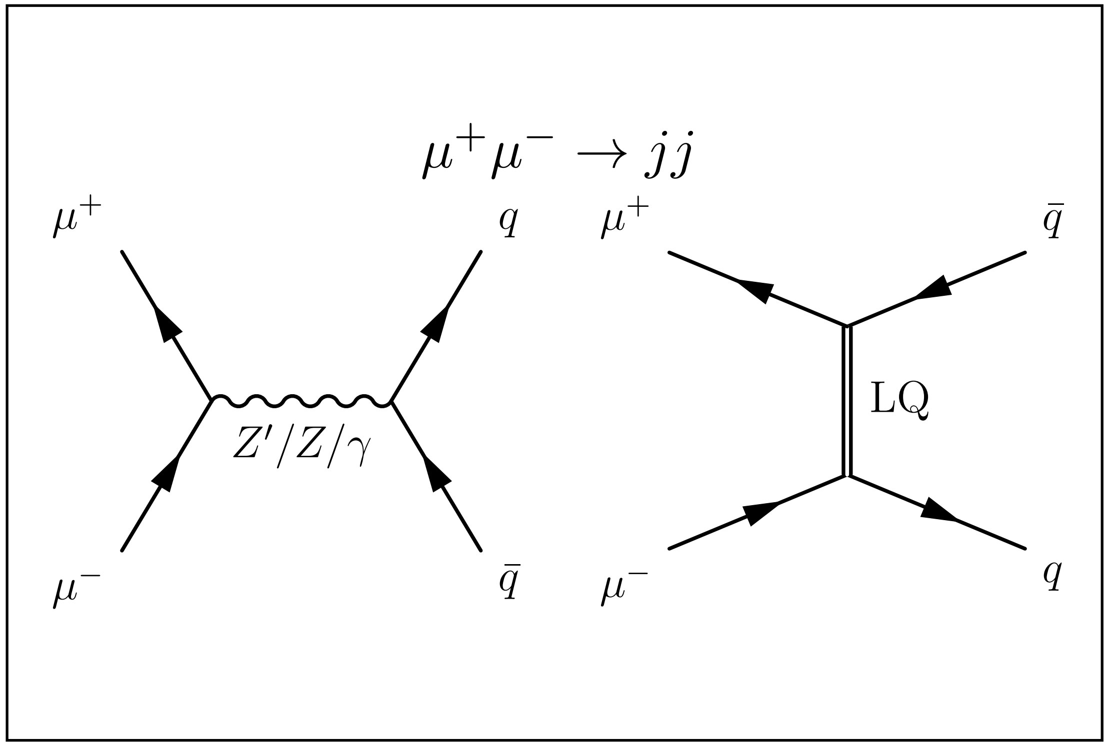
$$\tau = m^2/s_0$$

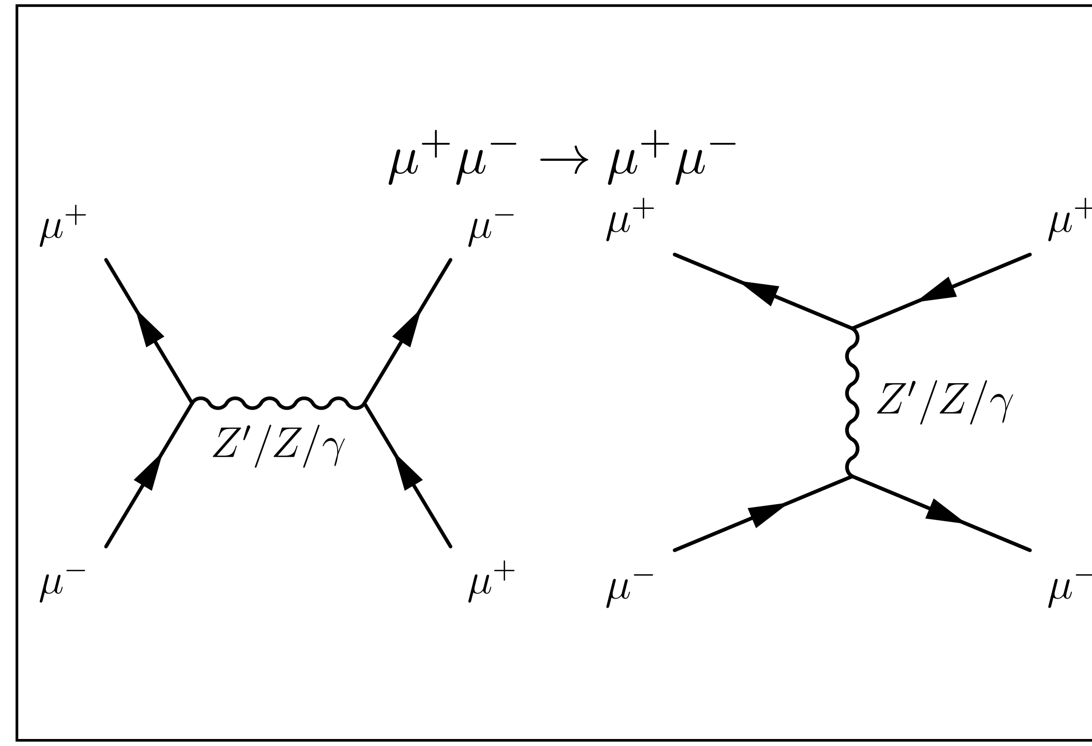
Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; 2205.13552

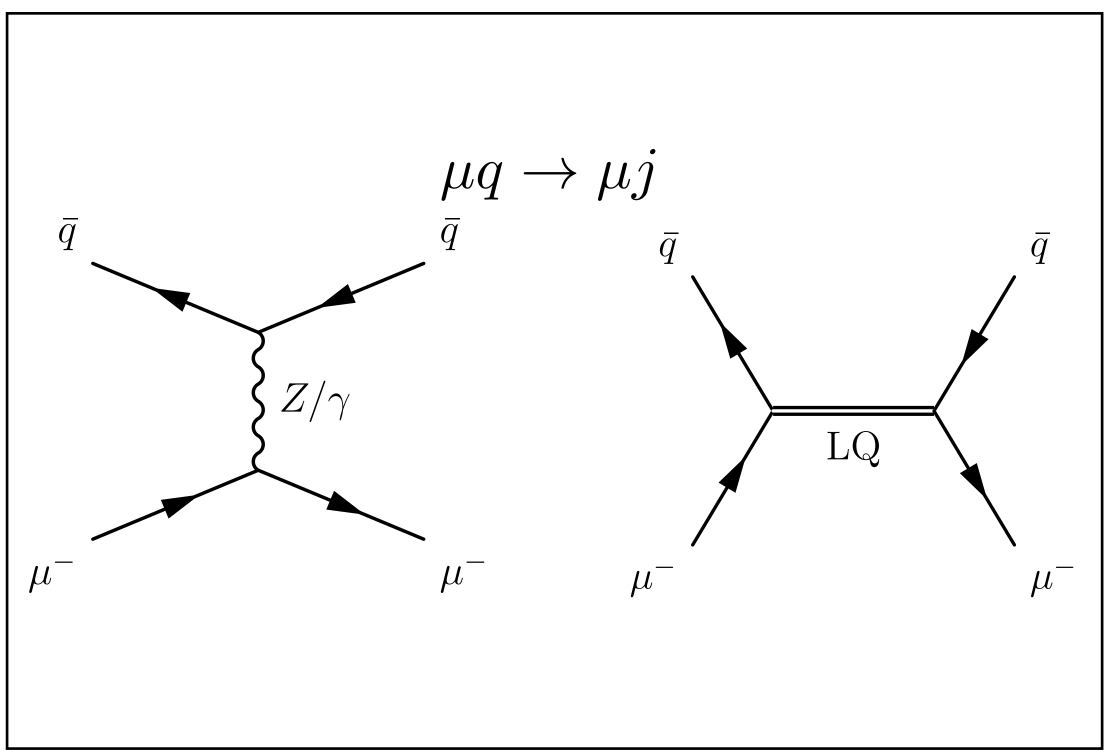


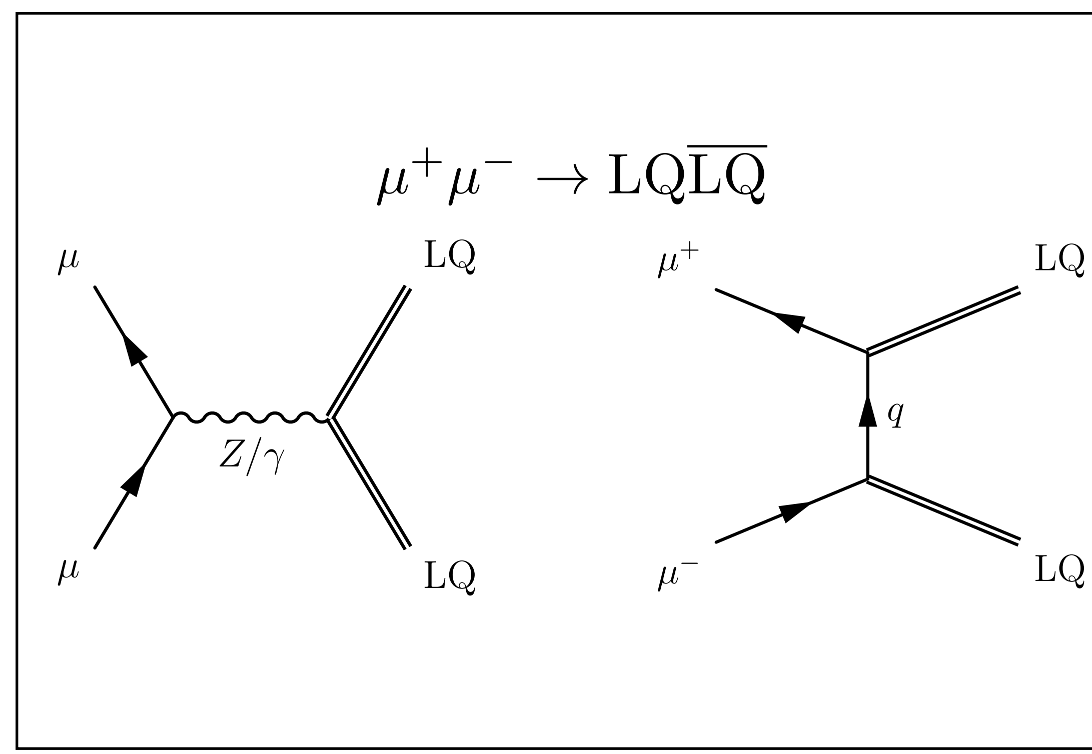


The signatures at MuC







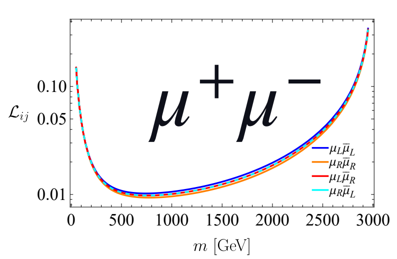


The signatures at MuC

$m_X < \sqrt{s_0}$

- 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

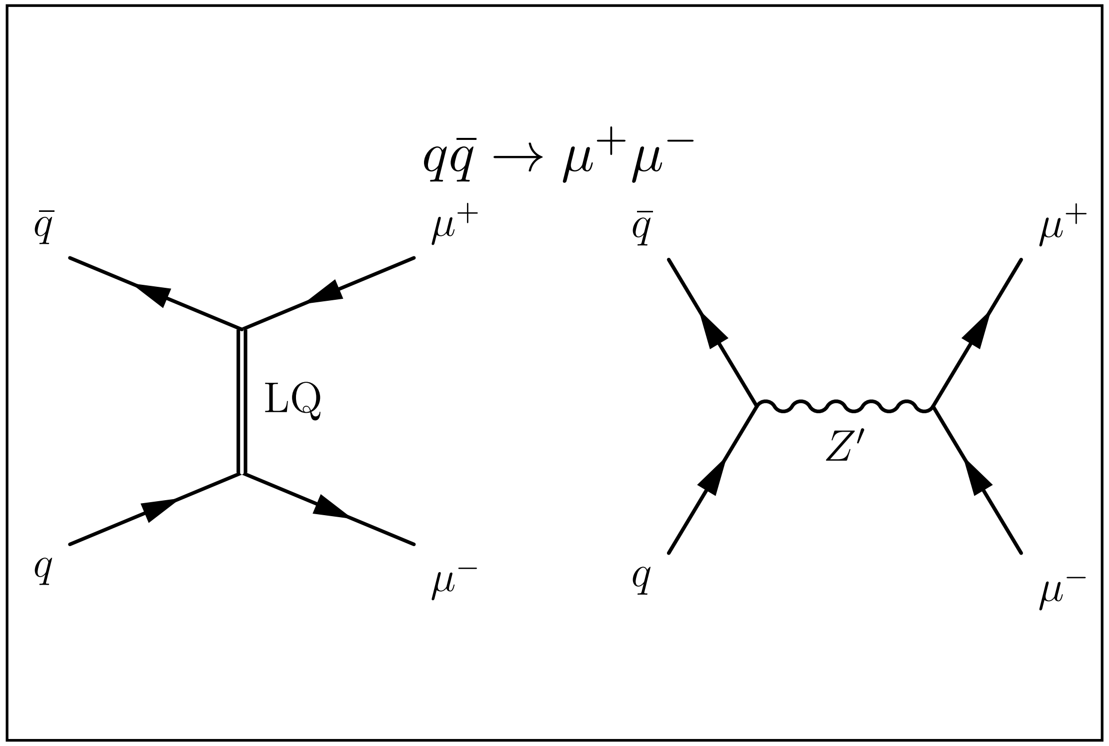


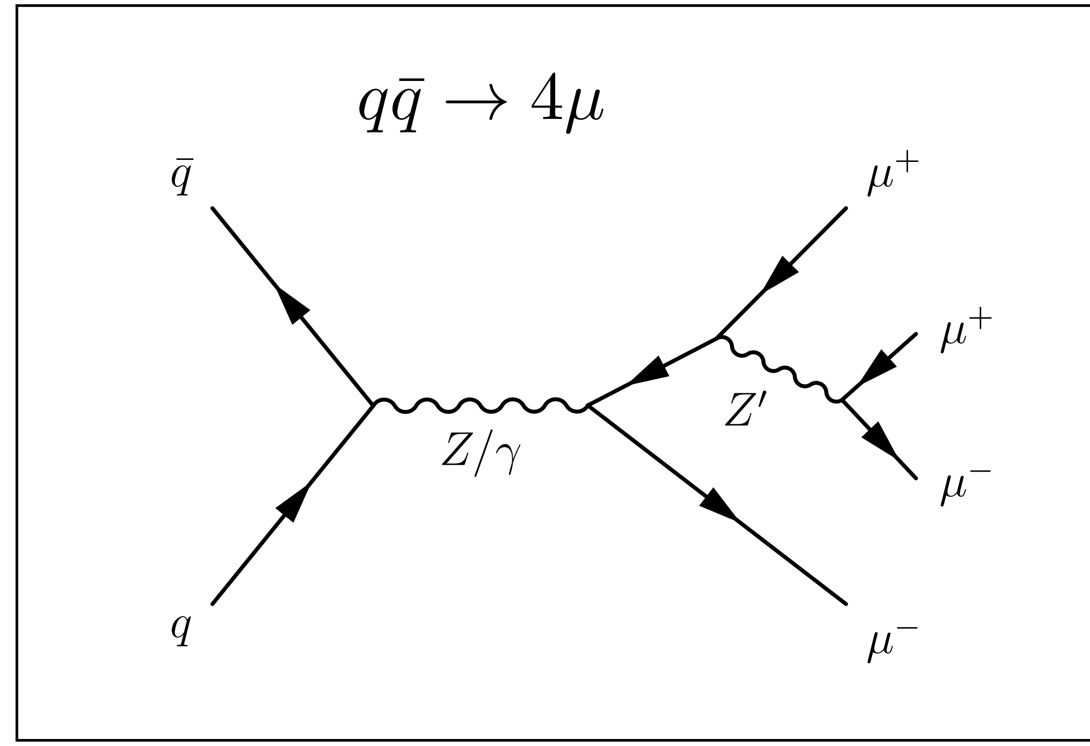
- Monotonously decreasing luminosities in proton colliders

$m_X > \sqrt{s_0}$

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

The signatures at hadron colliders

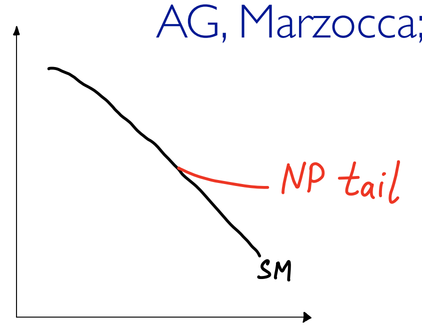


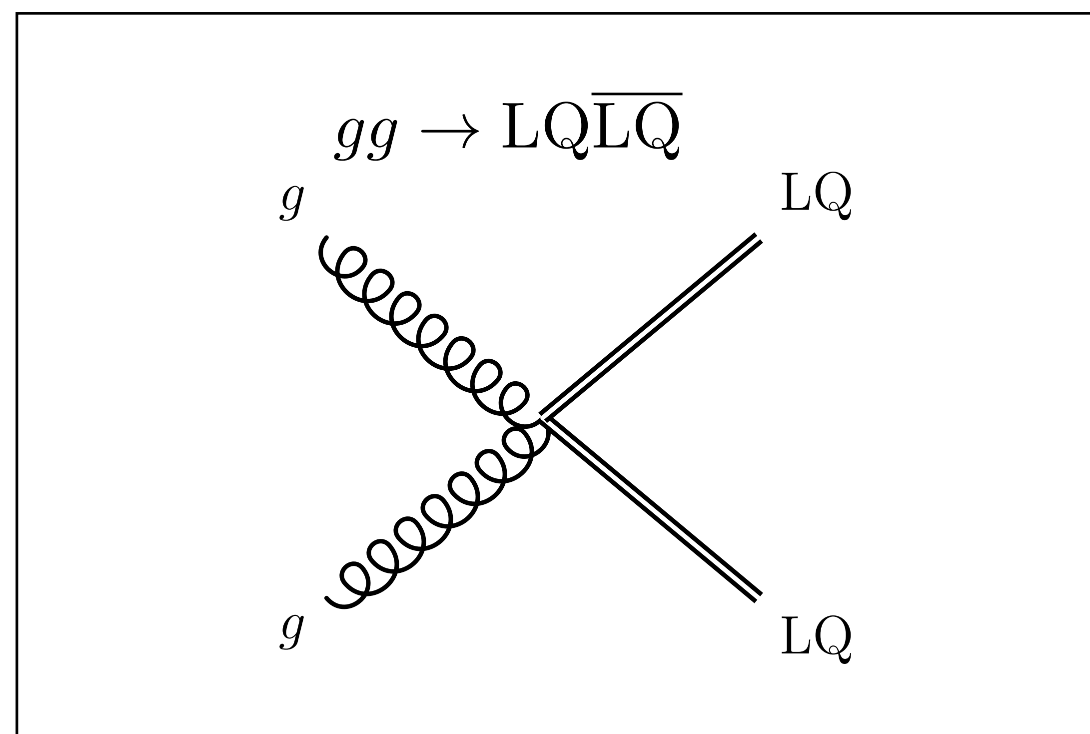


- Corrections to the high-mass Drell-Yan
- LHC data already useful to constrain models for $b \to s\mu\mu$

AG, Marzocca; 1704.09015

EFT limit





Results

Contact interactions

The pessimistic case

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

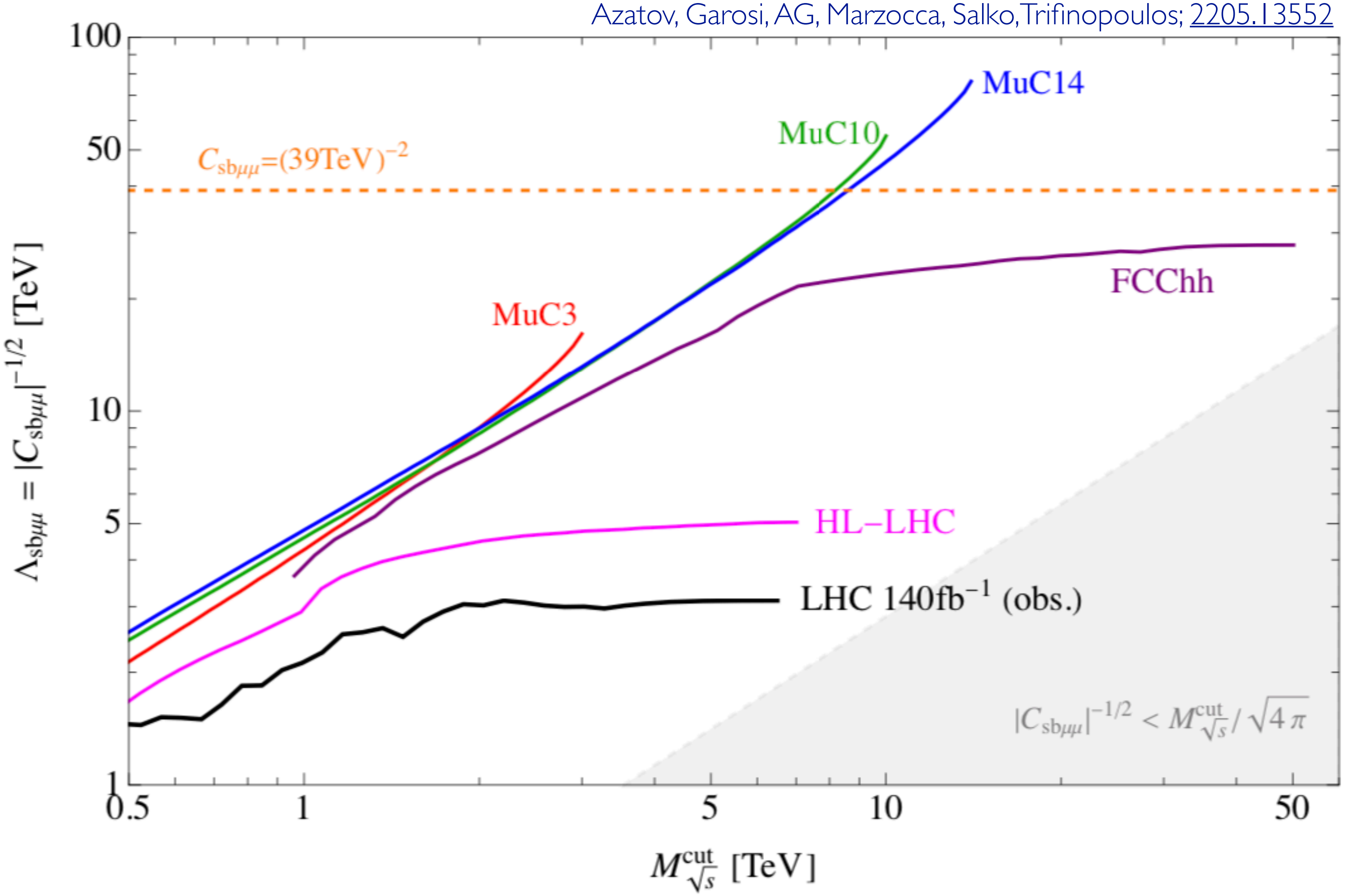


Figure 7. Sensitivity reach (95%CL) for the $(\bar{s}_L\gamma_\alpha b_L)(\bar{\mu}_L\gamma^\alpha\mu_L)$ contact interaction as function of the upper cut on the final-state invariant mass, compared to the value required to fit $bs\mu\mu$ anomalies (dashed orange line).

Contact interactions

The realistic case ★

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

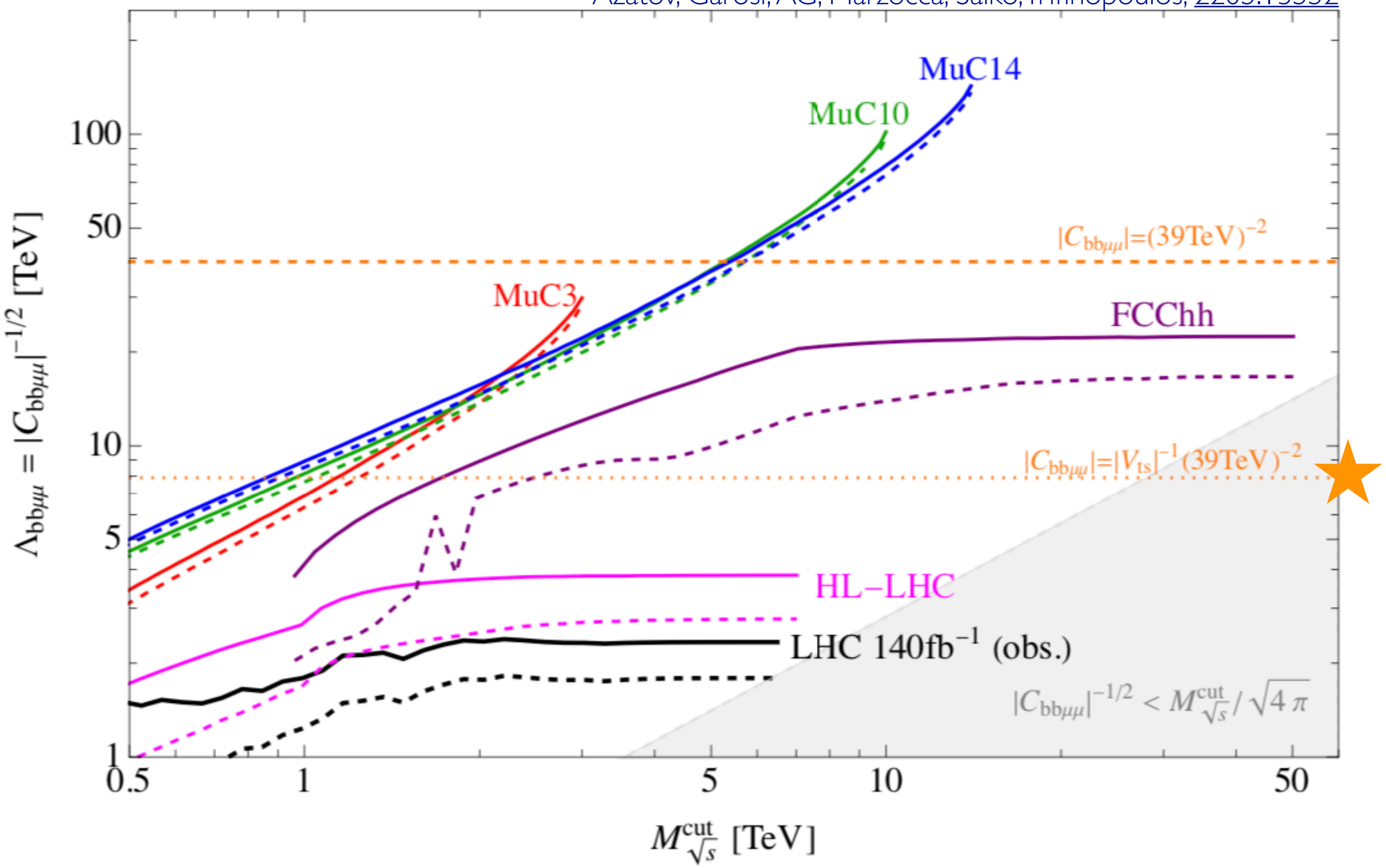


Figure 8. Sensitivity reach (95%CL) for the $(\bar{b}_L\gamma_\alpha b_L)(\bar{\mu}_L\gamma^\alpha\mu_L)$ contact interaction as function of the upper cut on the final-state invariant mass. Solid (dashed) lines represent the limit for positive (negative) values of $C_{bb\mu\mu}$. The orange dotted and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

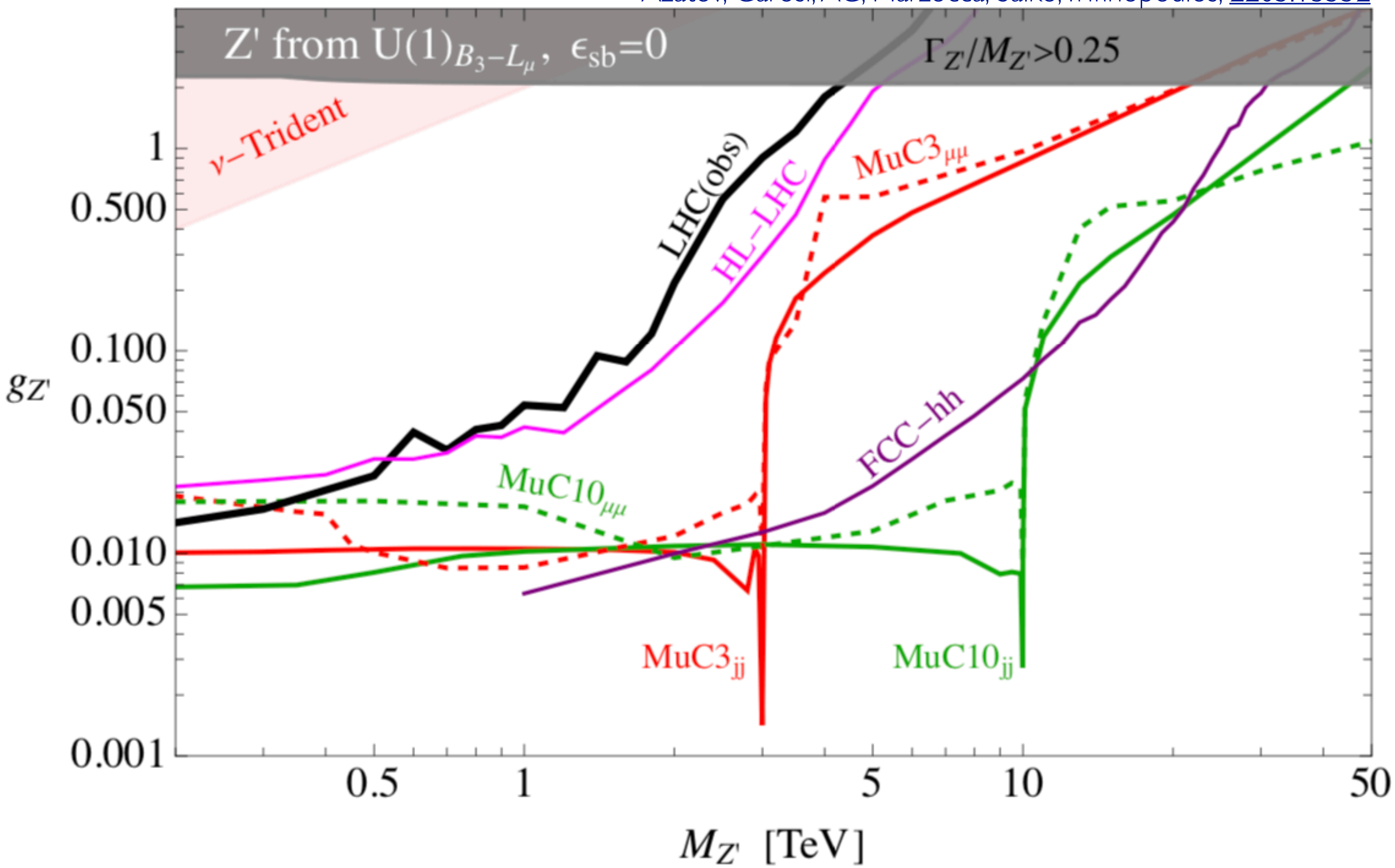
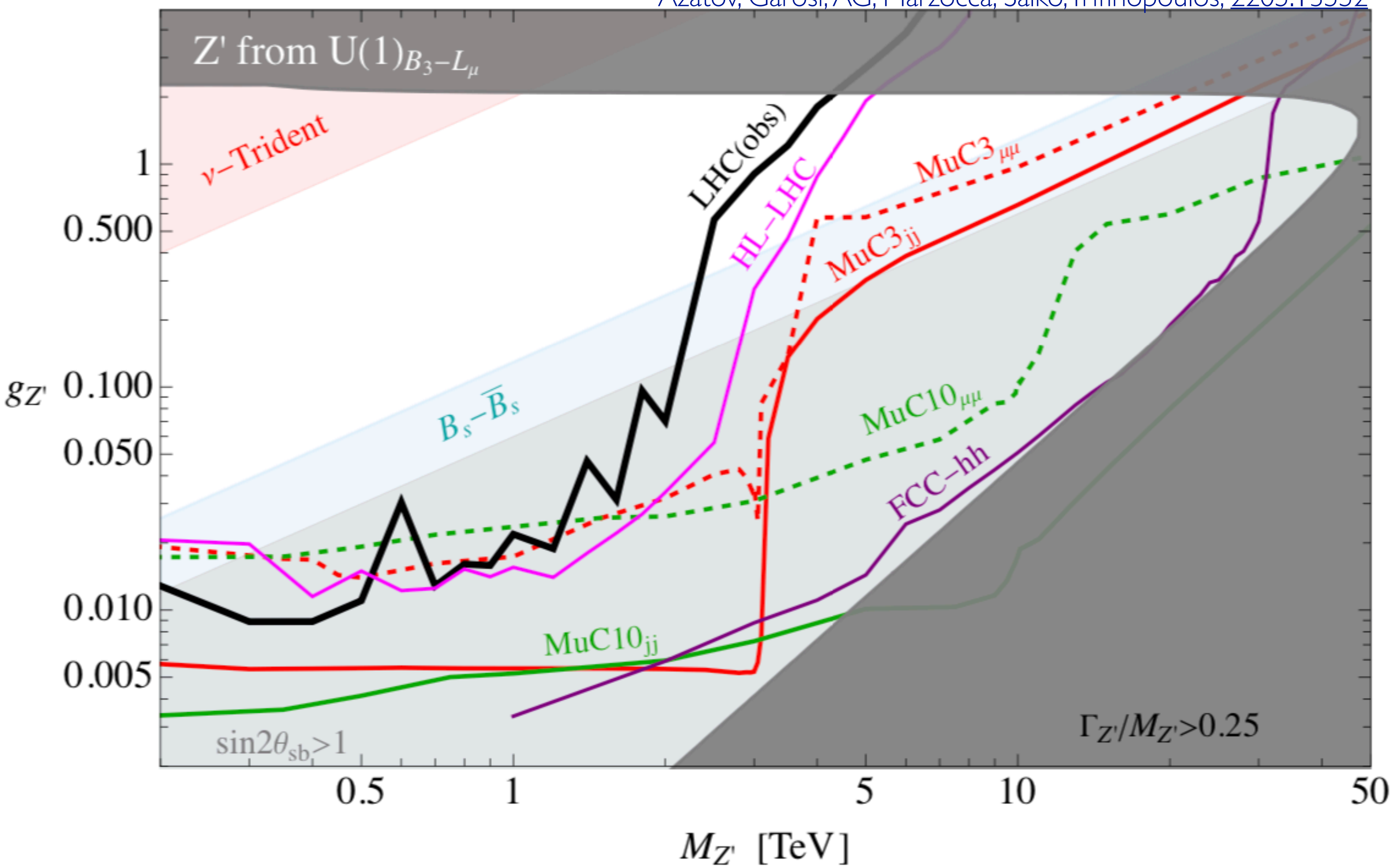


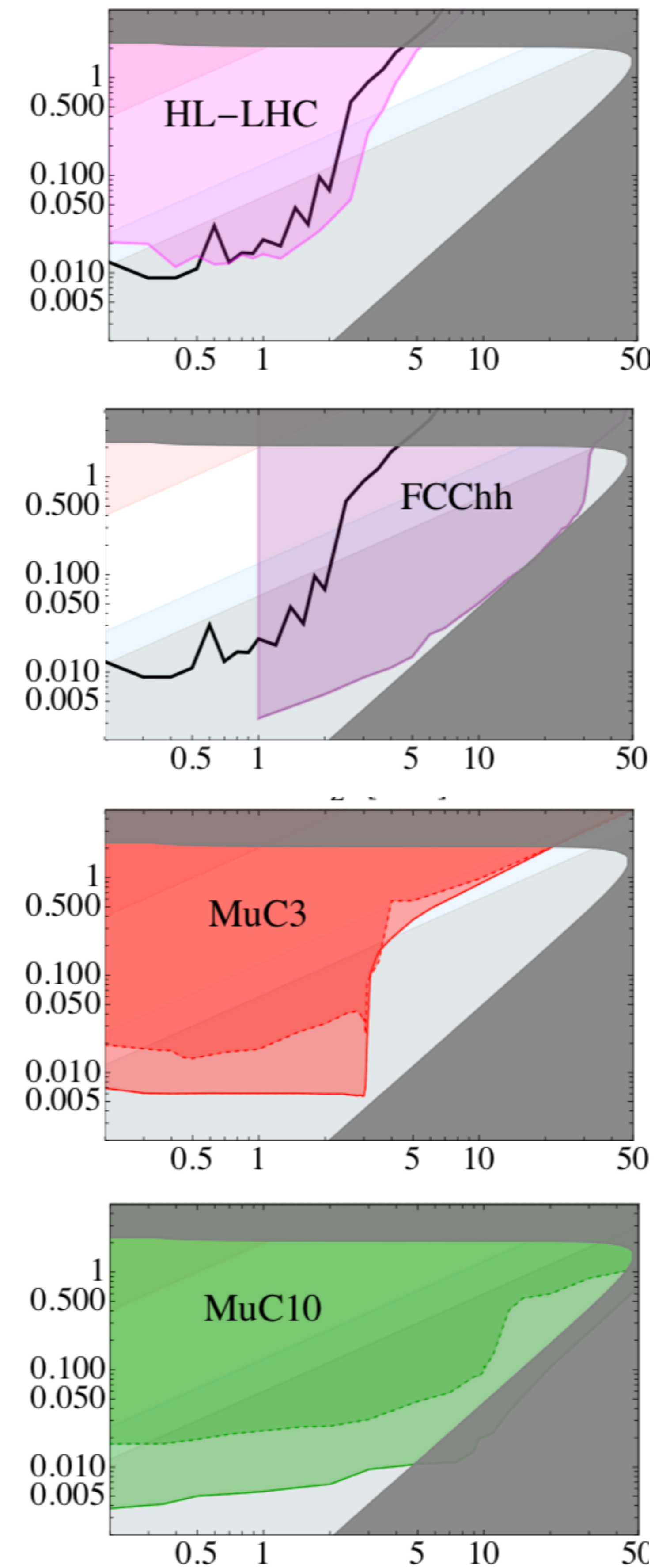
Figure 9. Discovery reach at 5σ for the $B_3 - L_\mu$ model with $\epsilon_{sb} = 0$, for different final states at each collider (as indicated by the labels). The region excluded at 95% CL by LHC [111] is above the black line while in the dark gray region the Z' has a large width, signaling a loss of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

Z' models: $B_3 - L_\mu$

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

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

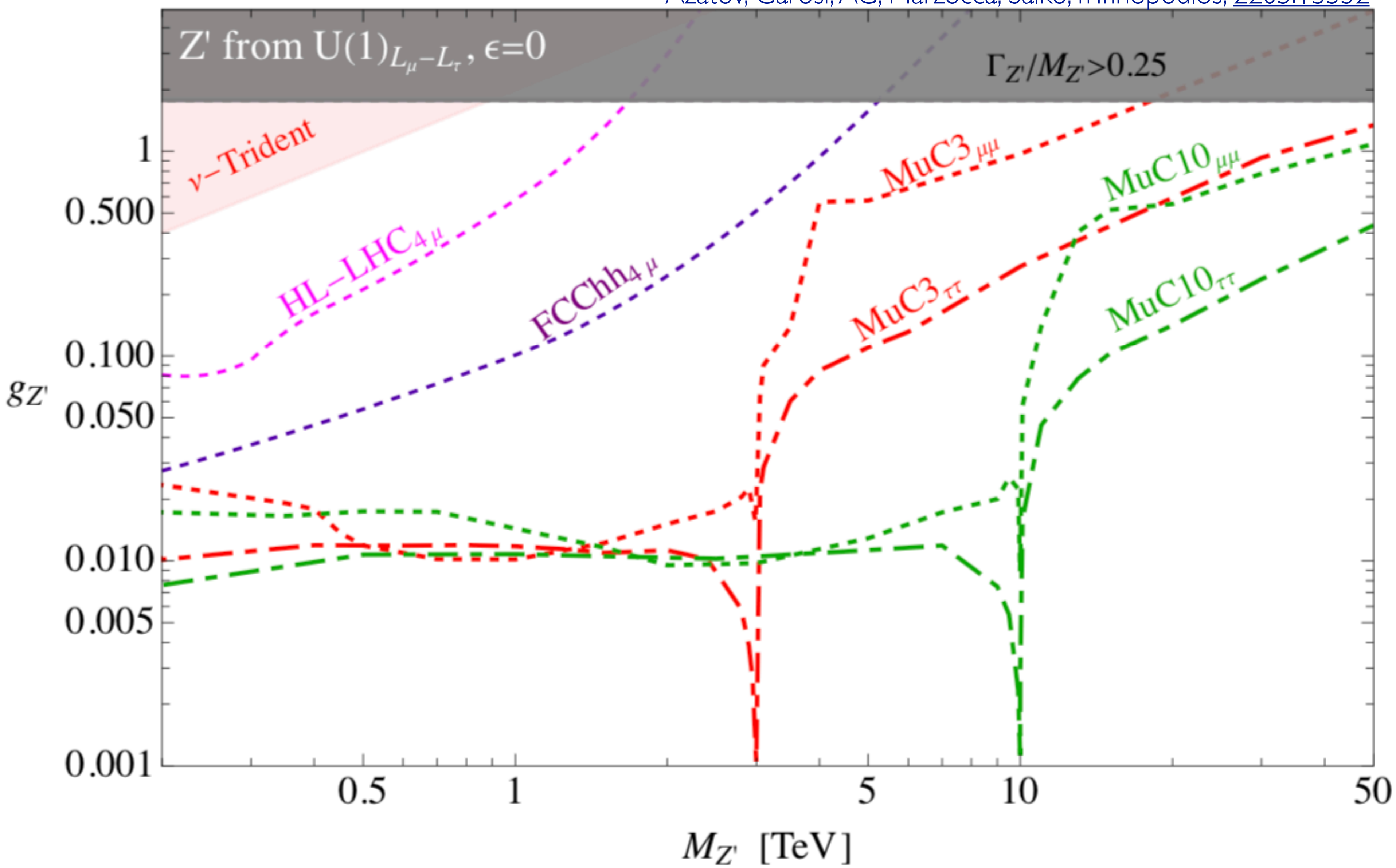


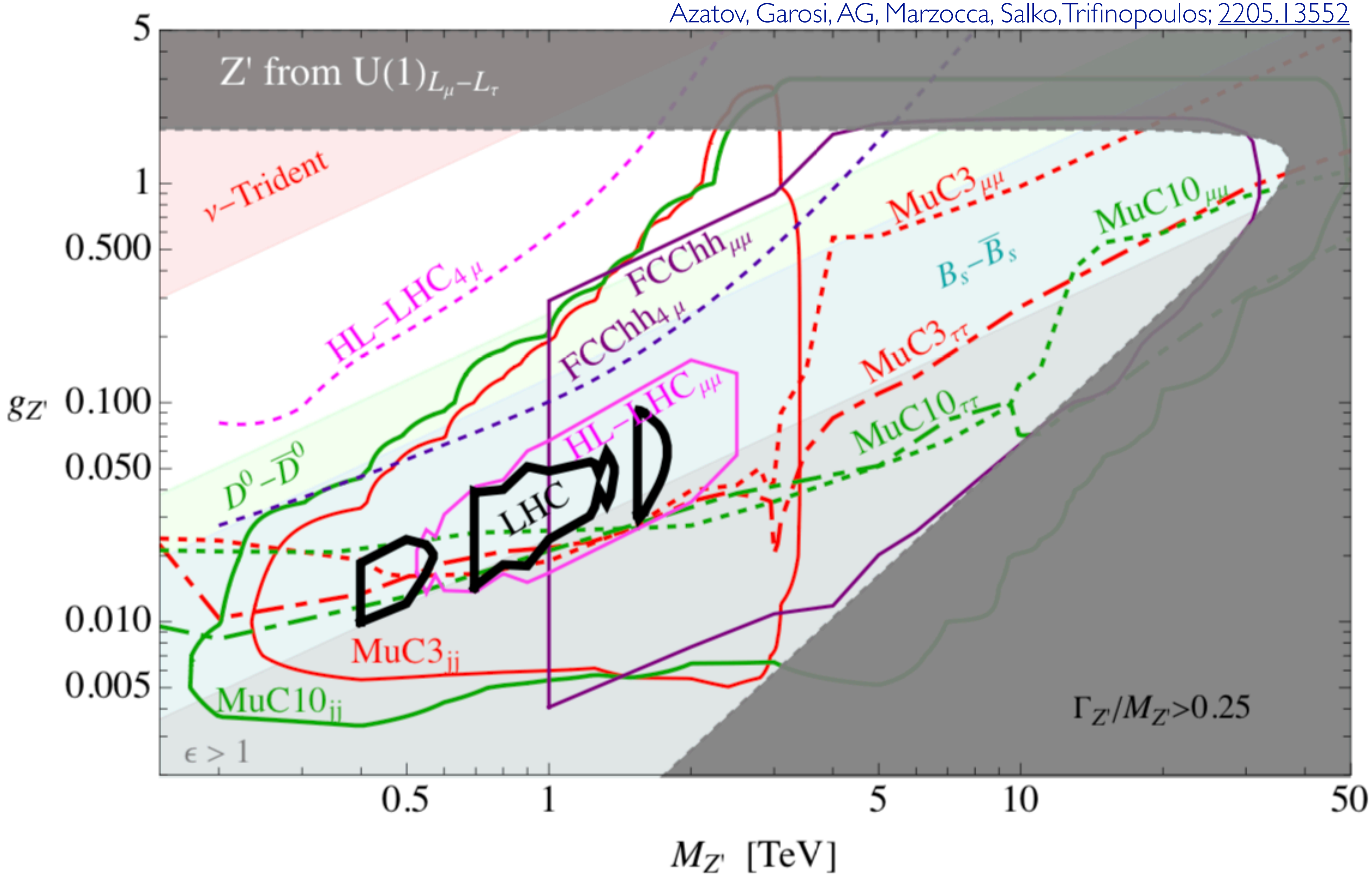
Figure 11. Discovery reach at 5σ for the $L_\mu - L_\tau$ model with $\epsilon_s = \epsilon_b = 0$ in Eq. (5.6). In the dark gray region the Z' has a large width, signaling a loss of perturbativity.

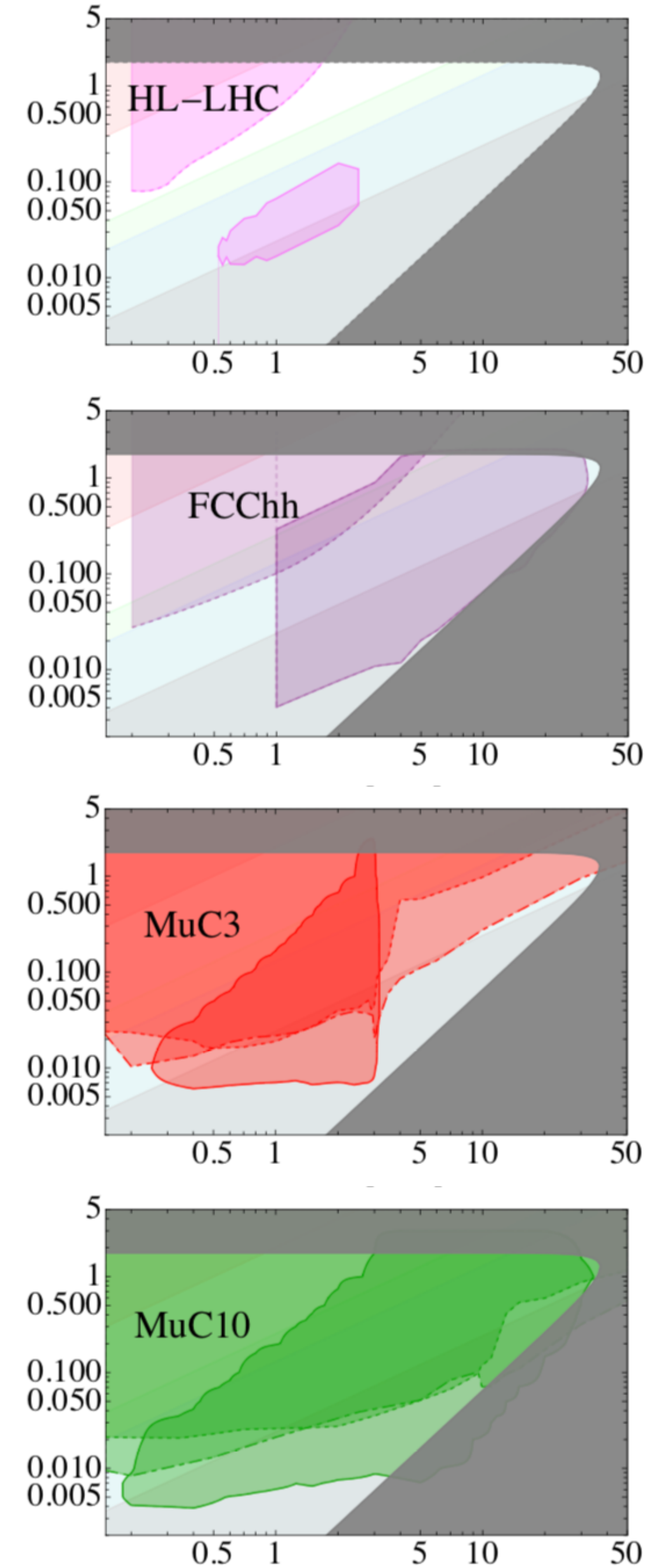
Z' models: $L_\mu - L_\tau$

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

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

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





Scalar Leptoquark

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

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

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

The only coupling → $\lambda_{b\mu}$

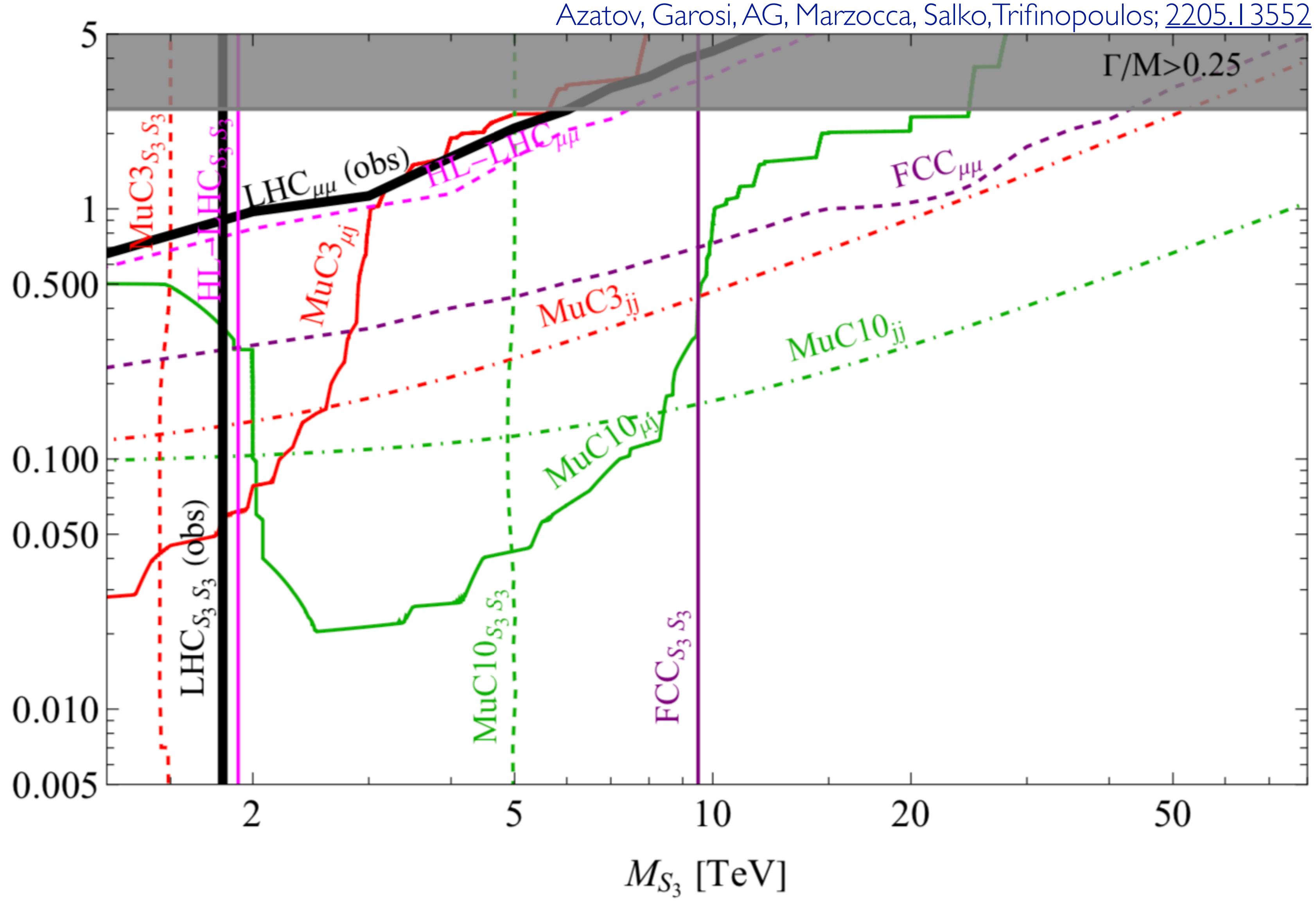
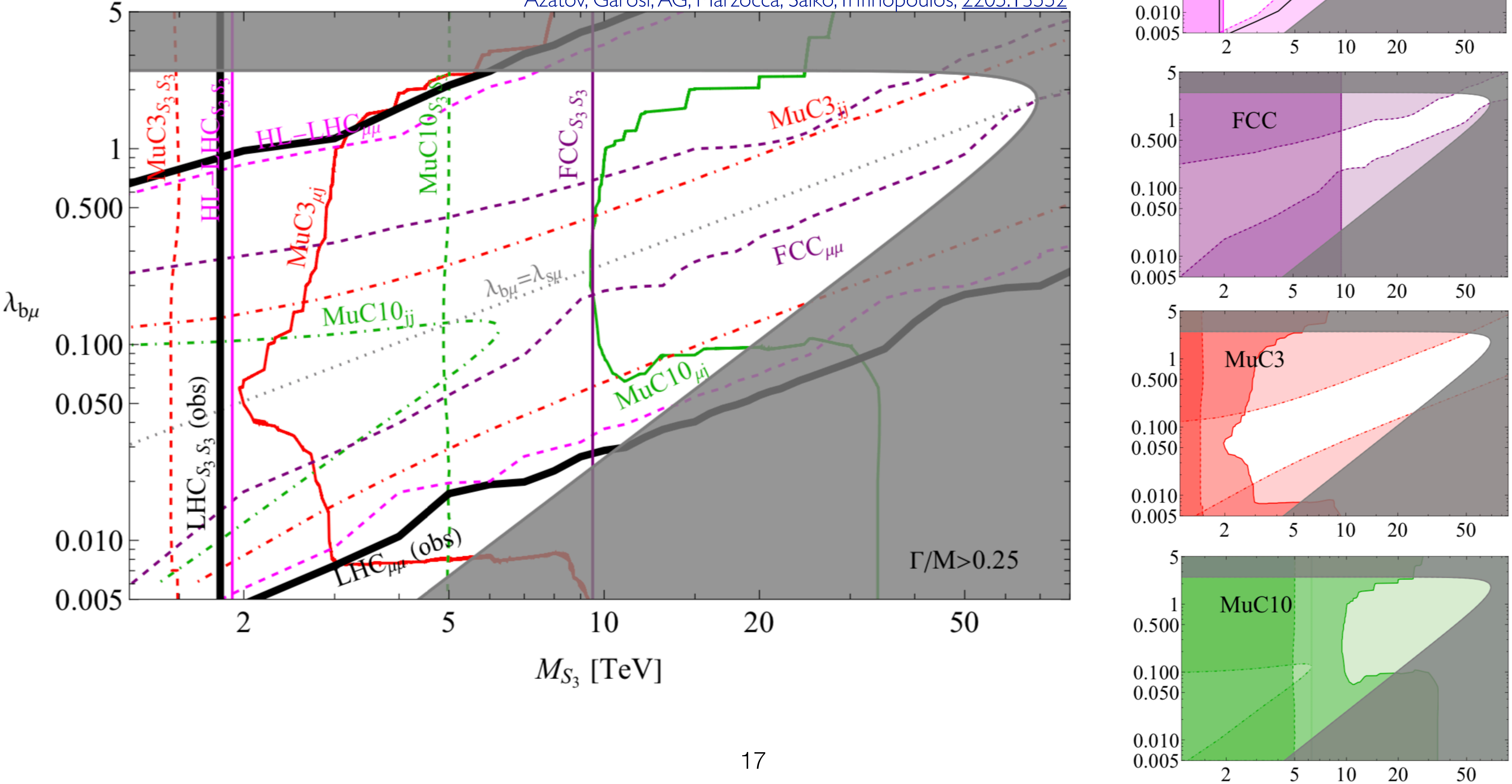


Figure 13. The 5σ discovery prospects at future colliders for the S_3 leptoquark assuming the $U(2)^3$ quark flavour symmetry and the exclusive leptoquark coupling to muons (see Section 6.1).

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



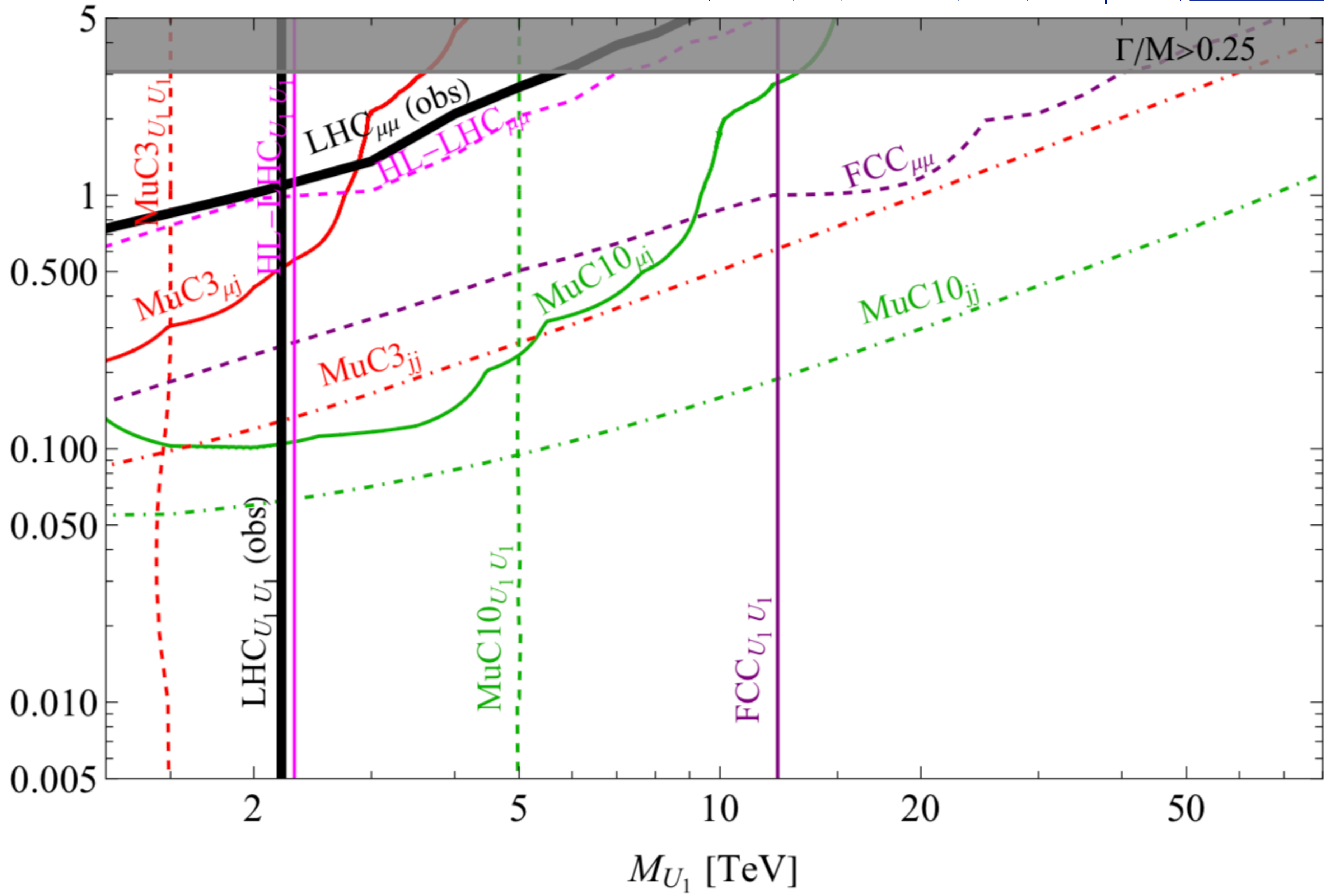
Vector Leptoquark

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

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

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

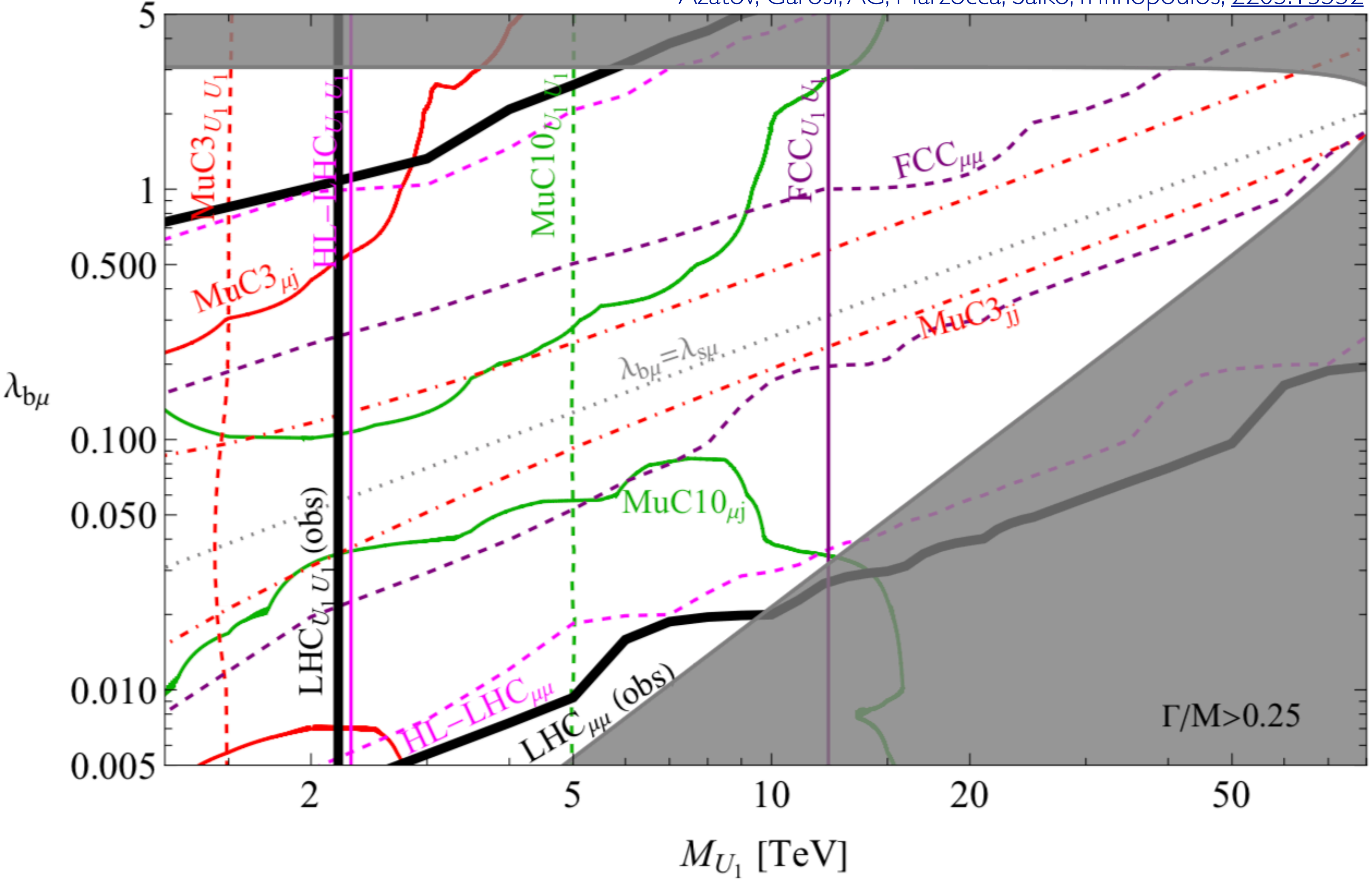
The only coupling → $\lambda_{b\mu}$

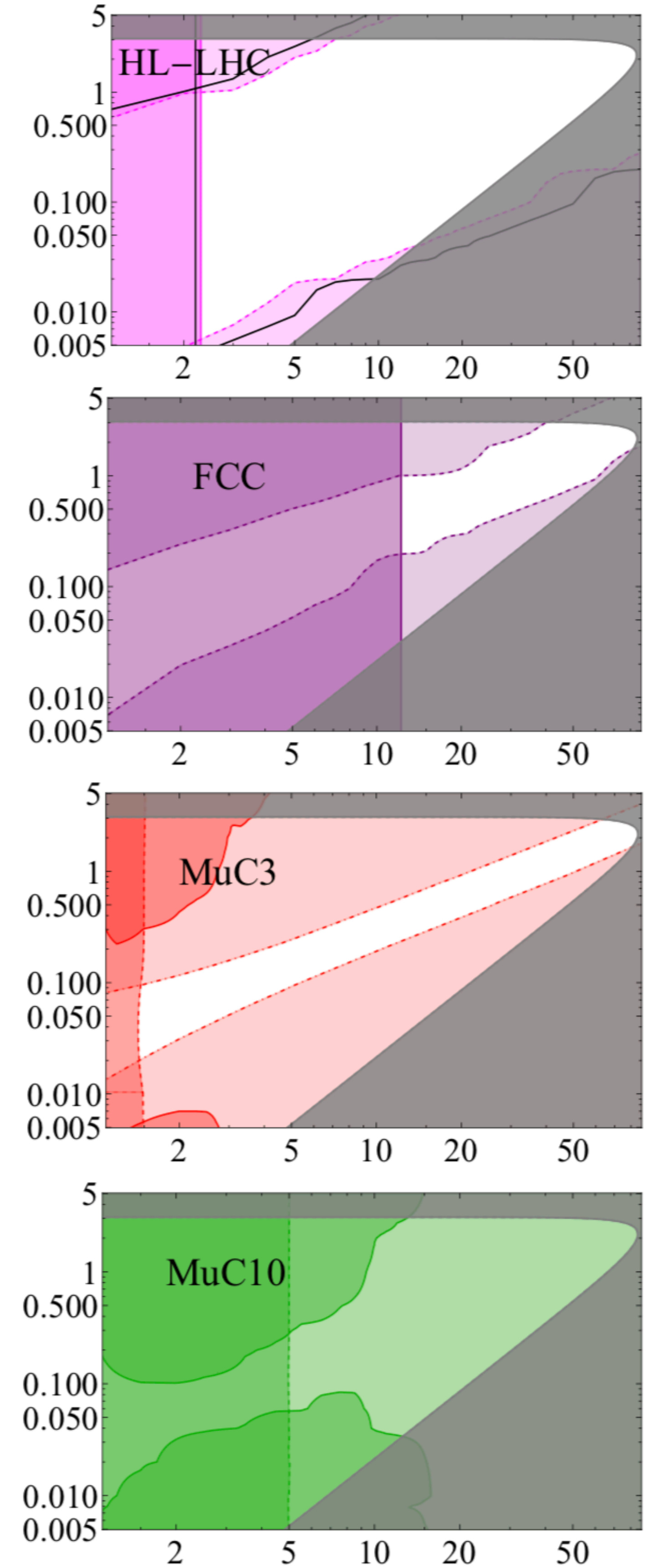


Vector Leptoquark

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

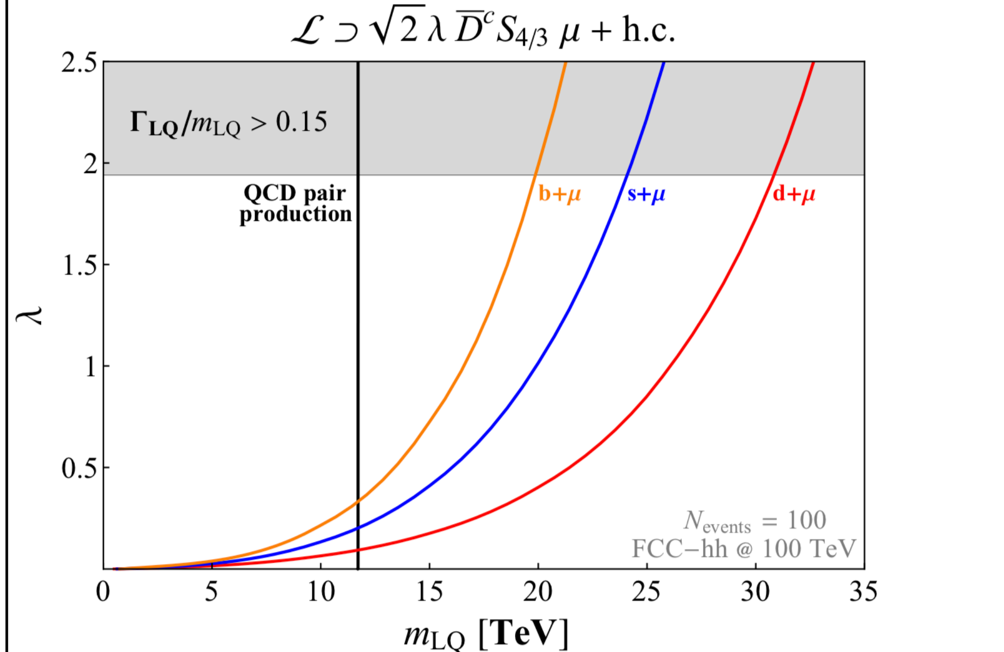
Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; 2205.13552





Backup

Resonant Leptoquark at FCC-hh



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