Muonic Force Behind Flavor Anomalies

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based on, Greljo, Soreq, Stangl, Thomsen, JZ, 2107.07518

TAU2021, Bloomington, IN (virtual), Sept 28 2021

EXPERIMENTAL ANOMALIES IN PROCESSES WITH MUONS&TAUS

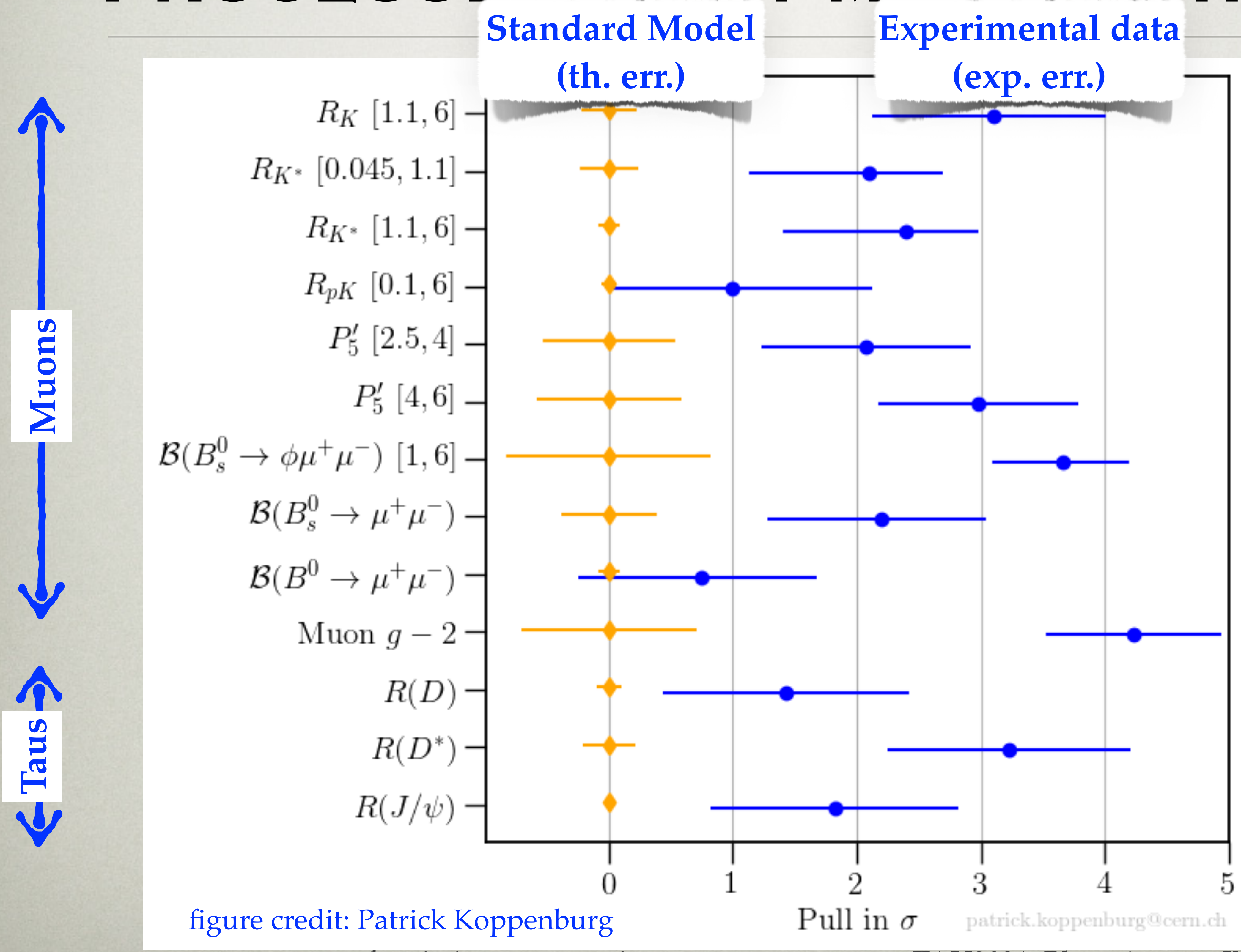


figure credit: Patrick Koppenburg

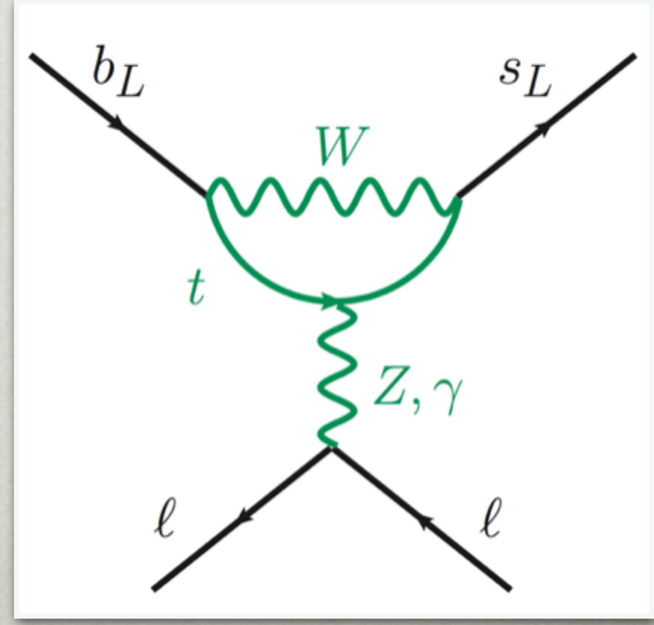
IF NEW PHYSICS...

- $b \to s\mu\mu$ quark level transitions shows $\gtrsim 4\sigma$ deviations from the SM
  - explanable with NP in $V - A$ quark currents
  - relatively high effective NP scale

$$\mathcal{L}_{\rm SMEFT} \supset \frac{1}{\Lambda^2_{Q_{ij}L_{kl}}} \left(\overline{Q}_i \gamma^\mu \sigma^A Q_j\right) \left(\overline{L}_k \gamma_\mu \sigma^A L_l\right)$$

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

$$\Lambda_{\rm NP} \sim 40\,\text{TeV}$$



IF NEW PHYSICS...

- $(g-2)_\mu$ showing 4.2σ deviation from the SM
  - in SMEFT from dim6 operator

$$\mathcal{L} \supset -\frac{\sqrt{2} e\, v}{(4\pi\Lambda_{ij})^2}\, \bar{\ell}^i_{\rm L} \sigma^{\mu\nu} \ell^j_{\rm R} F_{\mu\nu} + {\rm h.c.}\ ,$$

$$(g-2)_\mu \Rightarrow \Lambda_{22} \sim 15\,\text{TeV}$$

Greljo, Stangl, Thomsen, 2103.13991

- note: any flavor violation needs to be highly suppressed $\mu \to e\gamma \Rightarrow \Lambda_{21} \gtrsim 3500\,\text{TeV}$
- a possible (natural) solution - a symmetry

OUTLINE

- gauged $U(1)_X$ and $(g-2)_\mu$+$R_{K^{(*)}}$
  - a single vector mediator? ⇒ no
- heavy (~TeV) leptoquarks for $R_{K^{(*)}}$, light vectors (~100MeV) for $(g-2)_\mu$
  - systematics of anomaly free $U(1)_X$
  - some benchmark models

SINGLE MEDIATOR?

Greljo, Soreq, Stangl, Thomsen, JZ, 2107.07518

- can a single mediator explain both $(g-2)_\mu$ and $b \to s\mu\mu$ anomalies?
  - each separately possible with neutral spin-1 boson X_μ
    - for $(g-2)_\mu$ required to be light, $m_X \lesssim \mathcal{O}(\text{few GeV})$
    - for $b \to s\mu\mu$ can be light ~GeV or very heavy ~10s TeV
- however, not possible to explain both at the same time
  - $\Rightarrow$ combined explanation requires at least two new states

SINGLE MEDIATOR?

Greljo, Soreq, Stangl, Thomsen, JZ, 2107.07518

- can a single mediator explain both $(g-2)_\mu$ and $b \to s\mu\mu$ anomalies?
- the relevant effective interactions

$$\mathcal{L}_{\text{eff}} \supset + g_X \, (q_V + q_A) \, \overline{\nu_{\mu L}} \, \not{X} \, \nu_{\mu L} + g_X \, \bar{\mu} \, \not{X} \, (q_V - q_A \, \gamma_5) \, \mu + \left[\bar{b} \, \not{X} \, (g_L^{bs} \, P_L + g_R^{bs} \, P_R) \, s \; + \; \text{H.c.} \right] ,$$

- for $(g-2)_\mu$ need $g_V \gg g_A$

$$g_X = \left(\frac{\Delta a_\mu}{251 \times 10^{-11}} \right)^{1/2} \begin{cases} 4.5 \times 10^{-4} \big[q_V^2 - 2 \, q_A^2 \, r_\mu^2 \big]^{-1/2}, & m_X \ll m_\mu, \\ 5.5 \times 10^{-4} r_\mu^{-1/2} \big[q_V^2 - 5 \, q_A^2 \big]^{-1/2}, & m_X \gg m_\mu. \end{cases}$$

- $\Rightarrow X_\mu$ necessarily couples to neutrinos*

* as long as EFT applies, i.e. dim 6 ops not cancelled by dim 8, see e.g., Darme et al, 2106.12582

SINGLE MEDIATOR?

Greljo, Soreq, Stangl, Thomsen, JZ, 2107.07518

- because of X_μ couplings to neutrinos competing requirements
  - $B \to K\nu\nu$ bound implies small g_L^{bs}
  - neutrino trident bound implies small $g_X(q_V + q_A)$
  - $B \to K\mu\mu$ requires large enough $g_L^{bs} g_X q_{V,A}$
  - $(g-2)_\mu$ requires large enough $g_X q_V$

SINGLE MEDIATOR?

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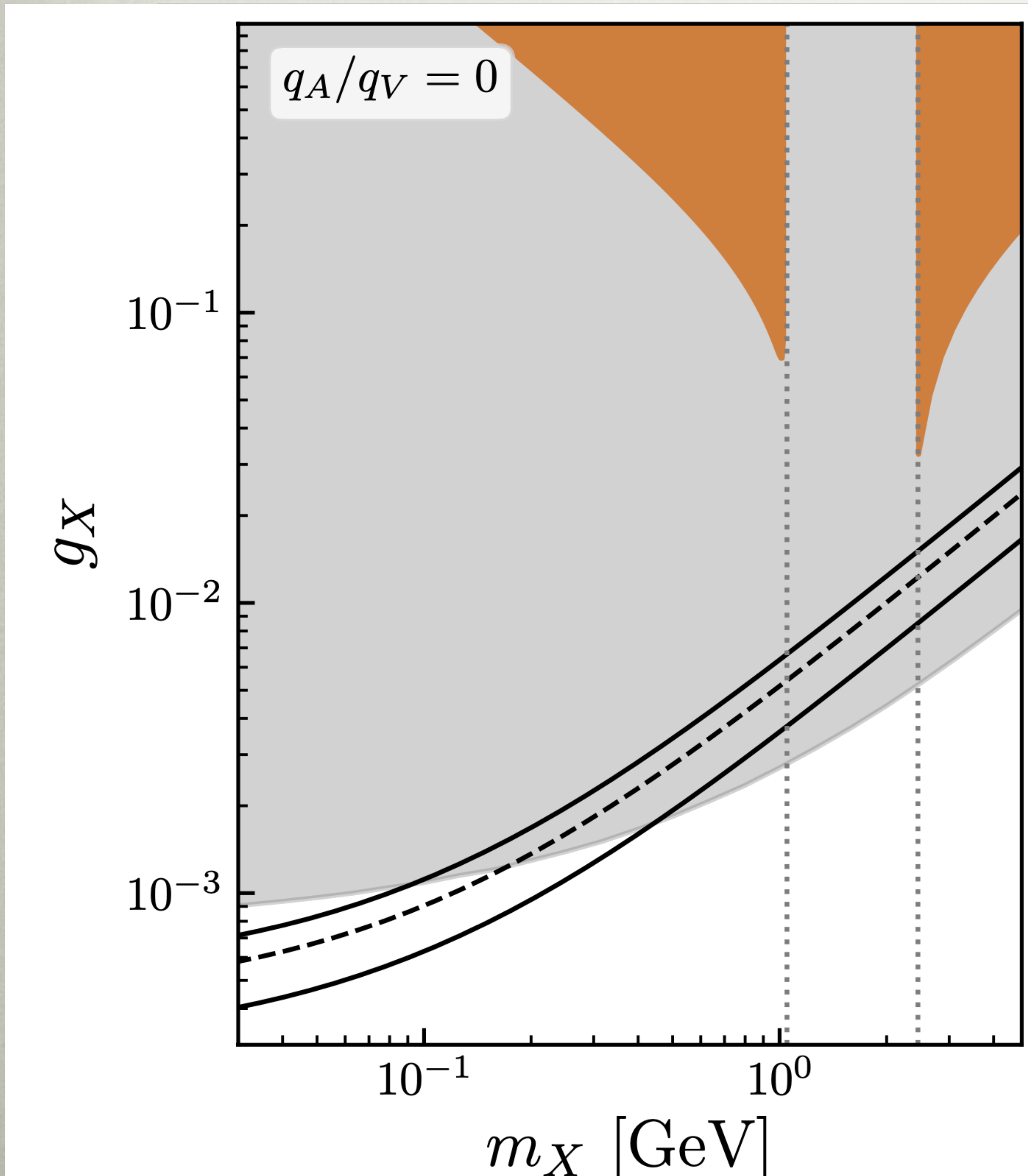

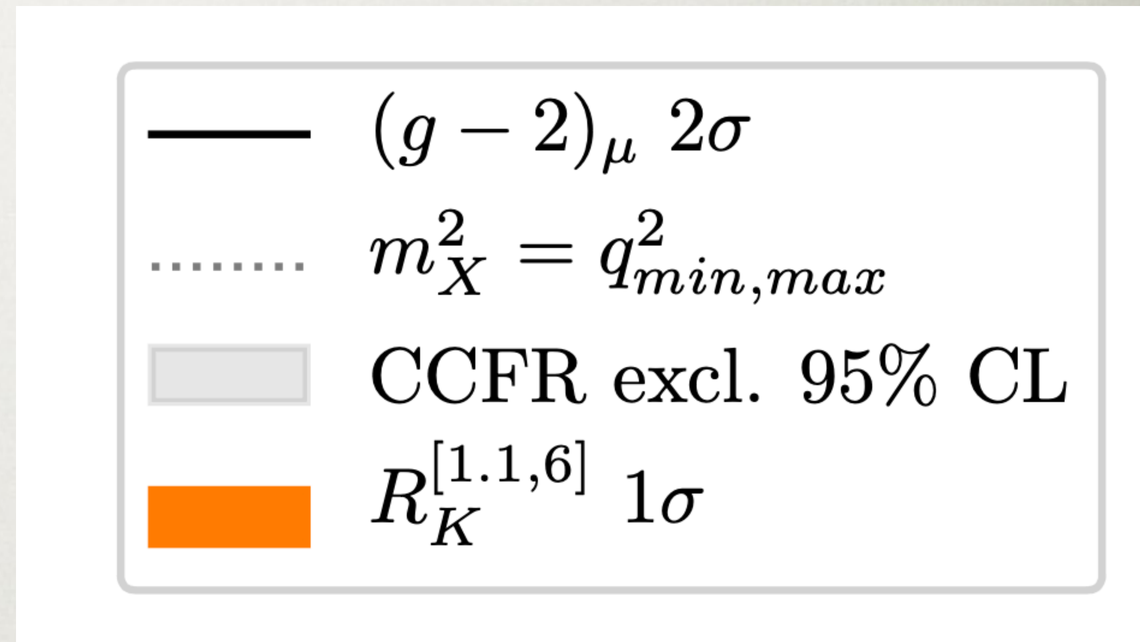

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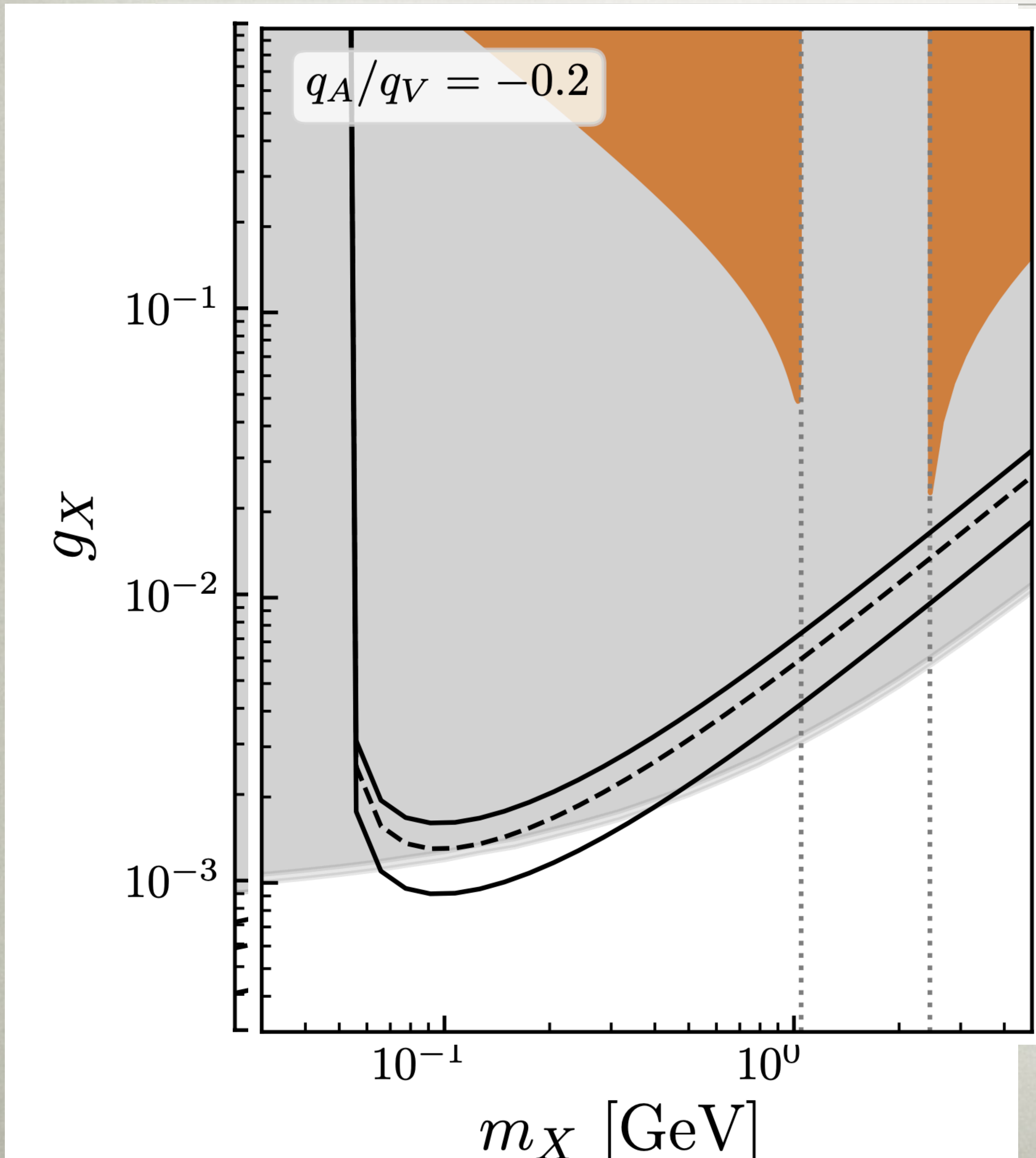
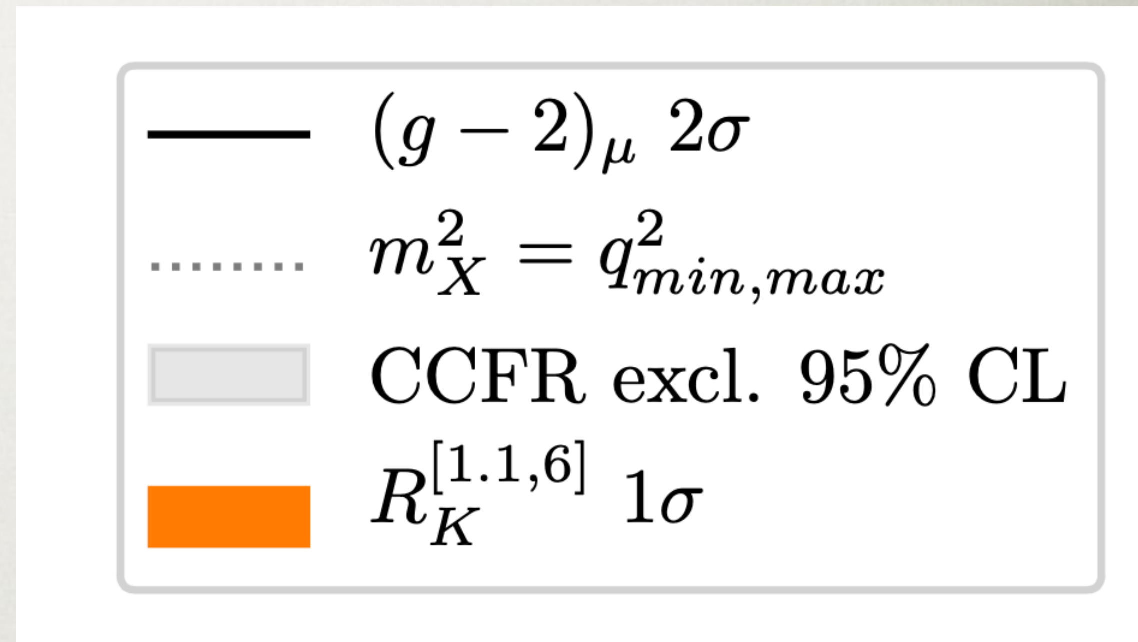


Greljo, Soreq, Stangl, Thomsen, JZ, 2107.07518



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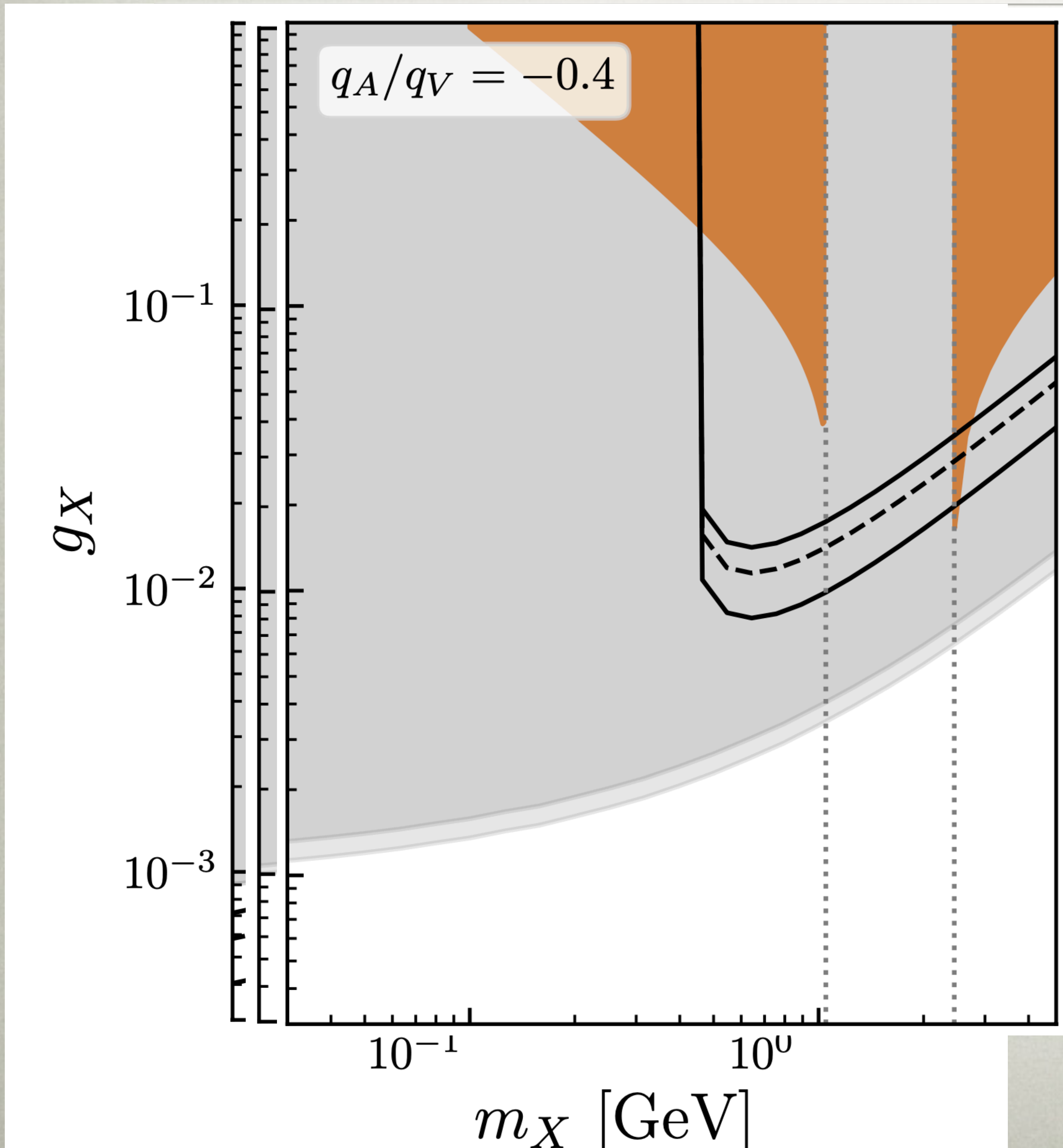
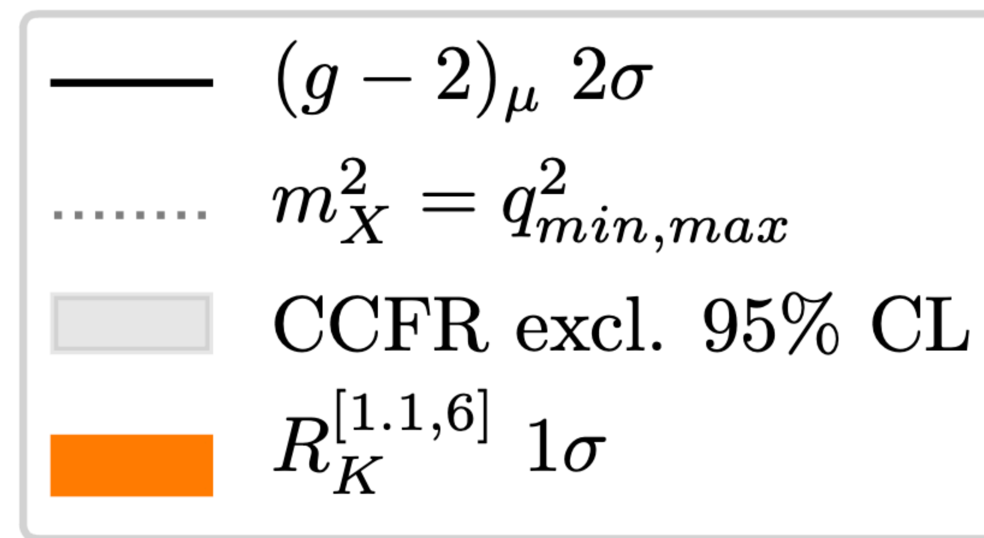


Greljo, Soreq, Stangl, Thomsen, JZ, 2107.07518



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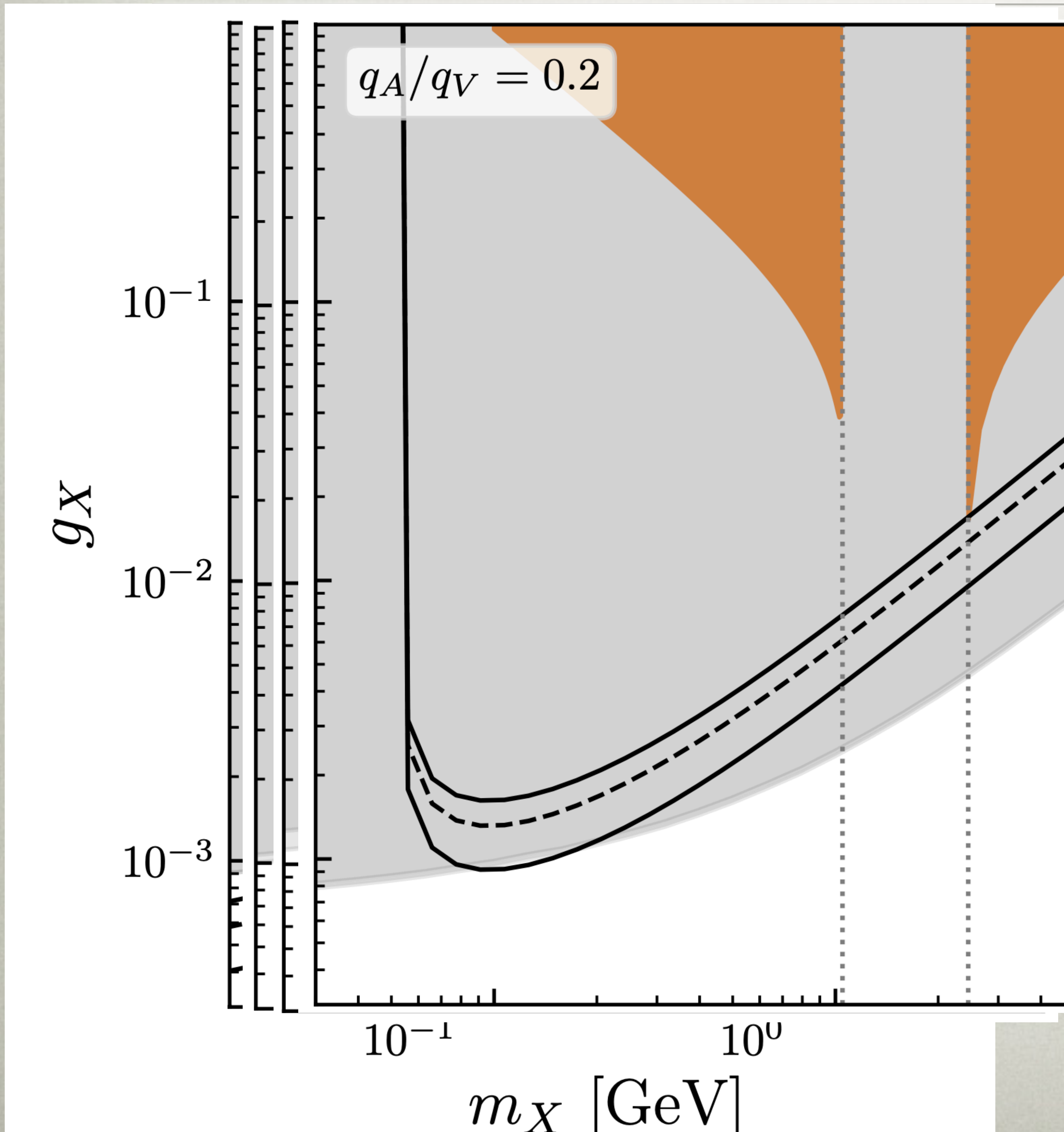

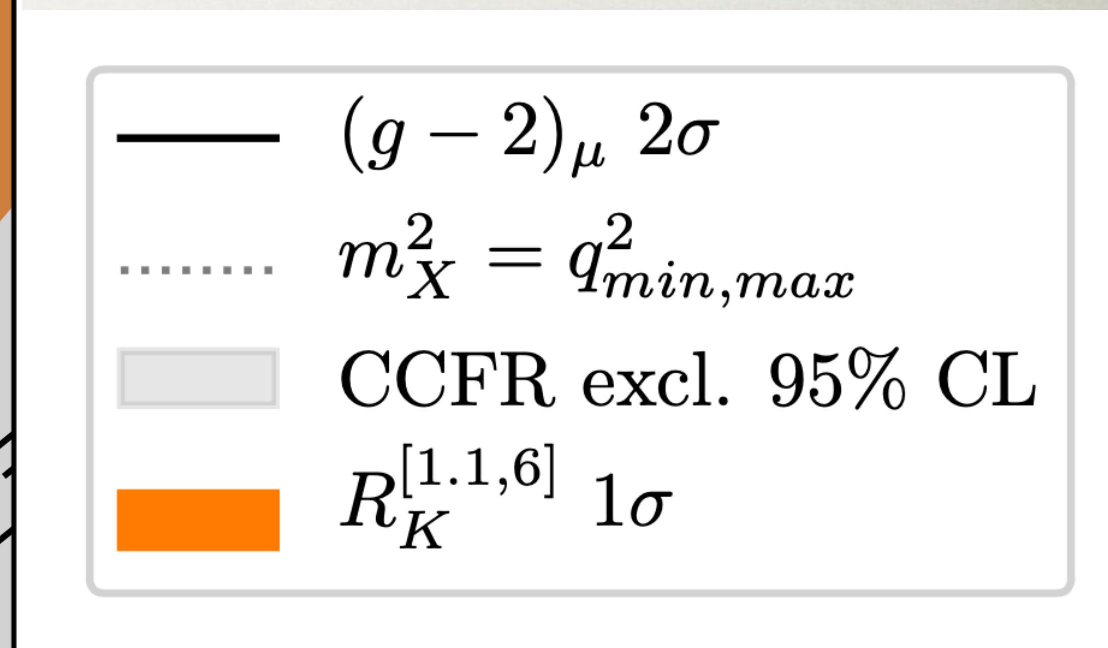

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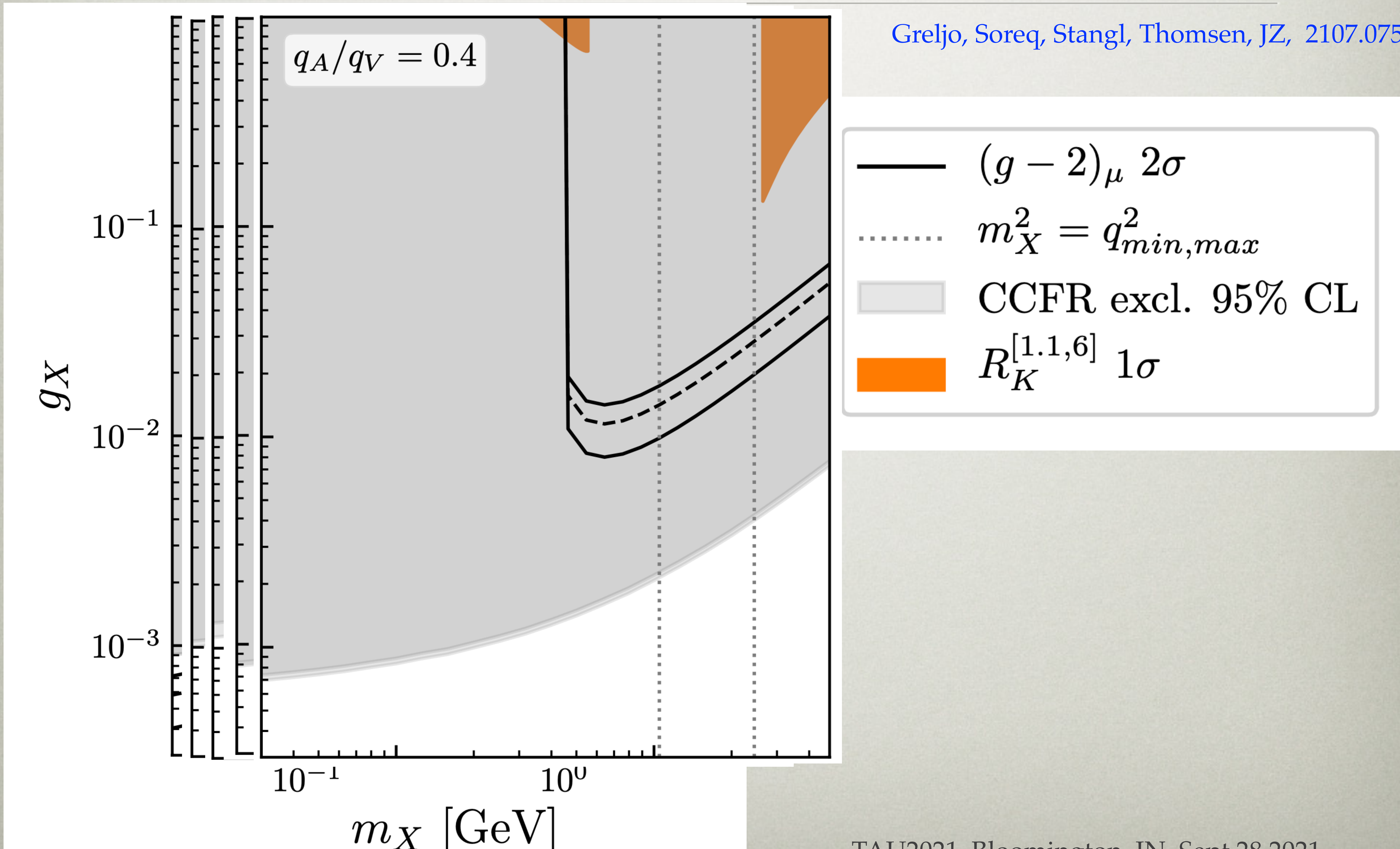

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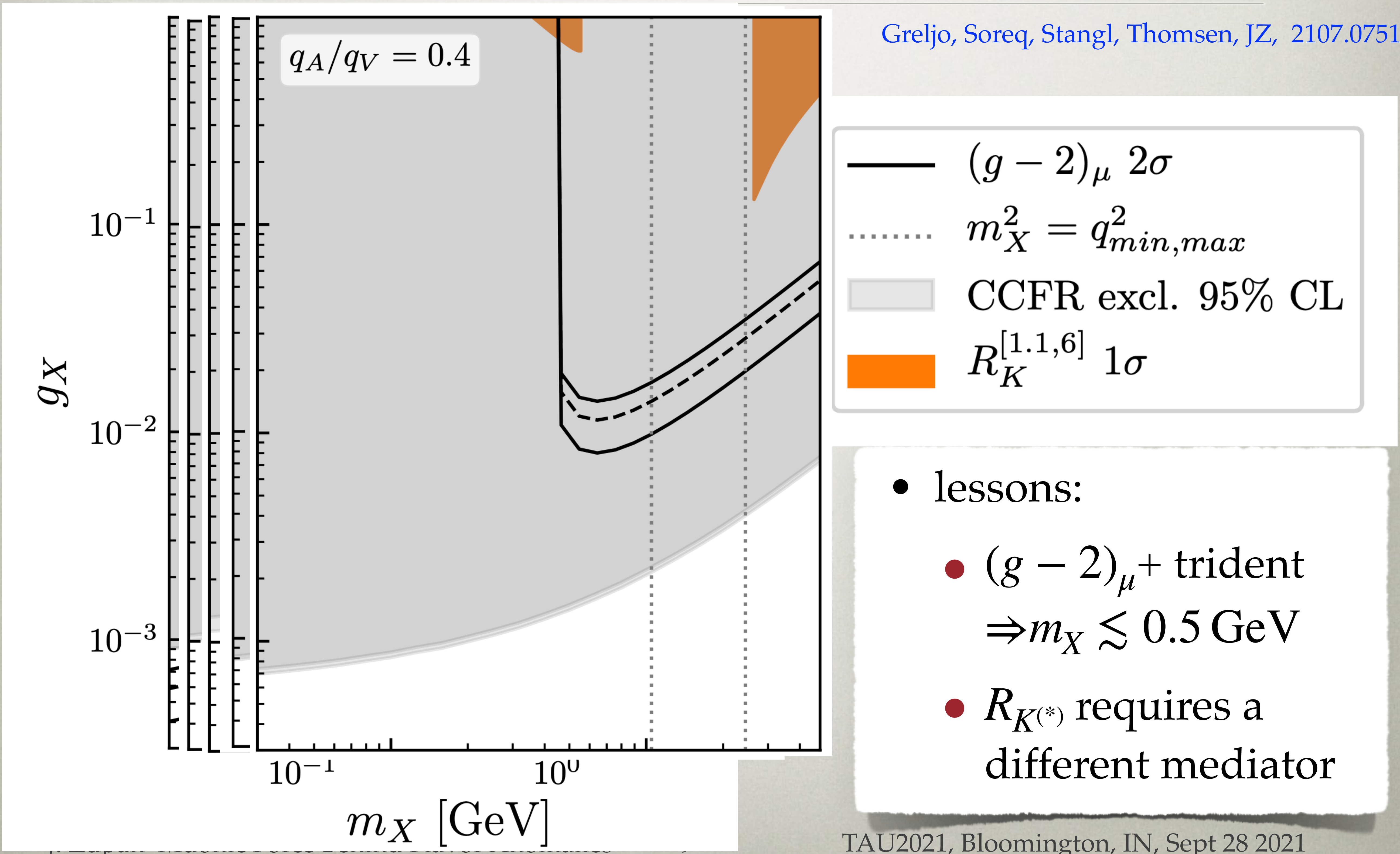


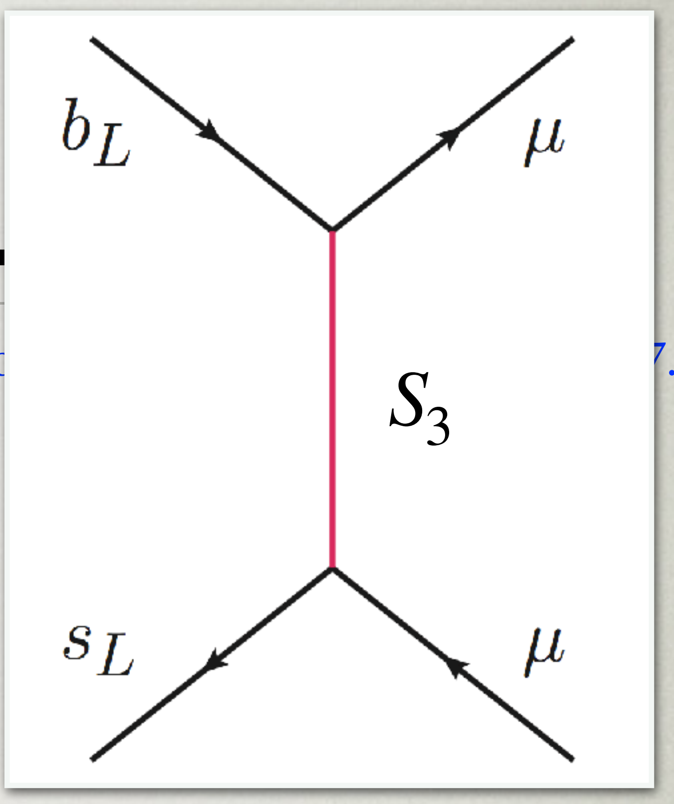
- lessons:
  - $(g-2)_\mu$+ trident $\Rightarrow m_X \lesssim 0.5$ GeV
  - $R_{K^{(*)}}$ requires a different mediator

$(g-2)_\mu$, $b \to s\mu\mu$ FROM $U(1)_X$ AND LQ

Greljo, Soreq, Stangl, Thomsen, JZ, 2107.07518

- $R_{K^{(*)}}$ from tree-level LQ exchange
  - for instance from $S_3 = (\bar{3}, 3, 1/3)_{8/3}$
- $(g-2)_\mu$ from $U(1)_X$ gauge boson
- the $U(1)_X$ solves the problem of potentially too large FCNCs
  - gauge charges such that S_3 only couples to muons, not $\tau, e \Rightarrow$ LQ is a "*muoquark*"
  - universal charges for quarks
  - gauge charges such that forbid (too fast) proton decay
    - no dim5 ops. mediating proton decay

$(g-2)_\mu$, $b \to s\mu\mu$ FROM $U(1)_X$ AND L



Greljo, Sc ... .07518

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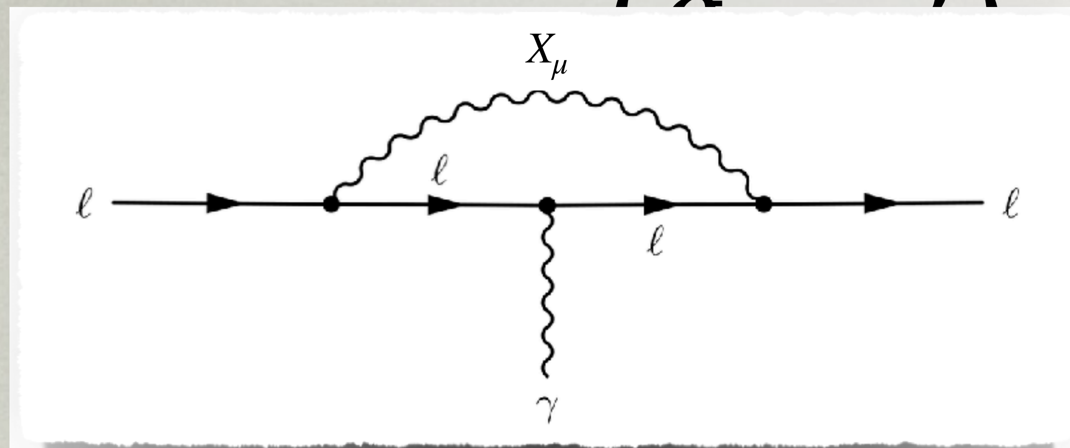
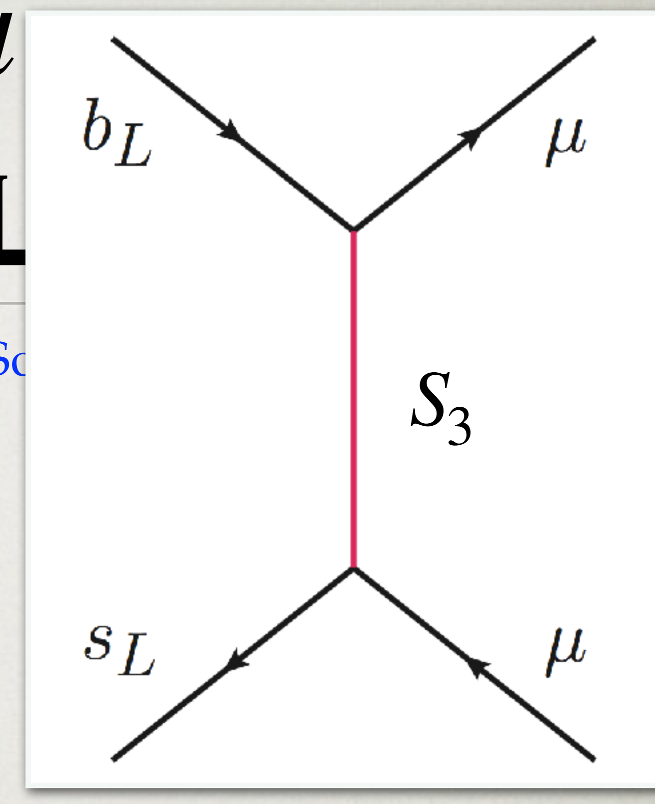
$(g-2)_\mu$, $b \to s\mu\mu$ … $1)_X$ AND L…





Greljo, Sc… …7.07518

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$(g-2)_\mu$, $b \to s\mu\mu$ FROM $U(1)_X$ AND LQ

Greljo, Soreq, Stangl, Thomsen, JZ, 2107.07518

- exploration of viable charge assignments for SM+3ν_R field content
- require anomaly free charge assignments
  - keeping max charge ratios ≤ 10 (integer charges) $\Rightarrow$ 273 models (out of ~ $2 \cdot 10^7$)

Allanach, Davighi, Melville, 1812.04602

  - two categories of charge assignments (up to flavor permutations)

$$\textbf{vector category}: \quad X_{L_i} = X_{E_i} \quad \text{for all} \quad i = 1,2,3\ ,$$
$$\textbf{chiral category}: \quad \text{the rest.}$$

252 solutions (vector category)

21 solutions (chiral category)

  - in vector category 3 parameter families of solutions, with the lepton charges given by (up to flavor permutations)

$$\begin{aligned}
&\text{Class 1}: \quad X_e = X_{N_1}, \quad X_\mu = X_{N_2}, \quad X_\tau = X_{N_3},\\
&\text{Class 2}: \quad X_e = X_{N_1}, \quad X_\mu = -X_\tau, \quad X_{N_2} = -X_{N_3},\\
&\text{Class 3}: \quad \text{the rest.}
\end{aligned}$$

  - note: the classes may overlap, e.g., $L_\mu - L_\tau$ is both Class 1 and 2

NON-UNIVERSAL $U(1)_X$ CHARGES IN QUARK SECTOR

- one can relax that the quark Yukawas are allowed: e.g., only 3rd generation Yukawas allowed
  - "2+1" charge assignments

$$X_{Q_i} = X_{U_j} = X_{D_k} \equiv X_{q_{12}} \quad \text{for all} \quad i, j, k = 1, 2, \quad \text{and}$$
$$X_{Q_3} = X_{U_3} = X_{D_3} \equiv X_{q_3} \ . \quad (X_H = 0)$$

  - the CKM elements (V_{td}, V_{ts}) at dim 5

$$\mathcal{L} \supset \frac{x_i^u}{\Lambda}\overline{Q}_i \tilde{H}\phi U_3 + \frac{x_i^d}{\Lambda}\overline{Q}_i H\phi D_3 + \text{H.c.}$$

  - anomalies satisfied if $2X_{q_{12}} + X_{q_3} = 3X_q$
- straightforward extension of quark universal charge assignments
  - slight changes in muoquark requirements ⇒ 171 inequivalent sols. (for $-10 \leq X_{F_i} \leq 10$)

MODELS

- several relevant constraints
  - neutrino trident, light resonance searches, neutrino electron scattering (Borexino), nonstandard neutrino interactions
- consider models of the following form
  - $b \to s\mu\mu$ through S_3 exchange
  - $(g-2)_\mu$ through $U(1)_X$ gauge boson
- the well studied solution for $(g-2)_\mu$: $L_\mu - L_\tau$
  - viable region $m_X \sim 10 - 200$MeV
  - dimuon resonance searches $m_X \lesssim 0.21$ GeV
  - BBN (cosmology): $m_X \gtrsim$ several MeV
  - electron bounds (NA64, Borexino): depend on assumed kinetic mixing

hep-ph/0104141,
hep-ph/0110146,
1311.0870,
1403.1269,
1406.2332,
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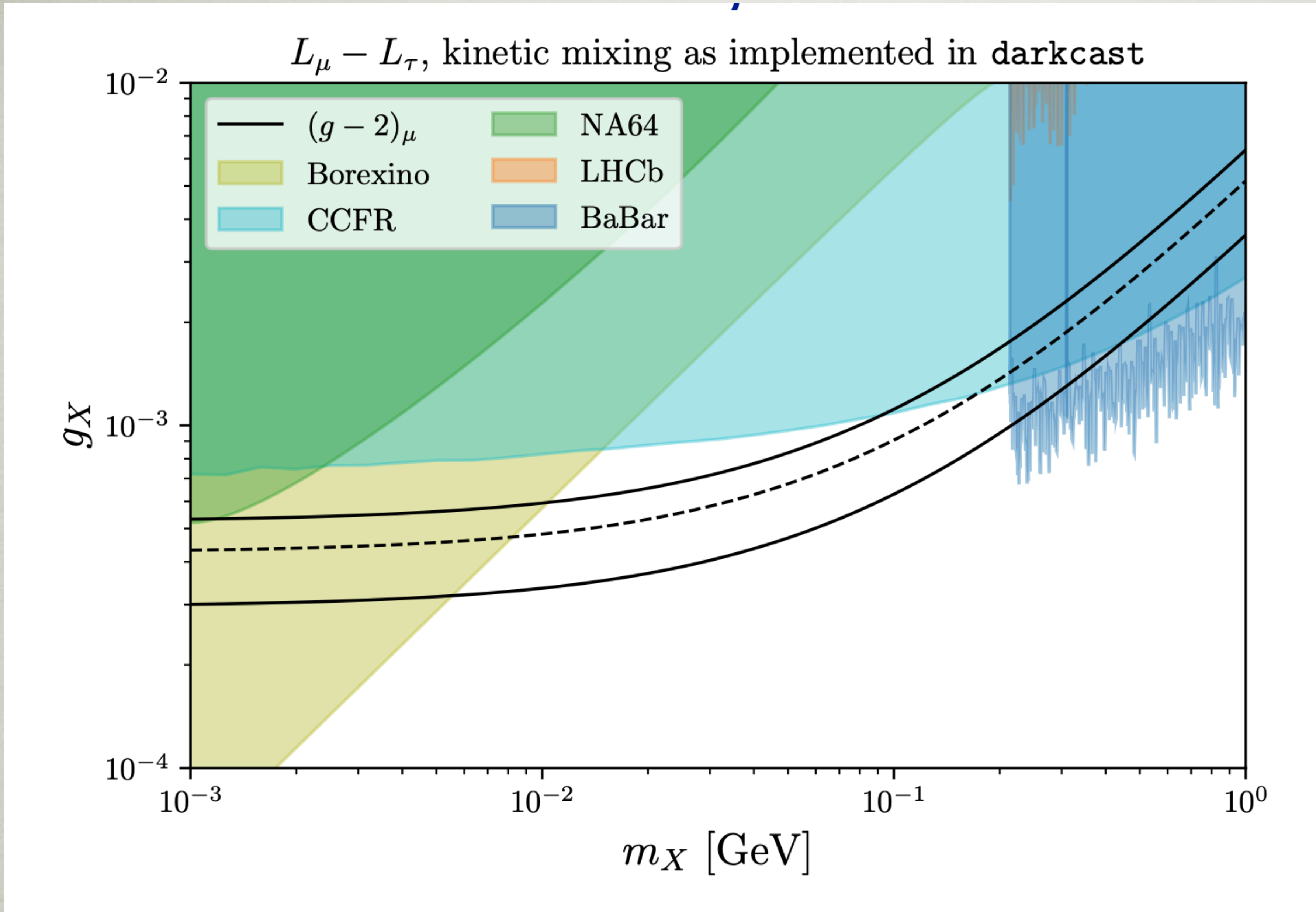

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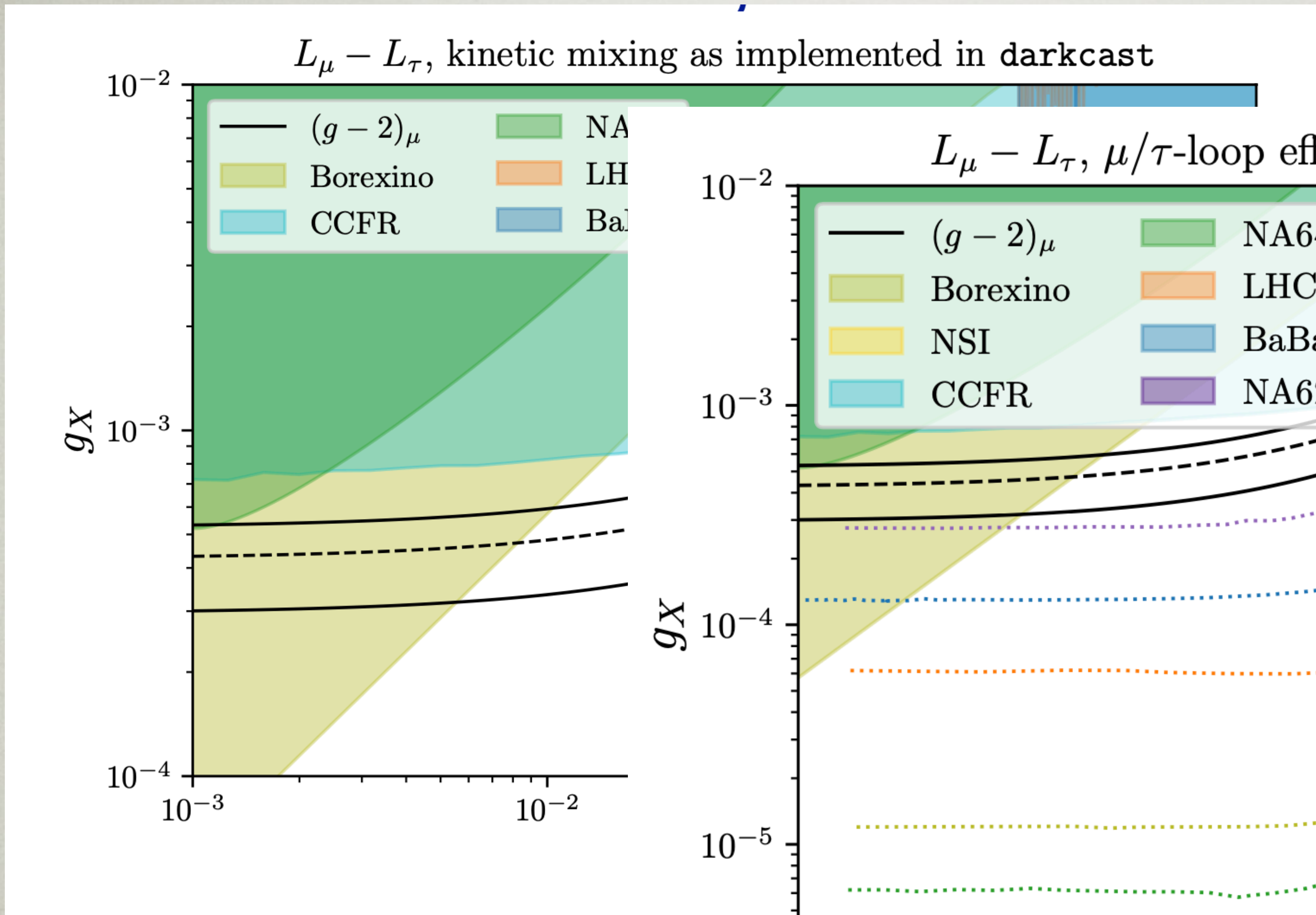
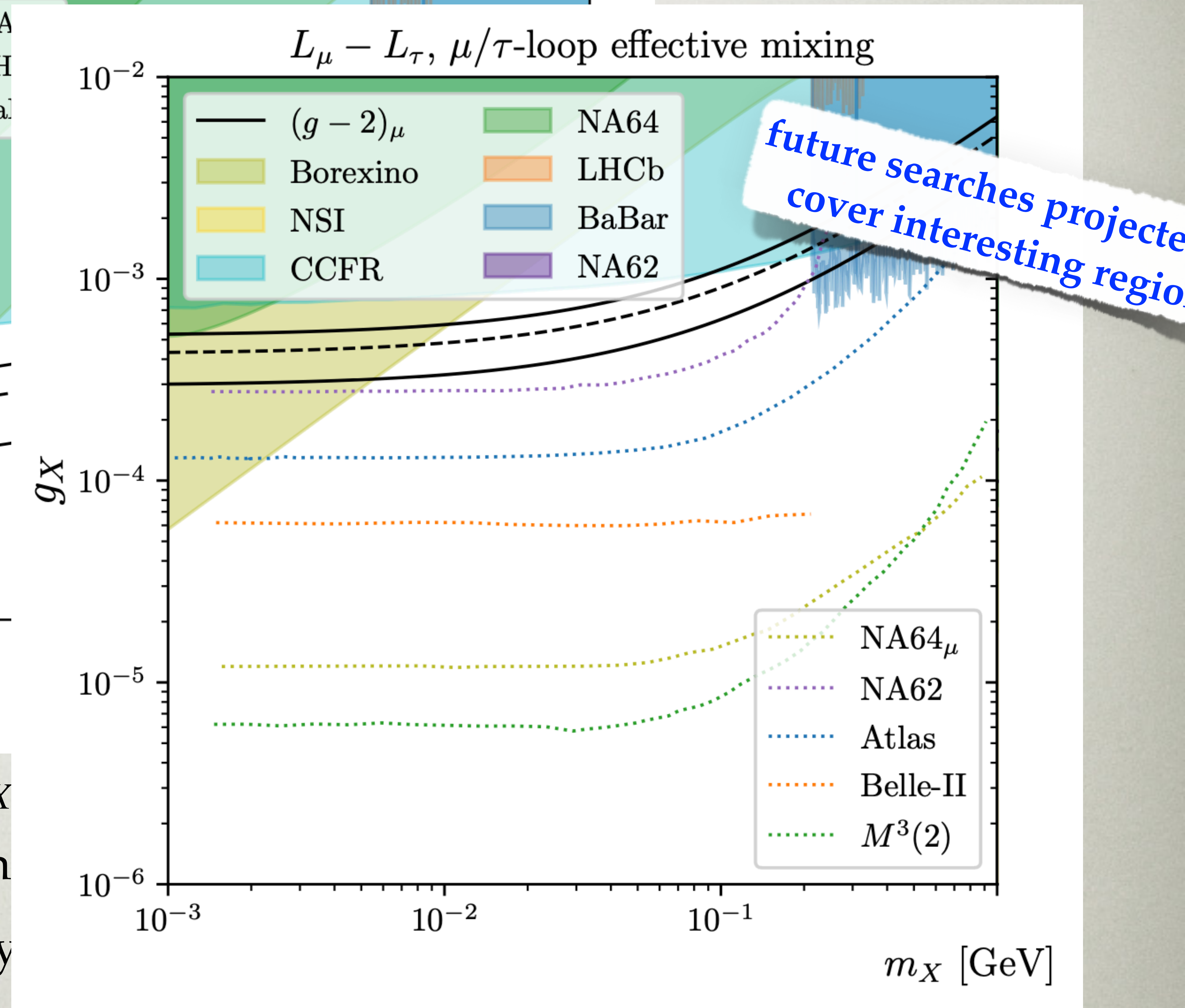




- viable region m_X
- dimuon resonan
- BBN (cosmology
- electron bounds (NA64, Borexino): depend on assumed kinetic mixing

BEYOND $L_\mu - L_\tau$

- most of the other possible $U(1)_X$ are experimentally excluded
  - viable $U(1)_X$ mostly of the form $c_1(L_\mu - L_\tau) + c_2 U(1)'_X$ with $c_1 \gg c_2$
  - there are exceptions, e.g., chiral $\tilde{L}_{\mu-\tau}$

$$(X_{L_1}, X_{L_2}, X_{L_3}) = (-1, 7, -6), \qquad (X_{E_1}, X_{E_2}, X_{E_3}) = (1, 6, -7),$$

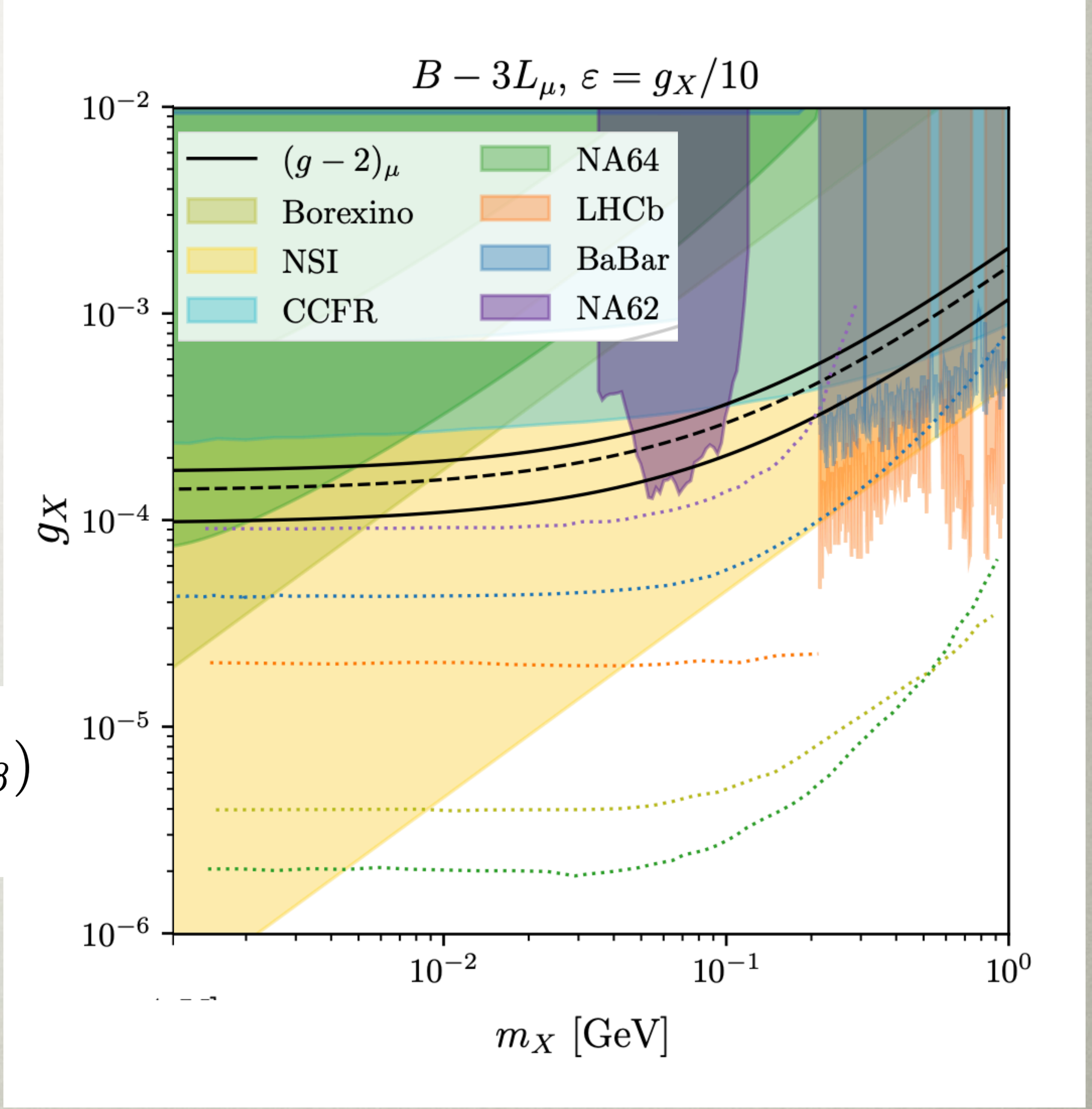
- axial couplings to electrons avoid bounds on NSI from ν osc.

GAUGED $B - 3L_\mu$

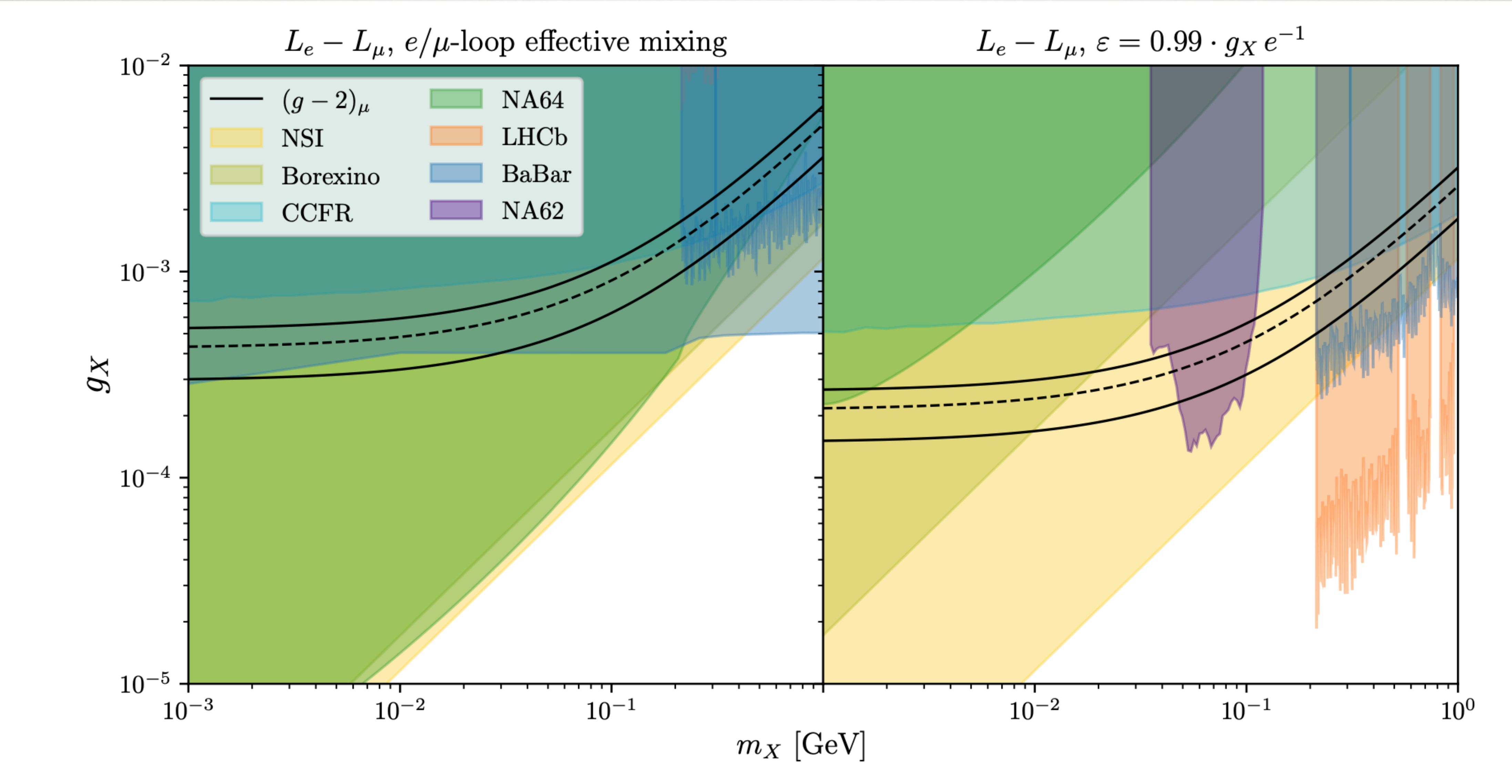
- NSI ν couplings to u, d, e tightly constrained by
  - ν oscillation fits
  - CEνNs (COHERENT,...)
  - $\nu_{\rm solar} - e$ scattering (Borexino, Xenon1T,...)

$$\mathcal{L}_{\rm NSI} = -\frac{G_F}{2\sqrt{2}} \sum_{f,\alpha\beta} \varepsilon^f_{\alpha\beta} (\bar{f}\gamma_\mu f)(\bar{\nu}_\alpha P_{\rm L} \nu_\beta)$$

$$f = \{e, p, n\}$$

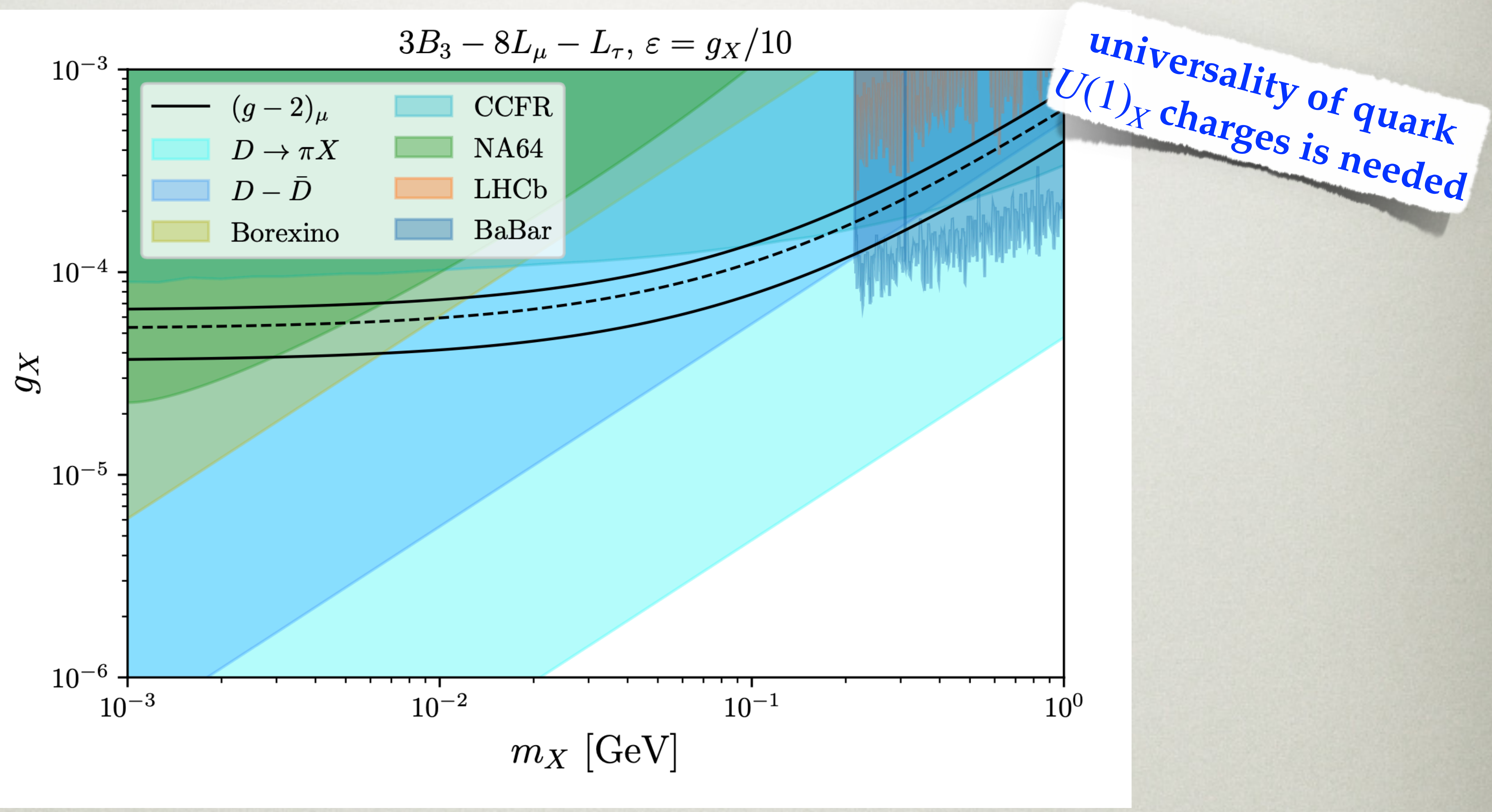


GAUGED $L_e - L_\mu$



- X_μ coupling to e bounded by NA64, Borexino, NSI
- by choosing kinetic mixing can tune away the first two, but not the NSI

GAUGED $9B_3 - 8L_\mu - L_\tau$



- only 3rd generation of quarks charged under $U(1)_X$
- even down alignment not enough to avoid FCNC constraints

CONCLUSIONS

- simultaneously explaining $(g-2)_\mu$ and $R_{K^{(*)}}$ requires more than one mediator
- gauged $U(1)_X$ leading to a muoquark explains the absence of FCNC signals
    - phenomenologically viable models are perturbations around $L_\mu - L_\tau$

BACKUP SLIDES

NEWS FROM EARLIER THIS YEAR

- theoretically "clean" observables
  - R_K went from 2.5σ to 3.1σ LHCb 1903.09252, 2103.11769
    - the first single measurement in B anomalies to cross the "evidence" threshold
  - $\lesssim 2\sigma$ tension in $B_s \to \mu^+\mu^-$ LHCb 2108.09284, 2108.09283
- theoretically "dirty" observables
  - $(g-2)_\mu$ went from 3.7σ to 4.2σ The Muon g−2 Collaboration, 2104.03281
  - $Br(B_s \to \phi\mu\mu)$ 3.6σ below the nominal SM prediction LHCb 2105.14007

COMBINED NP EXPLANATIONS

- all anomalies or a subset?
- $R_{K^{(*)}}$ and $R_{D^{(*)}}$
  - vector leptoquark $U_1 \sim (3,1,2/3)$ — Cornella et al., 2103.16558 + many refs.
    - UV realization: 4321 model?
  - 2 scalar leptoquarks $S_3 \sim (\bar{3},3,1/3)$, $S_1 \sim (\bar{3},1,1/3)$
    - UV realization: composite Higgs? — Crivellin, Muller, Ota, 1703.09226 +many refs.
- $R_{K^{(*)}}$ and $(g-2)_\mu$
  - 2 scalar leptoquarks $S_3 \sim (\bar{3},3,1/3)$, $S_1 \sim (\bar{3},1,1/3)$ — Greljo et al, 2103.13991
  - from simplified DM models in the loop — Arcadi, Calibbi, Fedele, Mescia, 2104.03228
- $R_{K^{(*)}}$ and $R_{D^{(*)}}$ and $(g-2)_\mu$