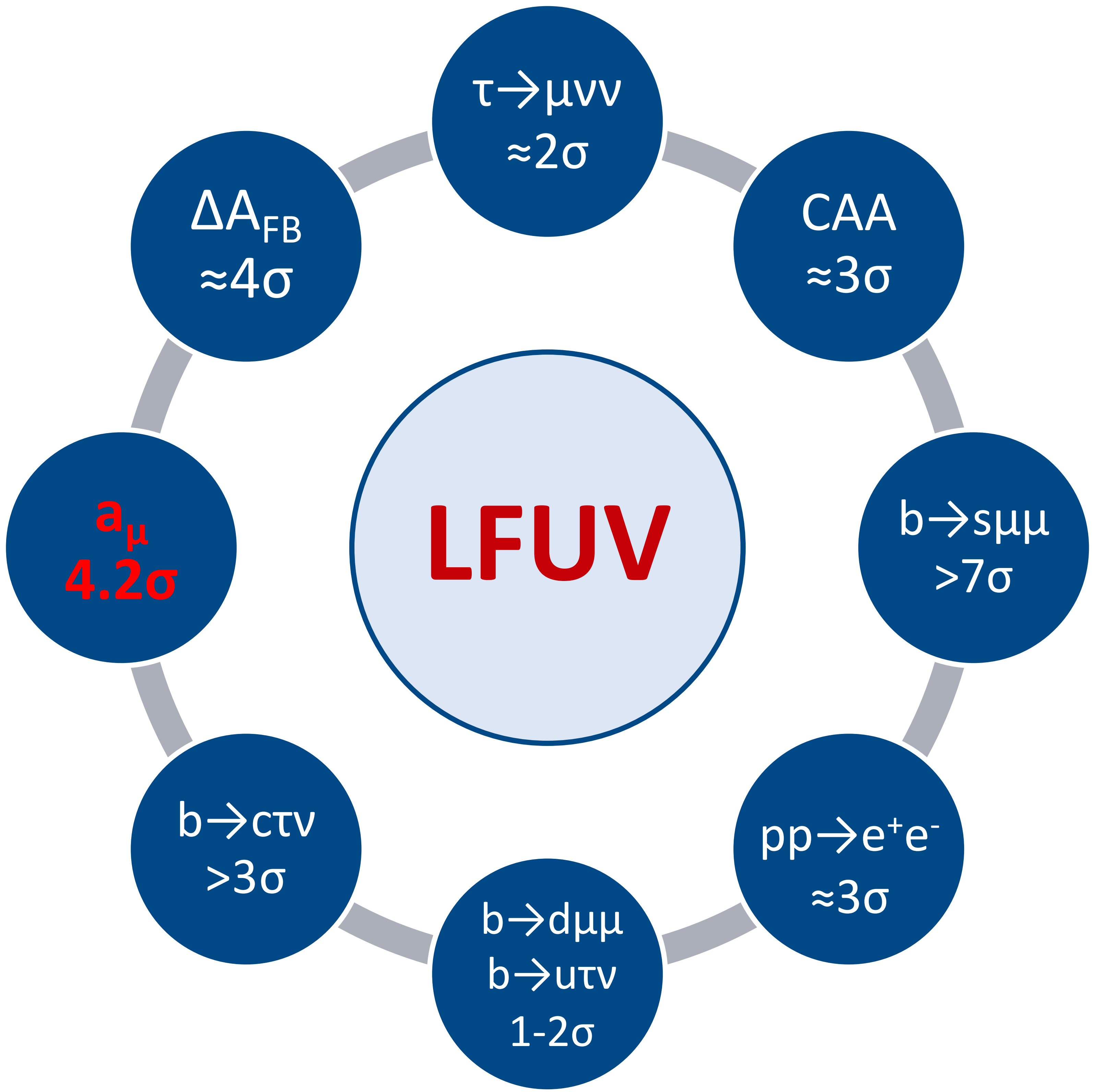
MODELS EXPLAINING $(g-2)_\mu$

Andreas Crivellin (Paul Scherrer inst.)
Jure Zupan (u. of cincinnati)

Beyond the flavor anomalies III, IPPP, Durham, Apr 26 2022

Flavour Anomalies



$$(g-2)_\mu$$

IF NEW PHYSICS...

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

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

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

Greljo, Stangl, Thomsen, 2103.13991

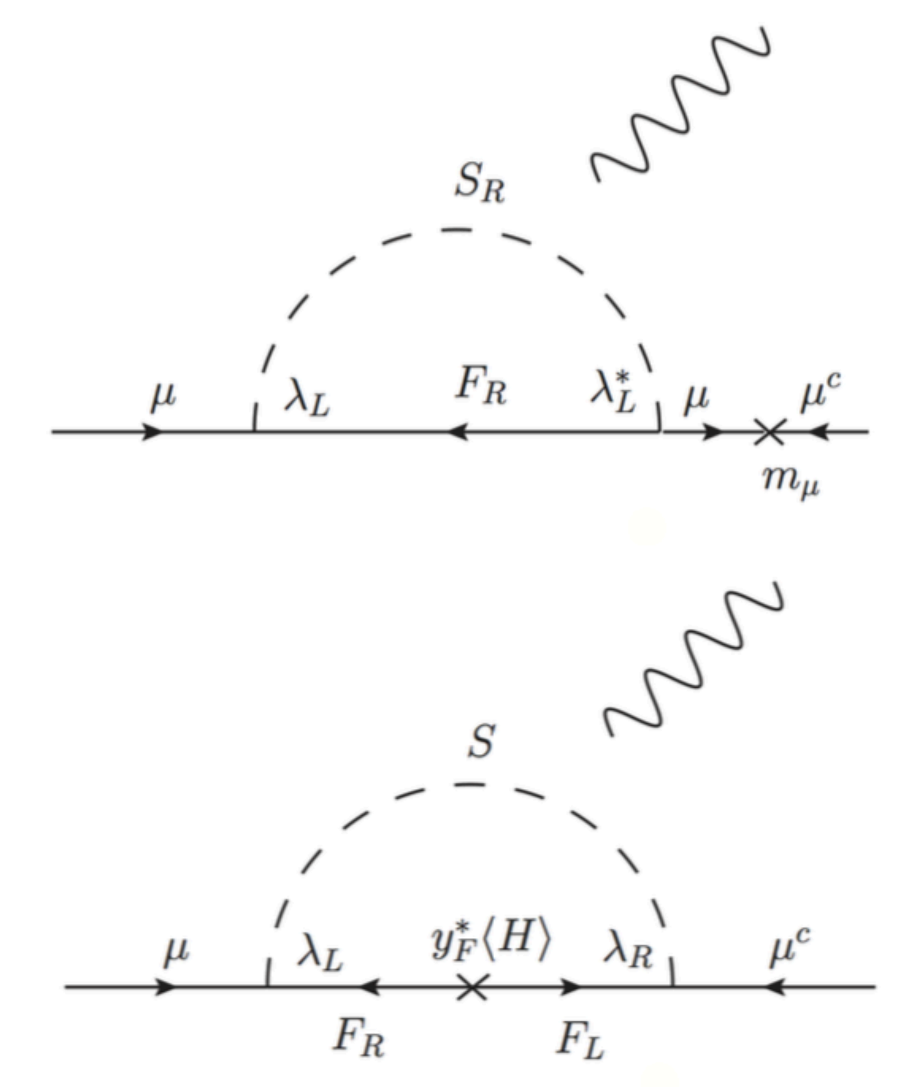
- note: any flavor violation needs to be highly suppressed $\mu \to e\gamma \Rightarrow \Lambda_{21} \gtrsim 3500\,\mathrm{TeV}$
- a possible (natural) solution - a symmetry

FOCUSING JUST ON $(g-2)_\mu$

$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = 251(59)\times 10^{-10}$$

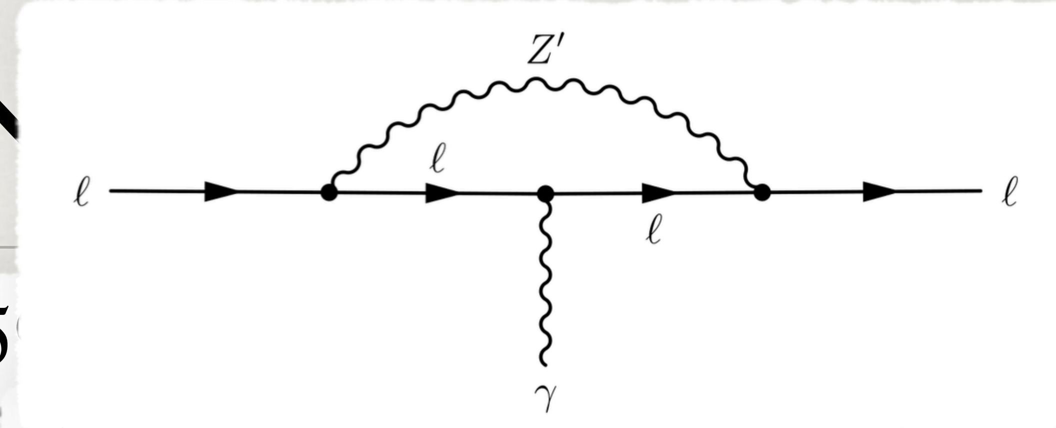
$$\frac{e}{8\pi^2}(\bar\mu\sigma^{\mu\nu}\mu)F_{\mu\nu}$$

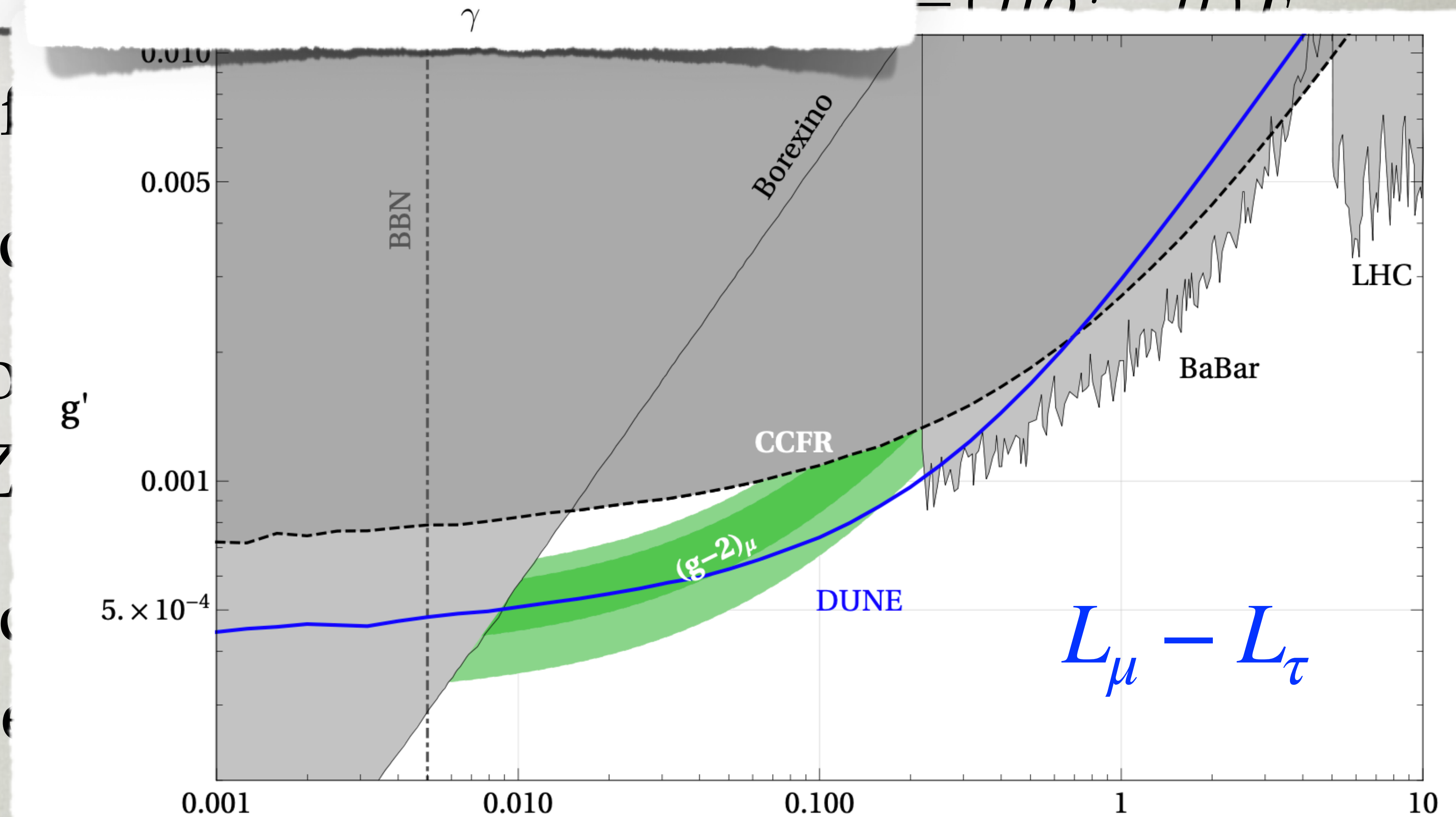
- NP models of two types
- chirality flip on SM fermion leg
  - NP need to be light, example: Z' from $L_\mu - L_\tau$
- chirality flip can be on the NP fermion leg
  - NP can be much heavier
  - example: minimal models with DM



FOCUSIN $- 2)_\mu$

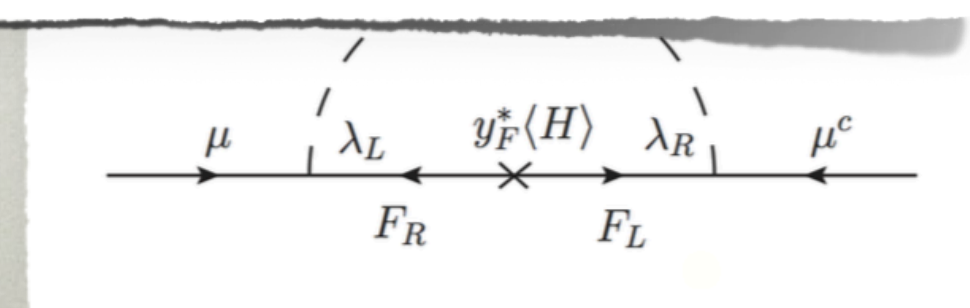
$a_\mu^{\rm exp} - a_\mu^{\rm SM} = 251(5$ $(\bar{\mu}\sigma^{\mu\nu}\mu)F$





Altmannshofer et al , 1902.06765

- NP models of
- chirality flip (
  - NP need to
    example: Z
- chirality flip (
  NP fermion l
  - NP can be
  - example: minimal models with DM

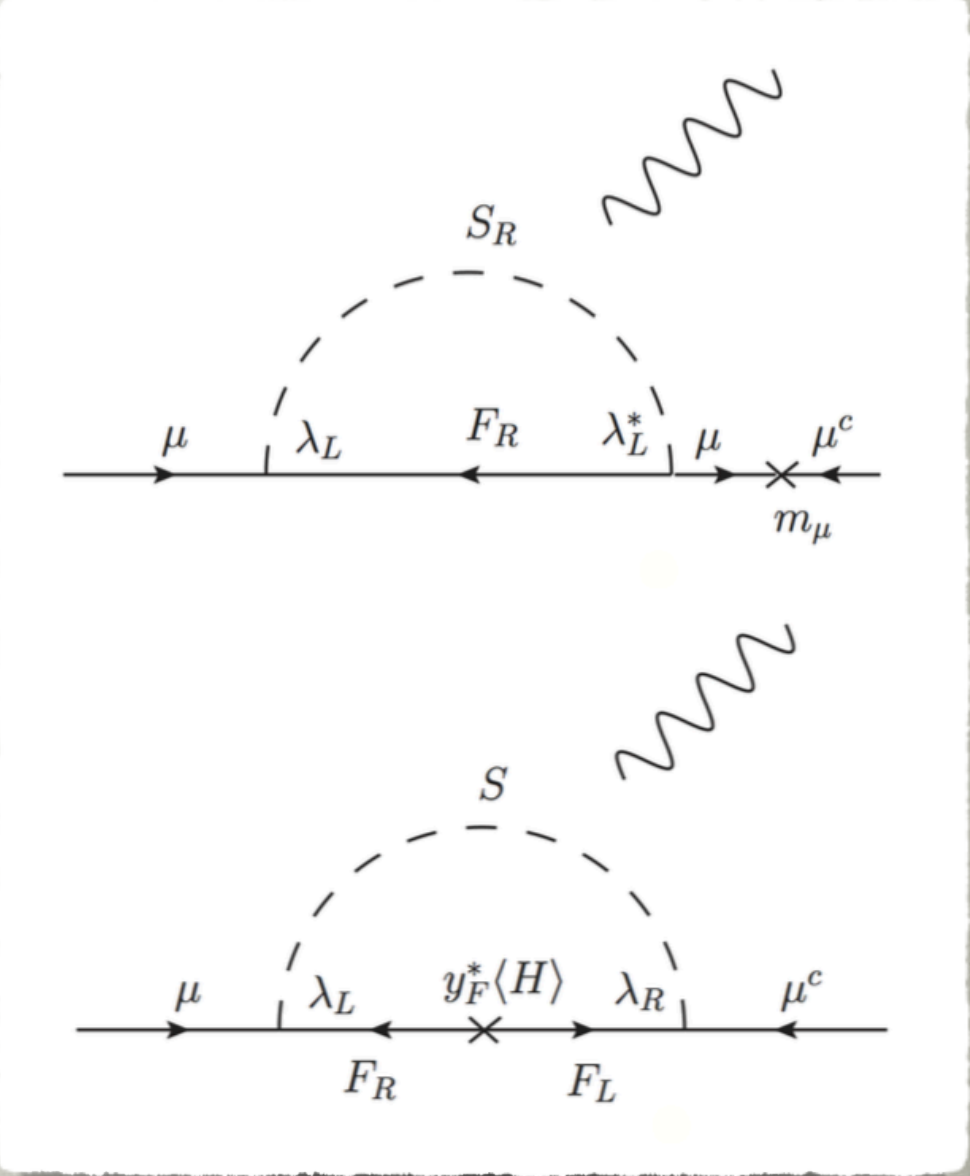


FOCUSING JUST ON $(g-2)_\mu$

$a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = 251(59) \times 10^{-10}$

$$\frac{e}{8\pi^2}(\bar{\mu}\sigma^{\mu\nu}\mu)F_{\mu\nu}$$

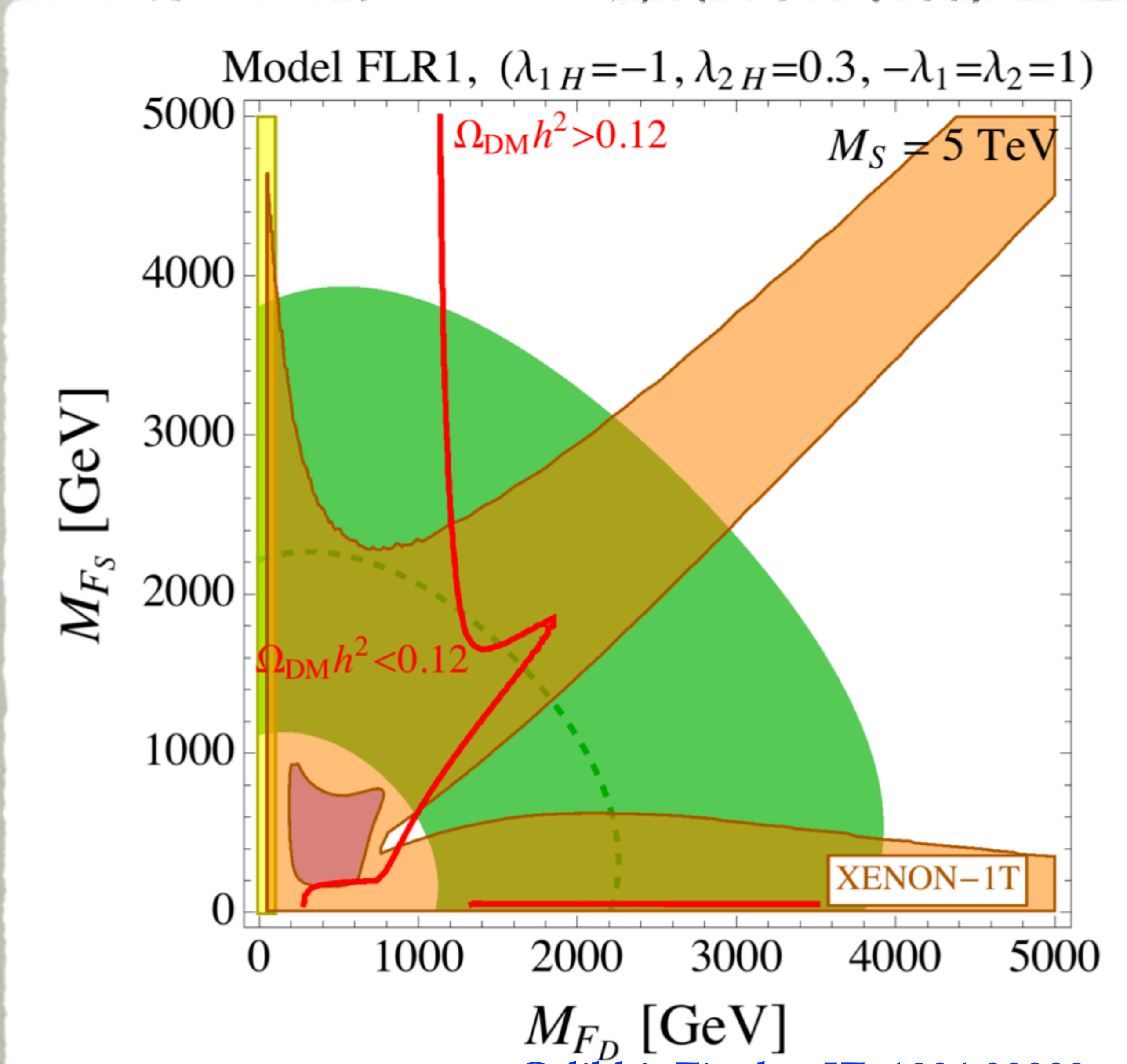
- NP models of two types
- chirality flip on SM fermion leg
  - NP need to be light, example: Z' from $L_\mu - L_\tau$
- chirality flip can be on the NP fermion leg
  - NP can be much heavier
  - example: minimal models with DM



FOCUSING JUST ON $(g-2)_\mu$

$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 251(59) \times 10^{-10}$

$$\frac{e}{8\pi^2}(\bar{\mu}\sigma^{\mu\nu}\mu)F_{\mu\nu}$$



Calibbi, Ziegler, JZ, 1804.00009

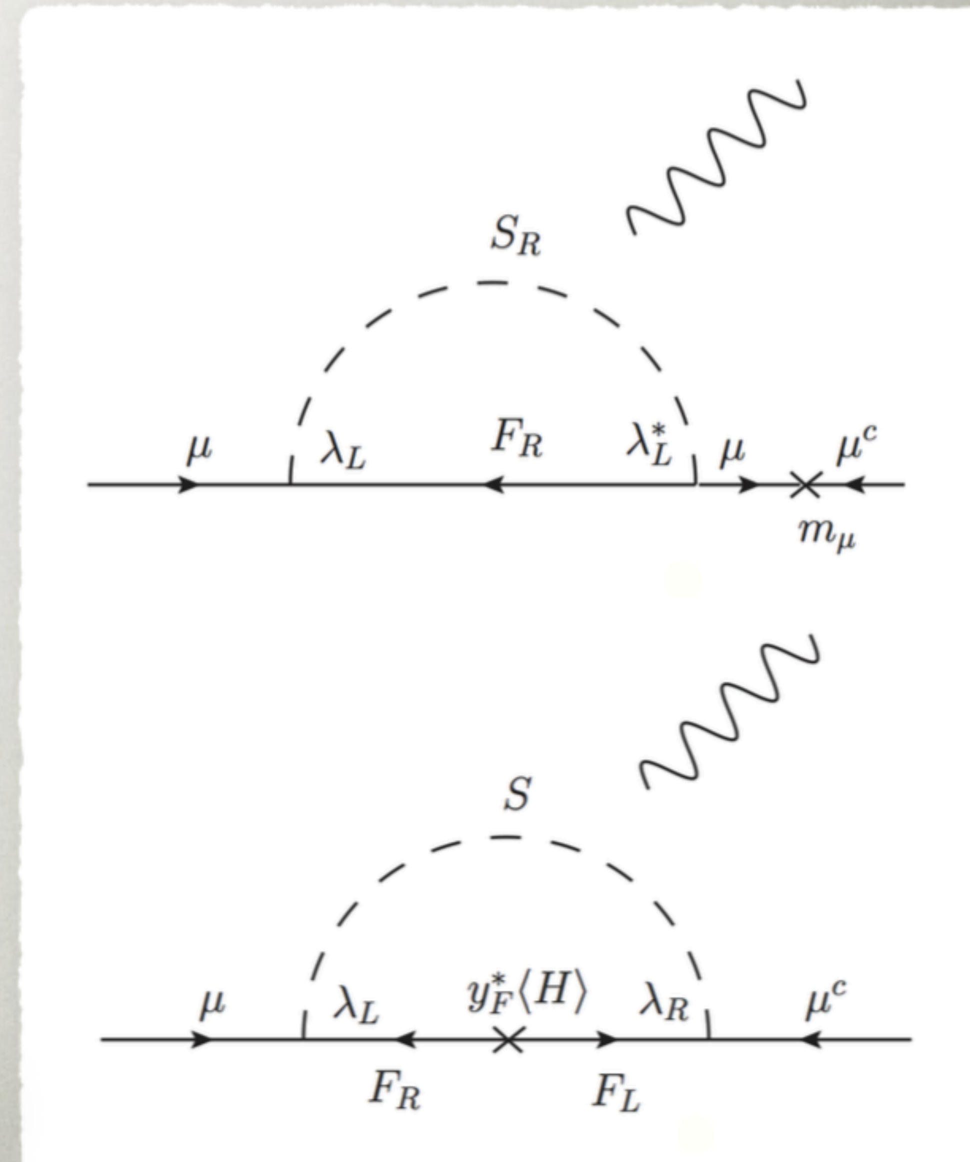
ion leg

L_τ

ne

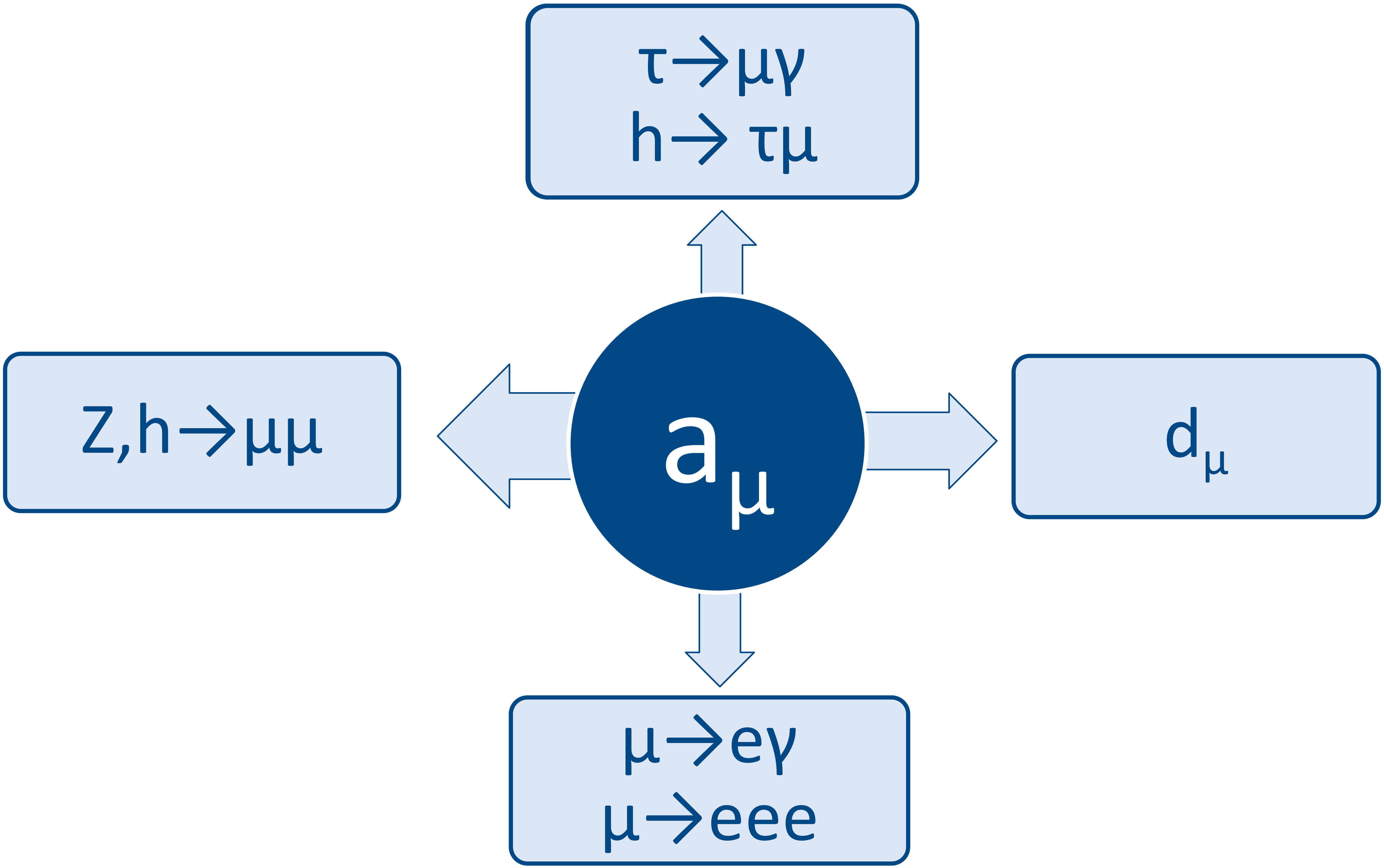
ier

dels



$F_S \equiv F_R \sim 1_0, \qquad F_D \equiv F_L \sim 2_{-1/2}, \qquad F_D^c \equiv F_L^c \sim 2^*_{1/2}, \qquad S \equiv S_R \sim 2_{1/2},$

Future Implications of a_μ



LIGHT NEW PHYSICS

based on Greljo, (Soreq,) Stangl, Thomsen, JZ, 2107.07518, 2203.13731

$U(1)_X$ SOLUTIONS

- a well studied scenario $U(1)_{L_\mu - L_\tau}$
  - forces the dimension-4 charged lepton Yukawa interactions to be diagonal
  - $L_\mu - L_\tau$ gauge boson X_μ with mass $m \in [10,210]$ MeV solves $(g-2)_\mu$
- is $U(1)_{L_\mu - L_\tau}$ the only phenomenologically viable option?
- can alternative models be experimentally disentangled from $U(1)_{L_\mu - L_\tau}$?

EXPLORING $U(1)_X$ SOLUTIONS

Greljo, (Soreq,) Stangl, Thomsen, JZ, 2107.07518, 2203.13731

- assume minimal field content: SM+$3\nu_R$
- require anomaly free charge assignments
  - quark flavor universality
  - keeping max charge ratios ≤ 10 (integer charges) Allanach, Davighi, Melville, 1812.04602
    $\Rightarrow$ up to flavor permutations: 276 models (out of $\sim 2 \cdot 10^7$)
  - two categories of charge assignments (up to flavor permutations)

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

255 solutions (419 w/ flavor perm.)

21 solutions

  - 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

VECTOR-LIKE $U(1)_X$ MODELS

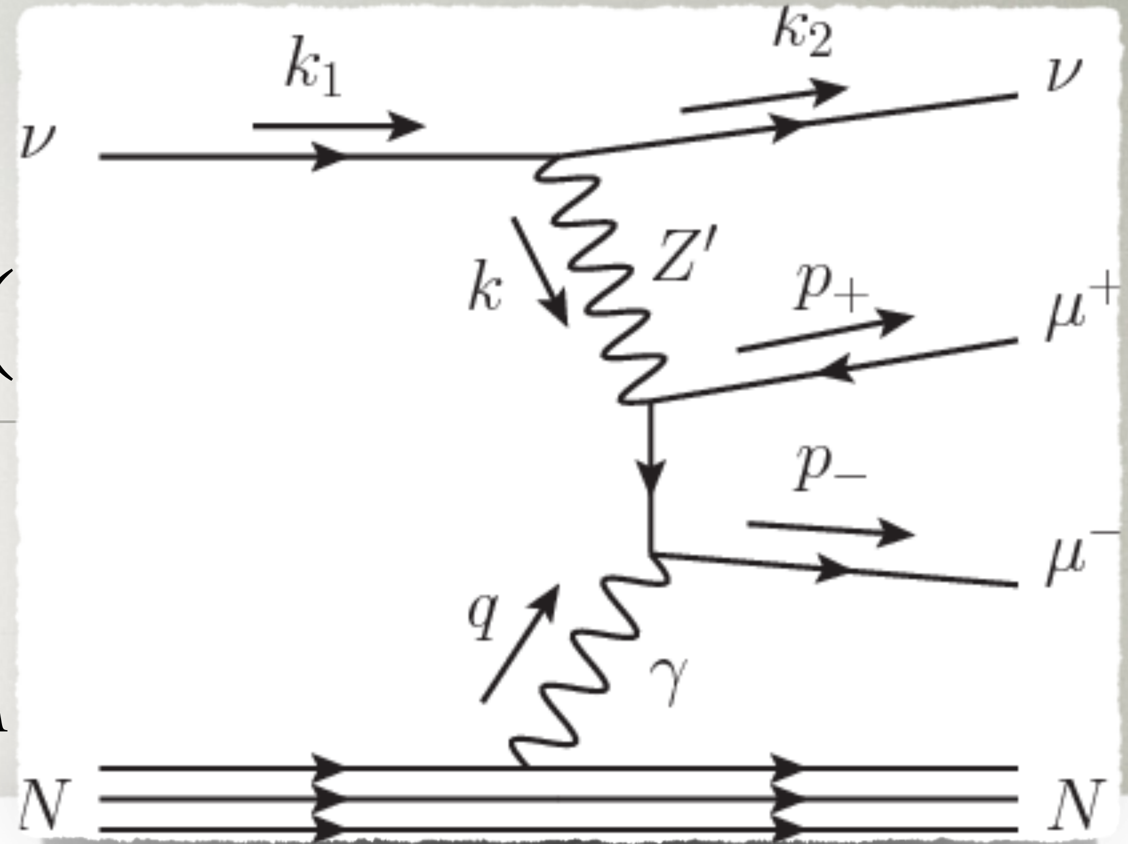
- for $(g-2)_\mu$ need $g_V \gg g_A$

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

- if no kin. mix.$\Rightarrow$ X_μ necessarily couples to neutrinos* $\Rightarrow$ trident + ν osc. constraints
- if kin. mixing $\Rightarrow$ couplings to electrons + Z mass constraints (EWPT)

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

VECTOR-LIKE $U($



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

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

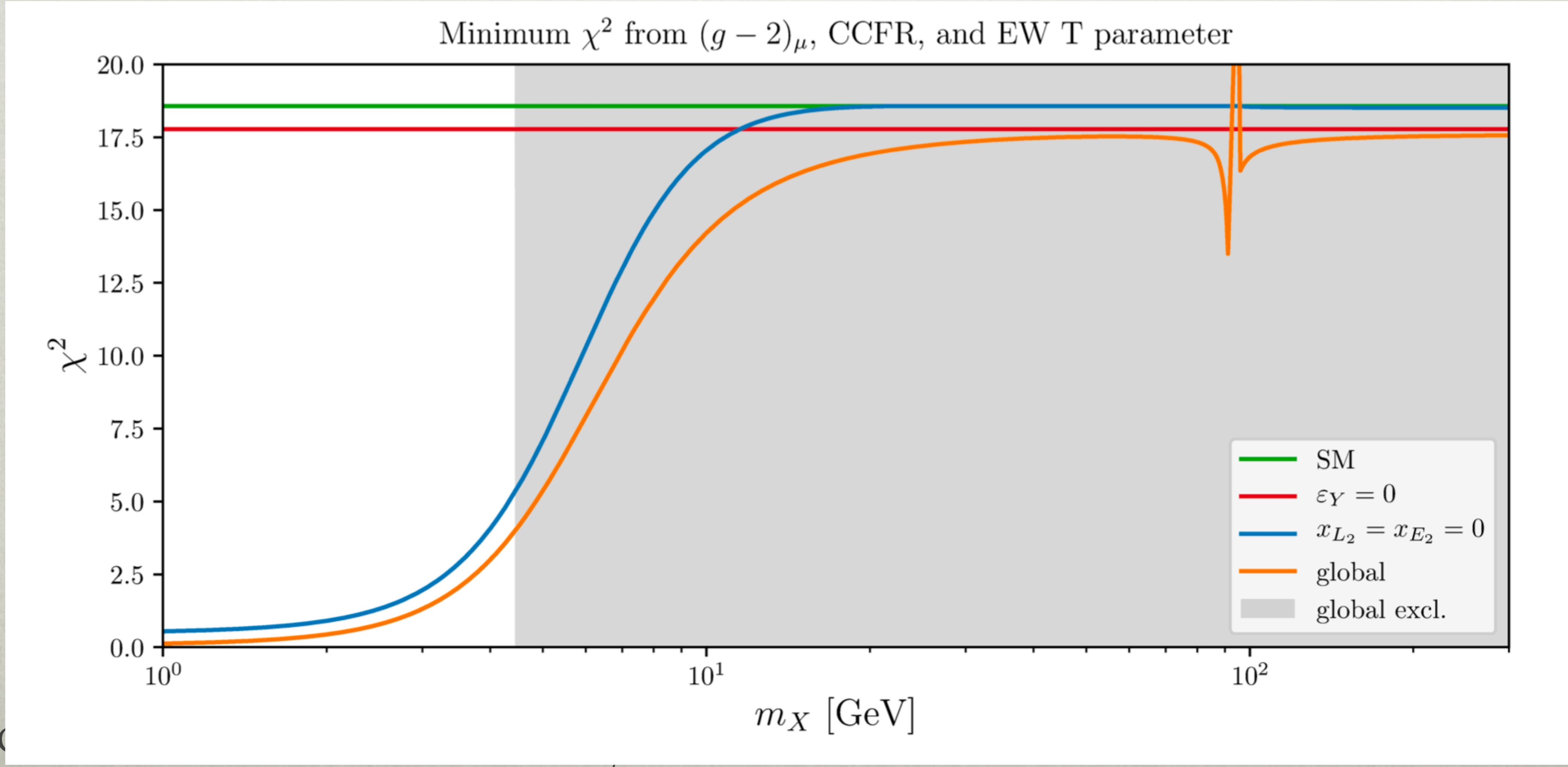
- if no kin. mix.⇒ X_μ necessarily couples to neutrinos* ⇒ trident + ν osc. constraints
- if kin. mixing ⇒ couplings to electrons + Z mass constraints (EWPT)

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

Greljo, Stangl, Thomsen, JZ, 2203.13731

X_μ MASS BOUND

- X_μ that explains $(g-2)_\mu$ has mass in the range
  - from BBN: $m_X \gtrsim 10\,\mathrm{MeV}$
  - from ν trident + T param.: $m_X \lesssim 4\,\mathrm{GeV}$

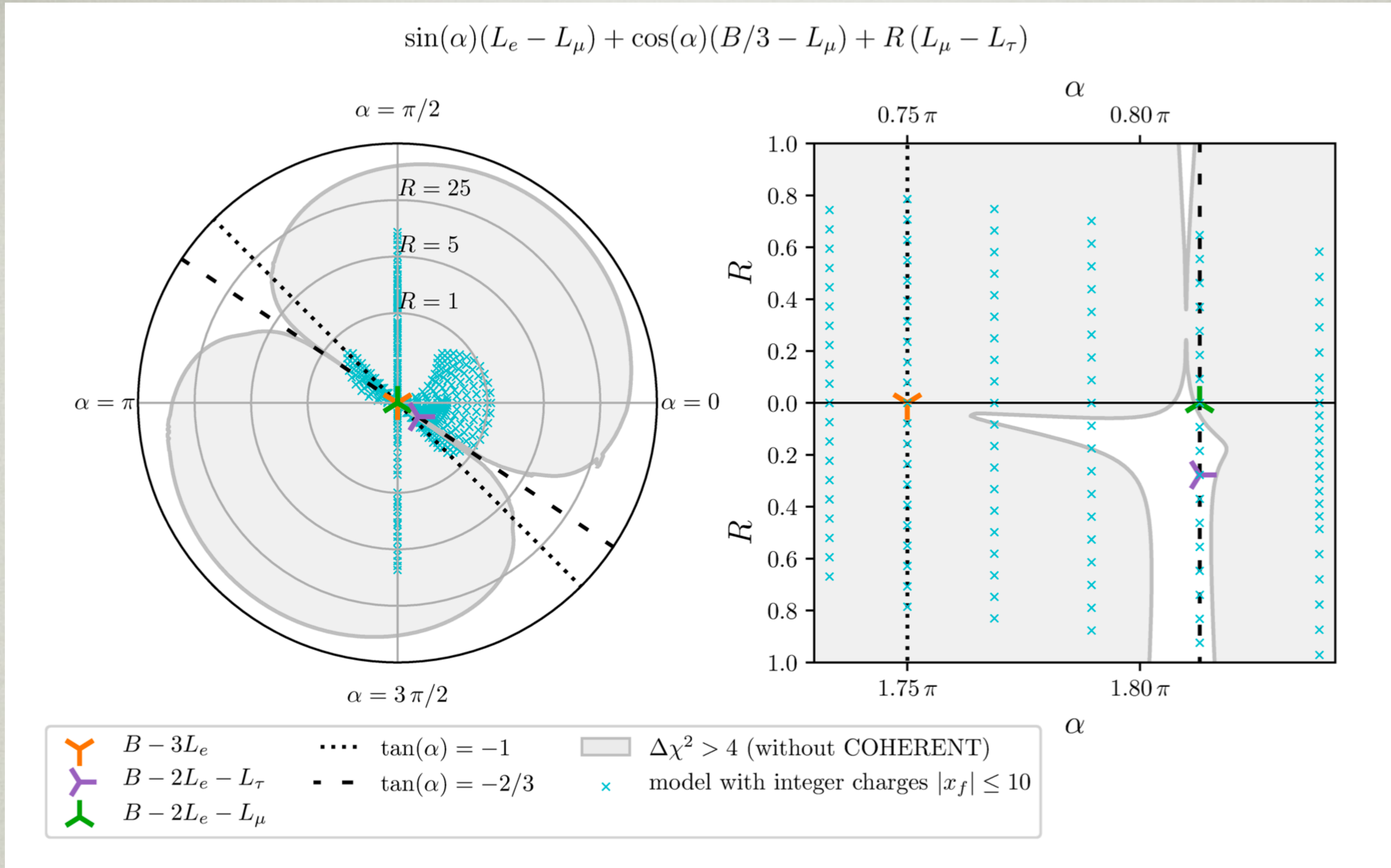


VECTORLIKE MODELS

- vector-like models parametrized as

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

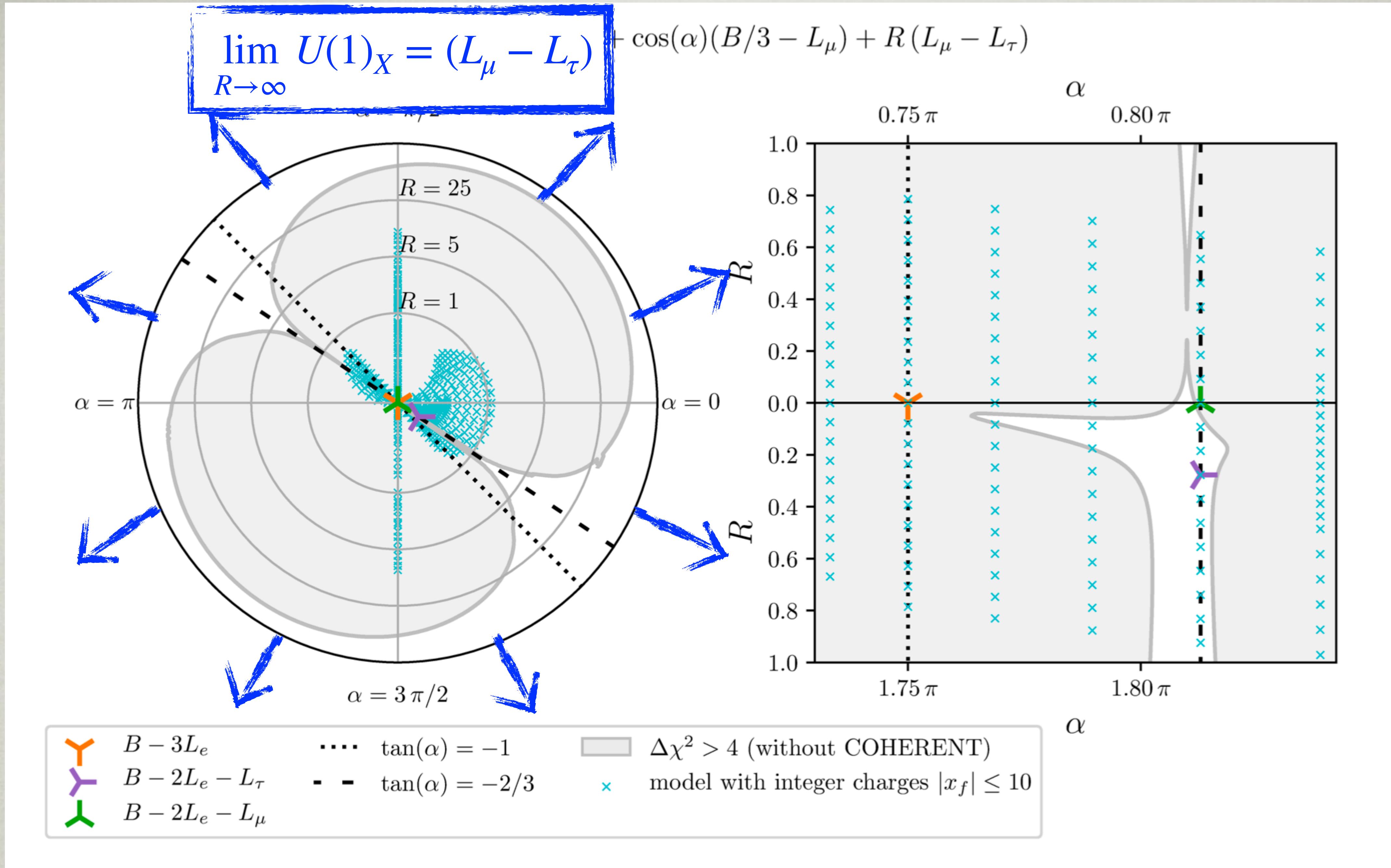
- a global fit to data
  - models "close" to $L_\mu - L_\tau$ viable
  - viable deformations mostly in the direction of $B - 2L_e - L_\tau$ admixture
    - minimizes constr. from ν osc.



Z, 2203.13731

- viable deformations mostly in the direction of $B - 2L_e - L_\tau$ admixture
- minimizes constr. from ν osc.

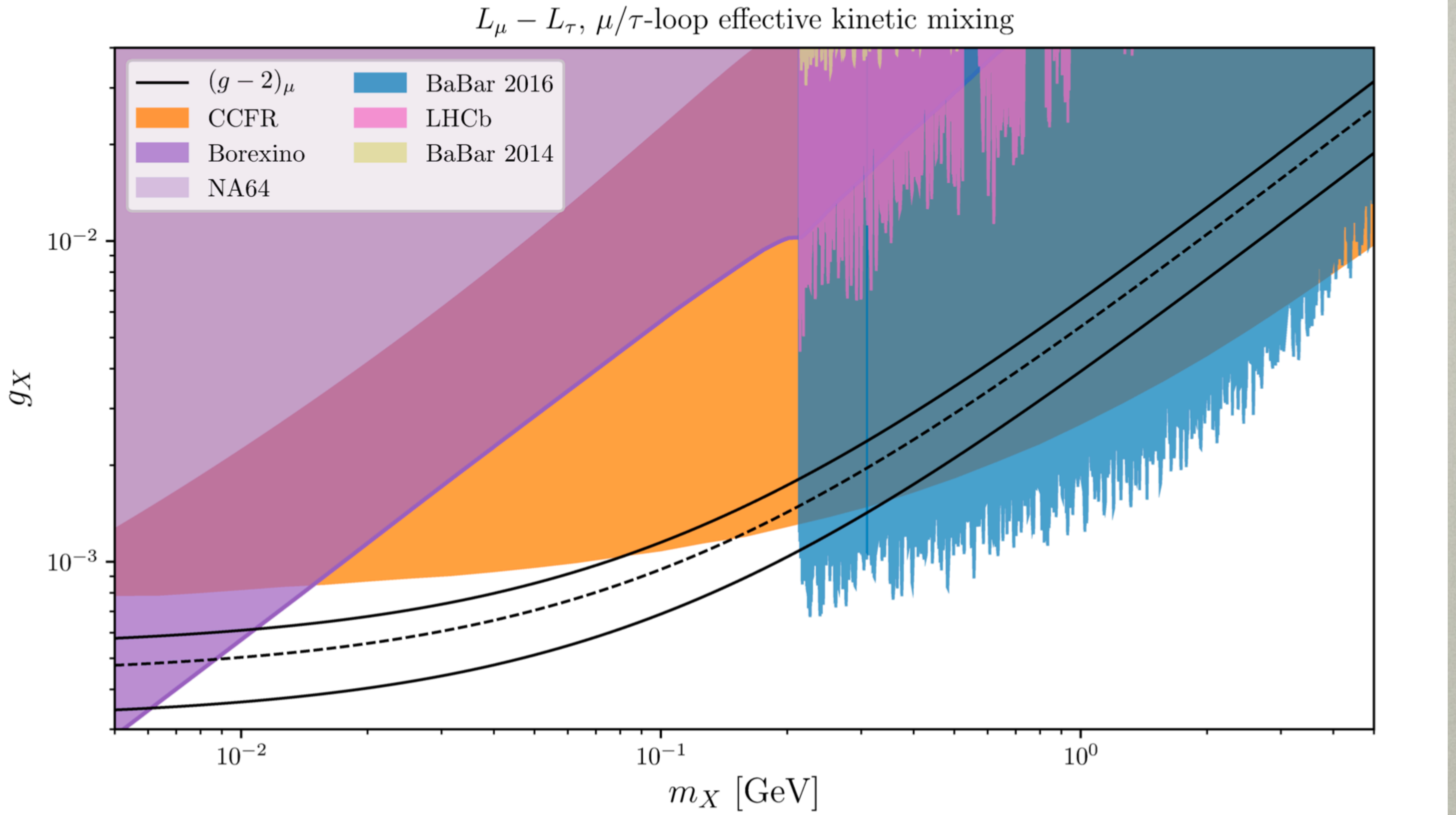
Z, 2203.13731



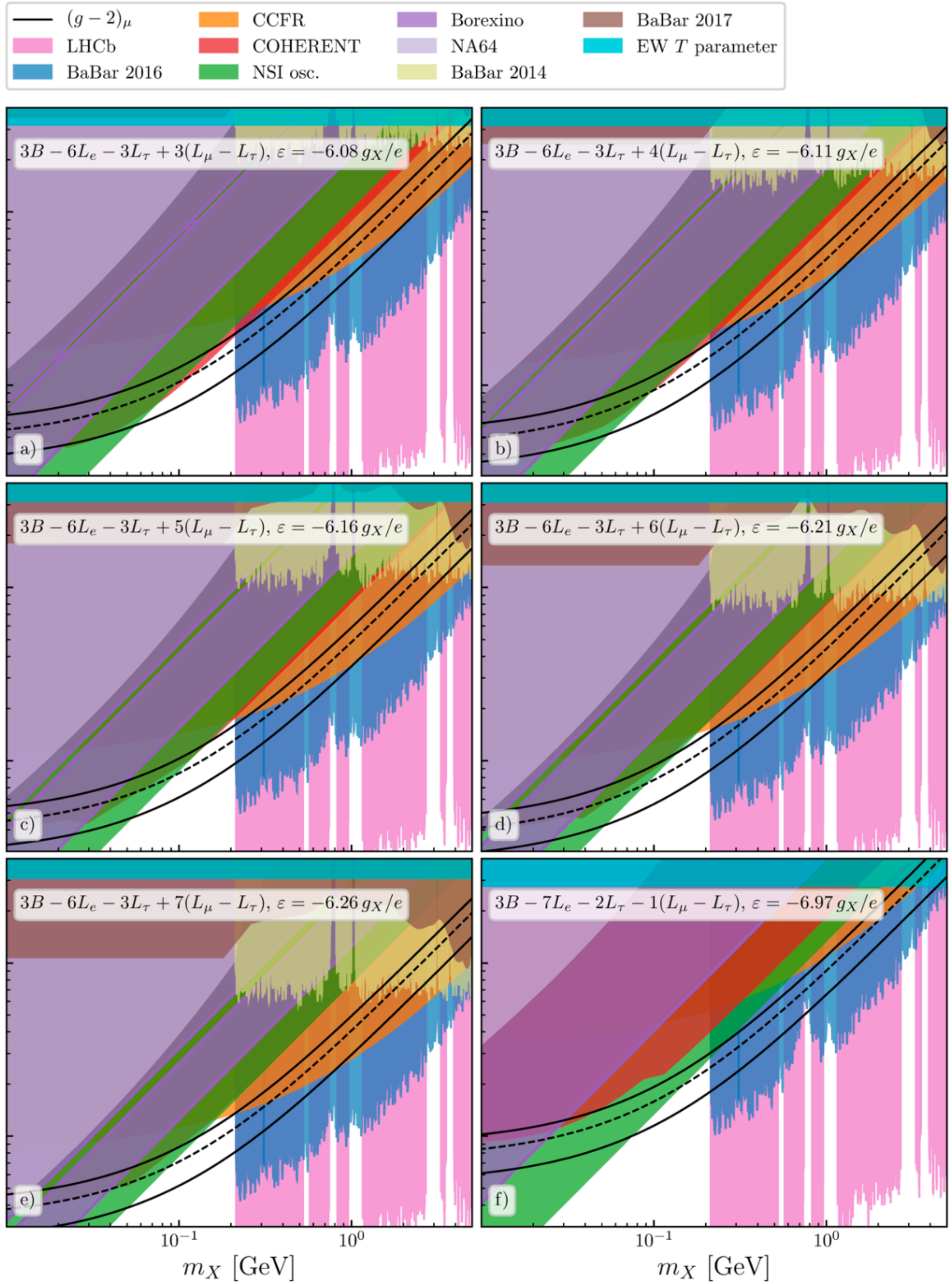
- viable deformations mostly in the direction of $B - 2L_e - L_\tau$ admixture
- minimizes constr. from ν osc.

UPSHOT

- adding COHERENT constr. ⇒ only 7 phenom. viable models
  - $L_\mu - L_\tau$ + deformations
- all allow/facilitate muoquark solutions to $b \to s\mu^+\mu^-$
- parameter space will be completely covered by upcoming searches:
  - NA62, Atlas, Belle-II NA64μ, M3



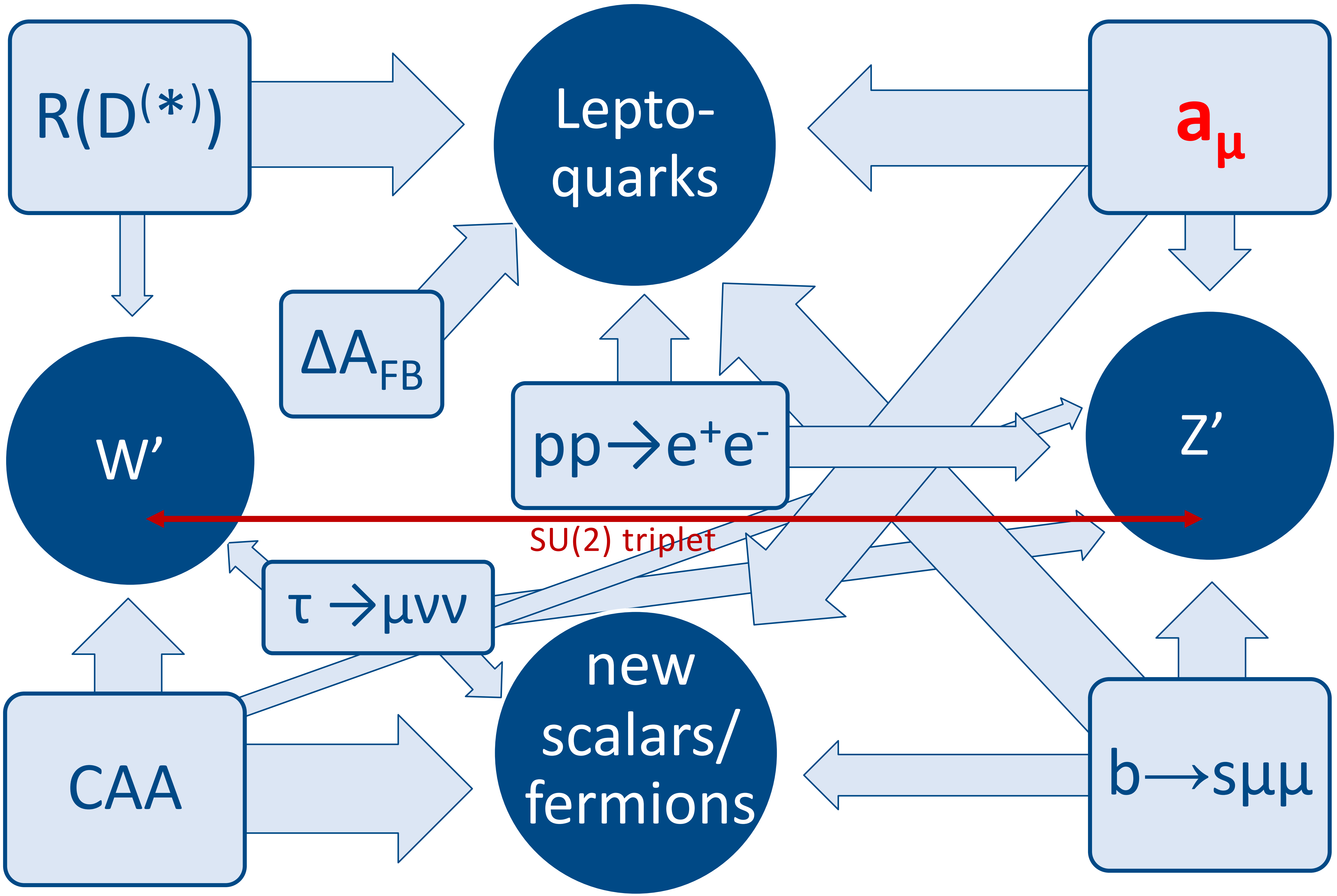
Greljo, Stangl, Thomsen, JZ, 2203.13731



Greljo, Stangl, Thomsen, JZ, 2203.13731

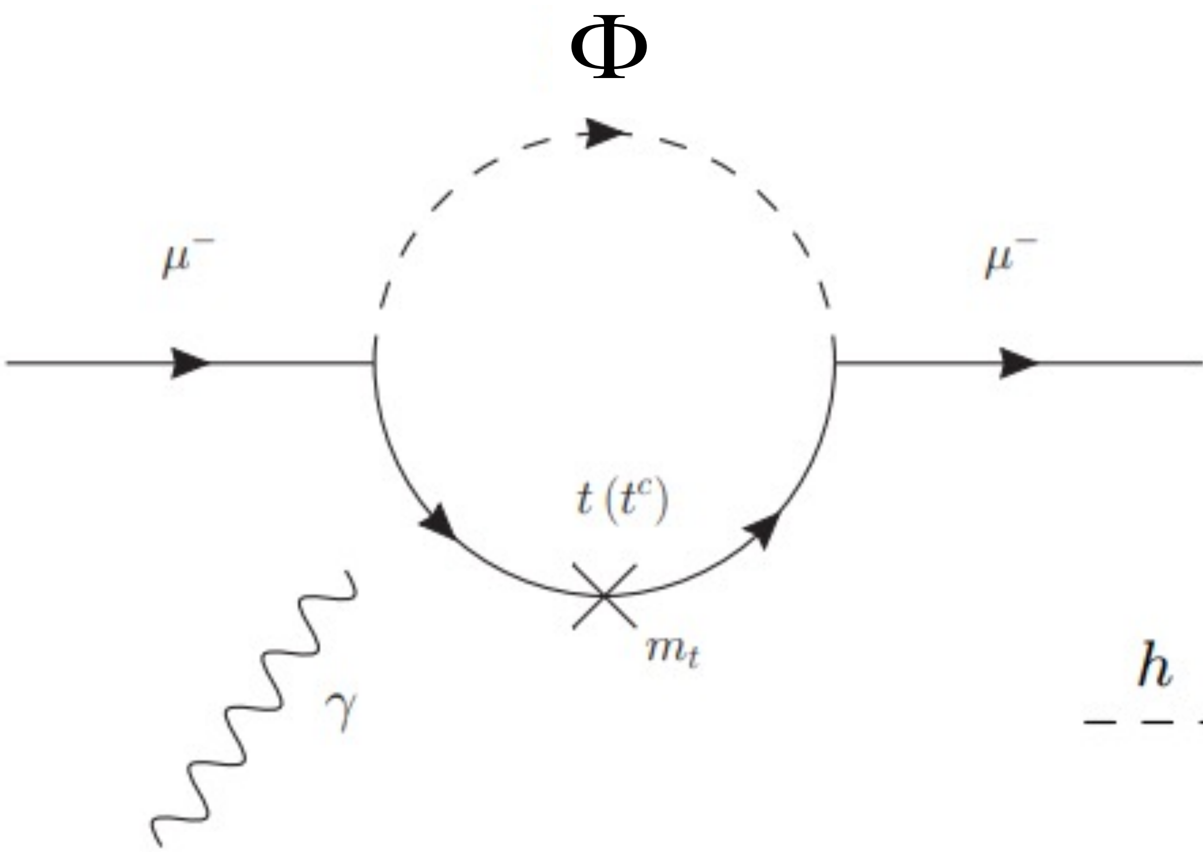
HEAVY NEW PHYSICS

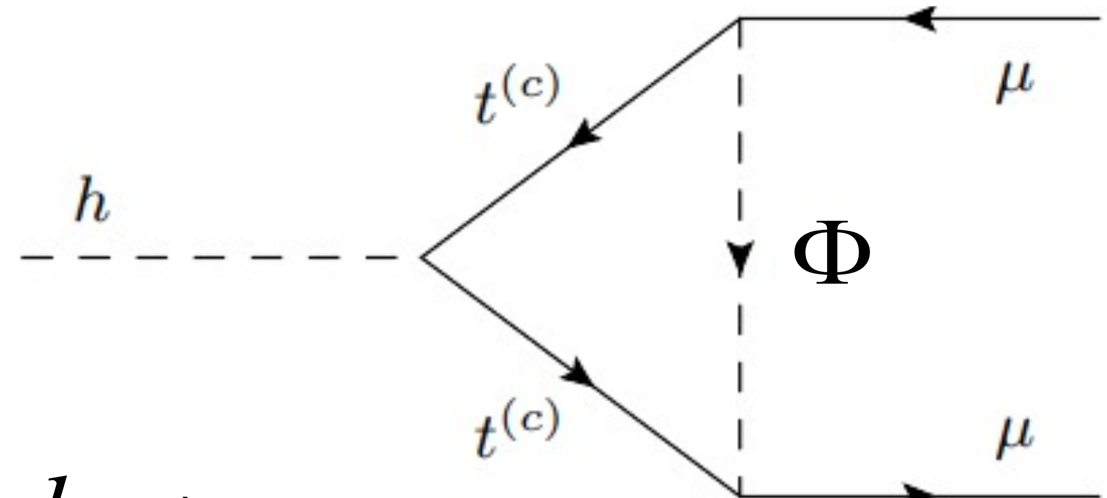
A guide towards New Physics



Leptoquarks in a_μ

- Chirally enhanced effects via top-loops



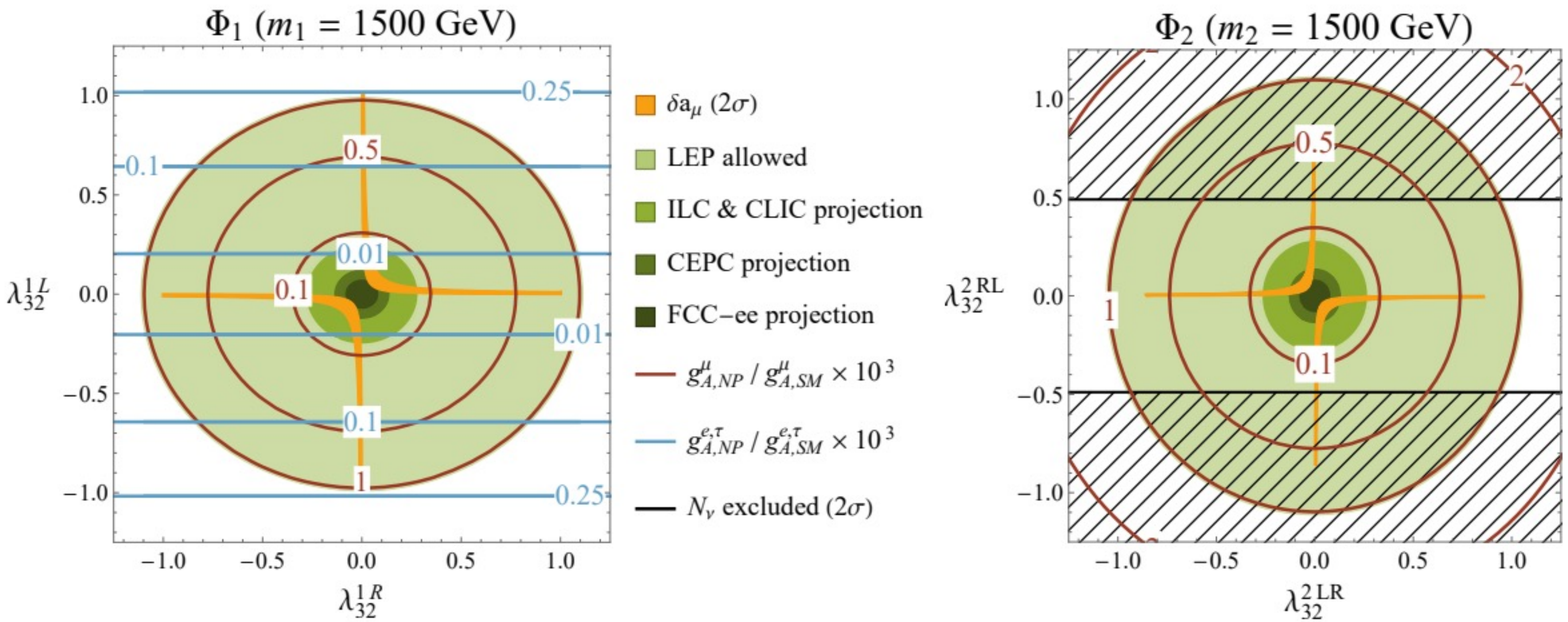


- m_t / m_μ enhanced effect $h \to \mu\mu$
- m_t^2 / m_Z^2 enhanced effect in $Z \to \mu\mu$

Correlations with h→μμ and Z→μμ

a_μ vs $Z\to\mu\mu$

- Chirally enhanced effects via top-loops



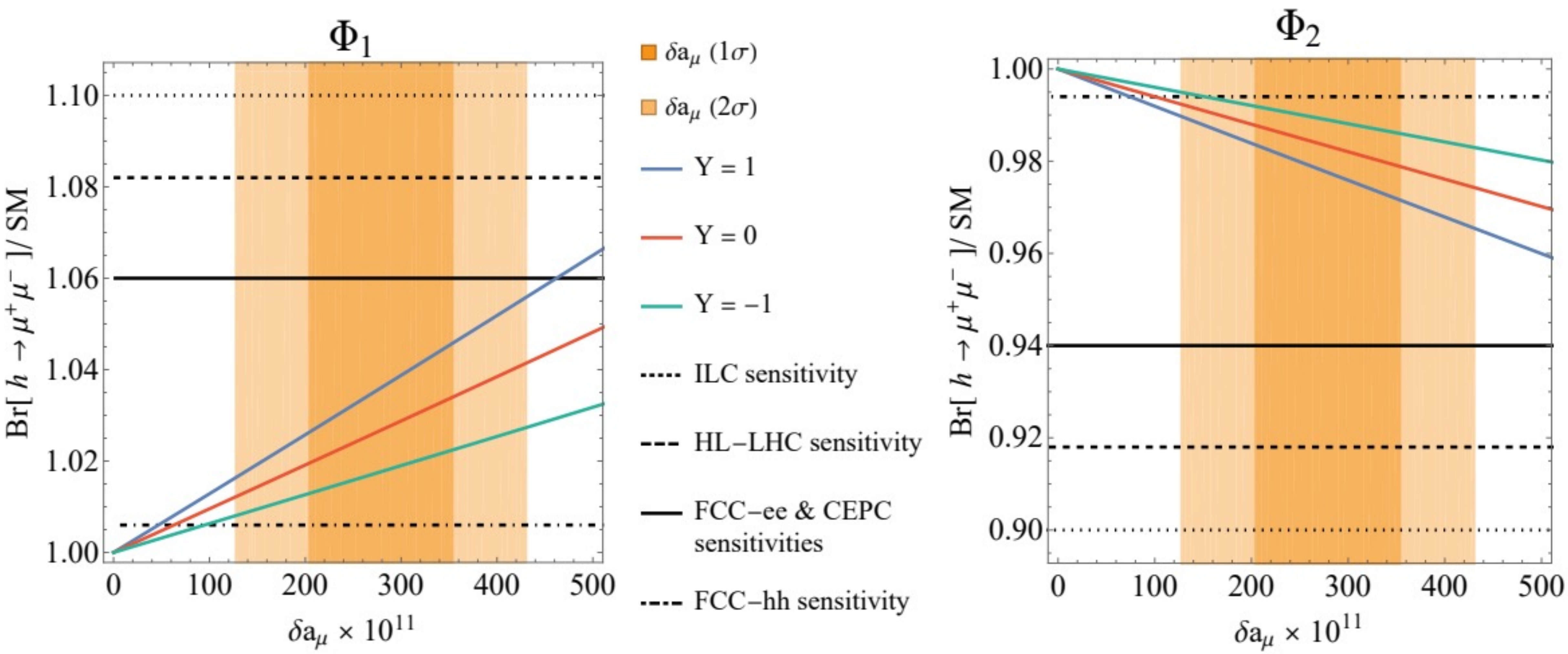
$\lambda_\mu^{L,R}$ Left-, right-handed muon-top coupling

E. Leskow, A.C., G. D'Ambrosio, D. Müller 1612.06858
A.C, C. Greub, D. Müller, F.Saturnino, 2010.06593

Z→μμ at future colliders

a_μ vs $h \to \mu\mu$

- Chirally enhanced effects via top-loops
- Same coupling structure → direct correlation



A.C., D. Mueller, F. Saturnino, 2008.02643

h→μμ at future colliders

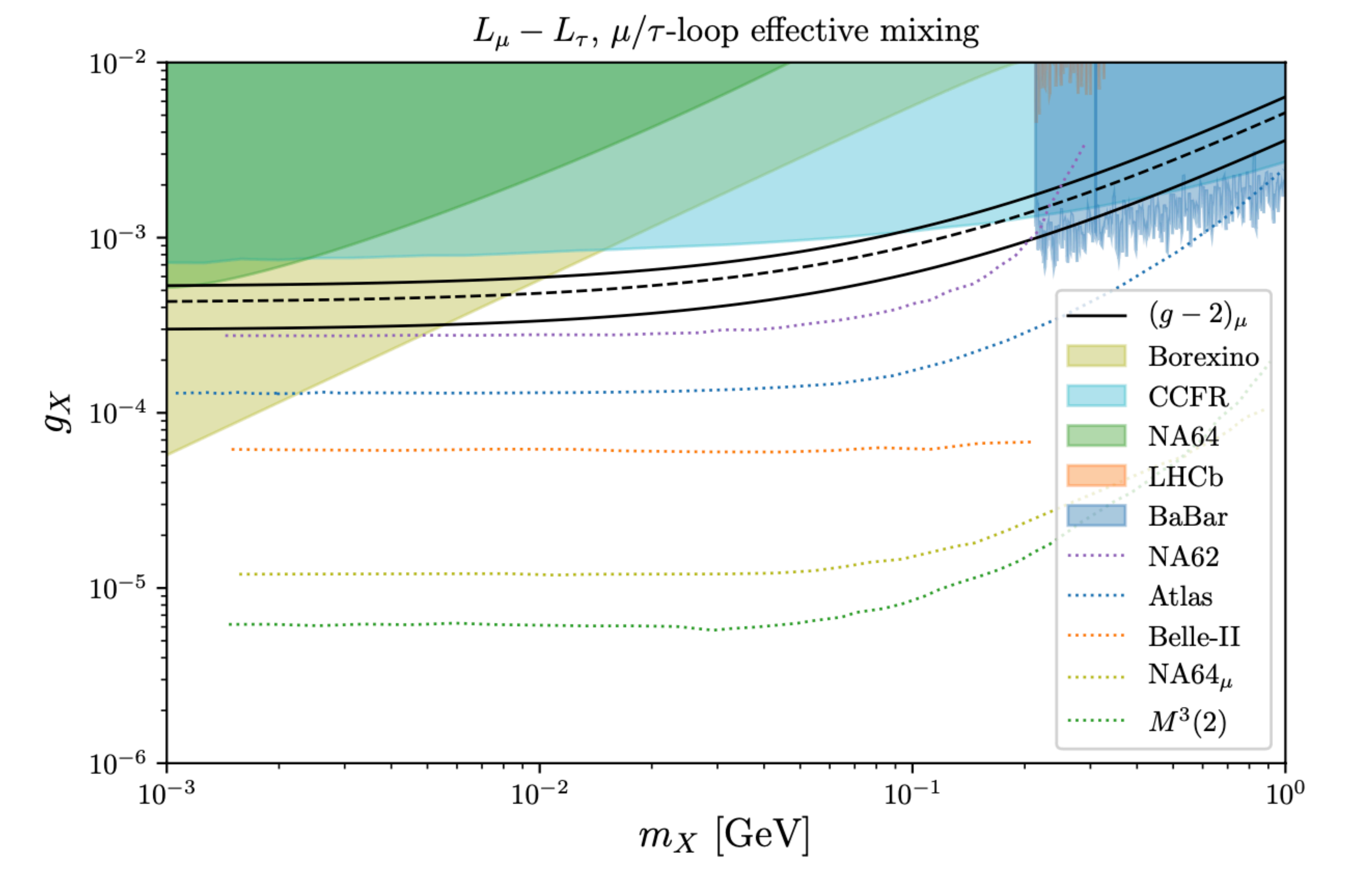
CONCLUSIONS

- two types of models that explain $(g-2)_\mu$
- light NP example: 10 MeV - 4 GeV gauged $U(1)_X$
  - viable models are perturbations around $L_\mu - L_\tau$
- heavy NP example:
  - leptoquark for $(g-2)_\mu$, more structure for other LFUV

BACKUP SLIDES

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 $(g-2)_\mu$



$L_\mu - L_\tau$, μ/τ-loop effective mixing
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
g_X
10^{-3}
10^{-2}
10^{-1}
10^{0}
m_X [GeV]
$(g-2)_\mu$
Borexino
CCFR
NA64
LHCb
BaBar
NA62
Atlas
Belle-II
NA64$_\mu$
$M^3(2)$