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Hunting Hidden Photons

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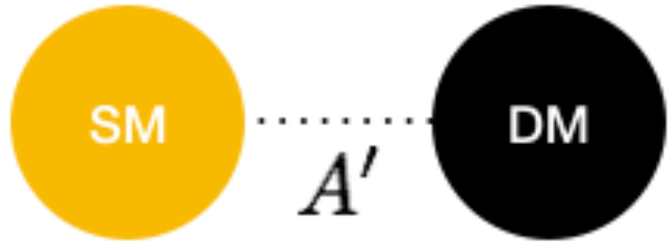
based on

[Bauer, PF, Jaeckel; arxiv:1803.05466]
[PF; arXiv:1808.03647]

Fourth LHC LLP workshop, Amsterdam — October 24, 2018

Motivation

- We have ample evidence for DM, but internal dynamics of dark sector is an open question.

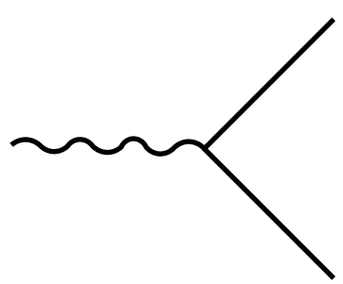


- If we add extra U(1), gauge invariance and renormalizability allow for the kinetic mixing portal term.

$$\mathcal{L}_{\rm kin} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}$$

- Bringing kinetic terms into canonical form:

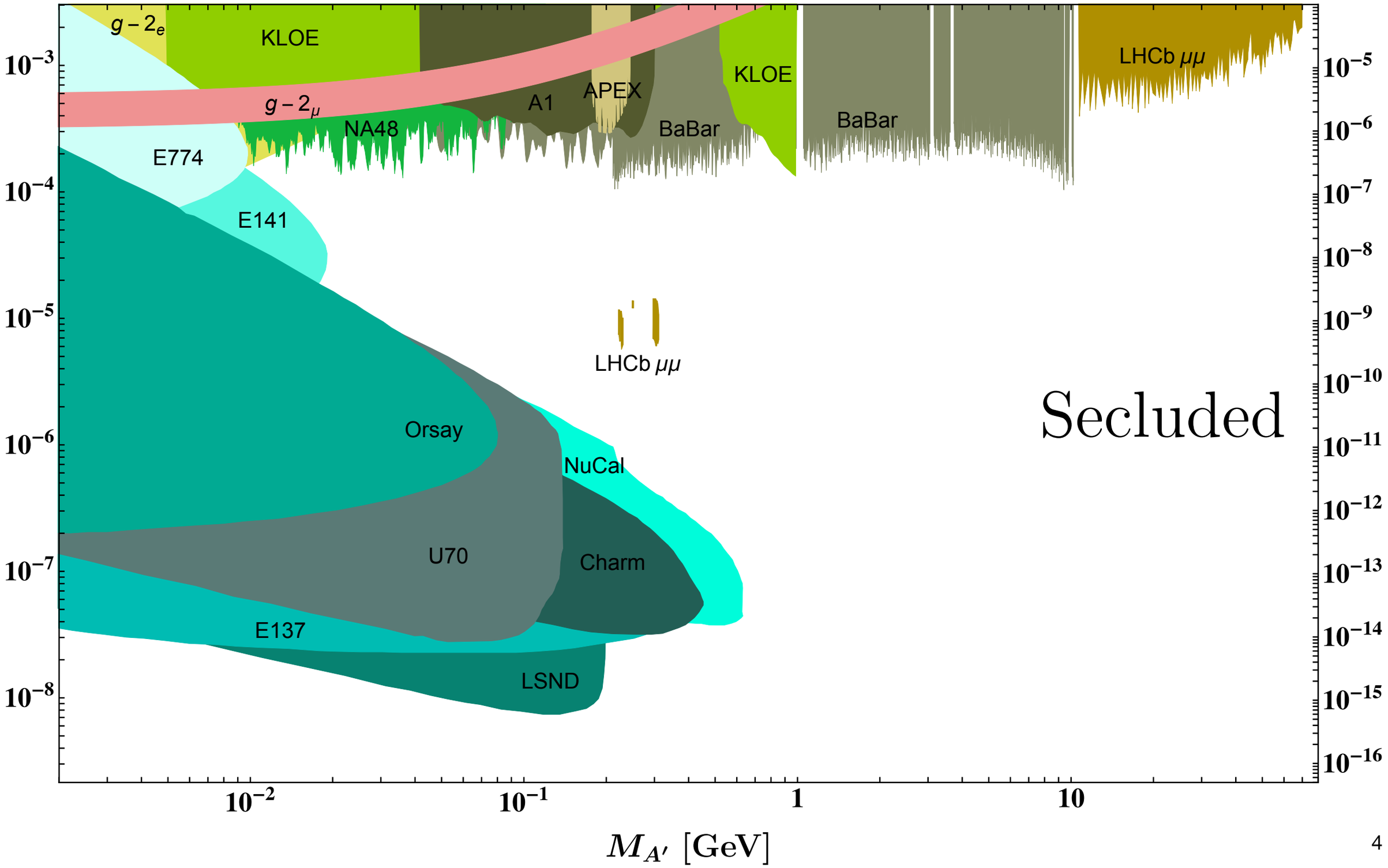
$$A^\mu \to A^\mu - \epsilon A'^\mu \quad \longrightarrow \quad eA_\mu J^\mu_{\rm EM} - \epsilon\, eA'_\mu J^\mu_{\rm EM}$$



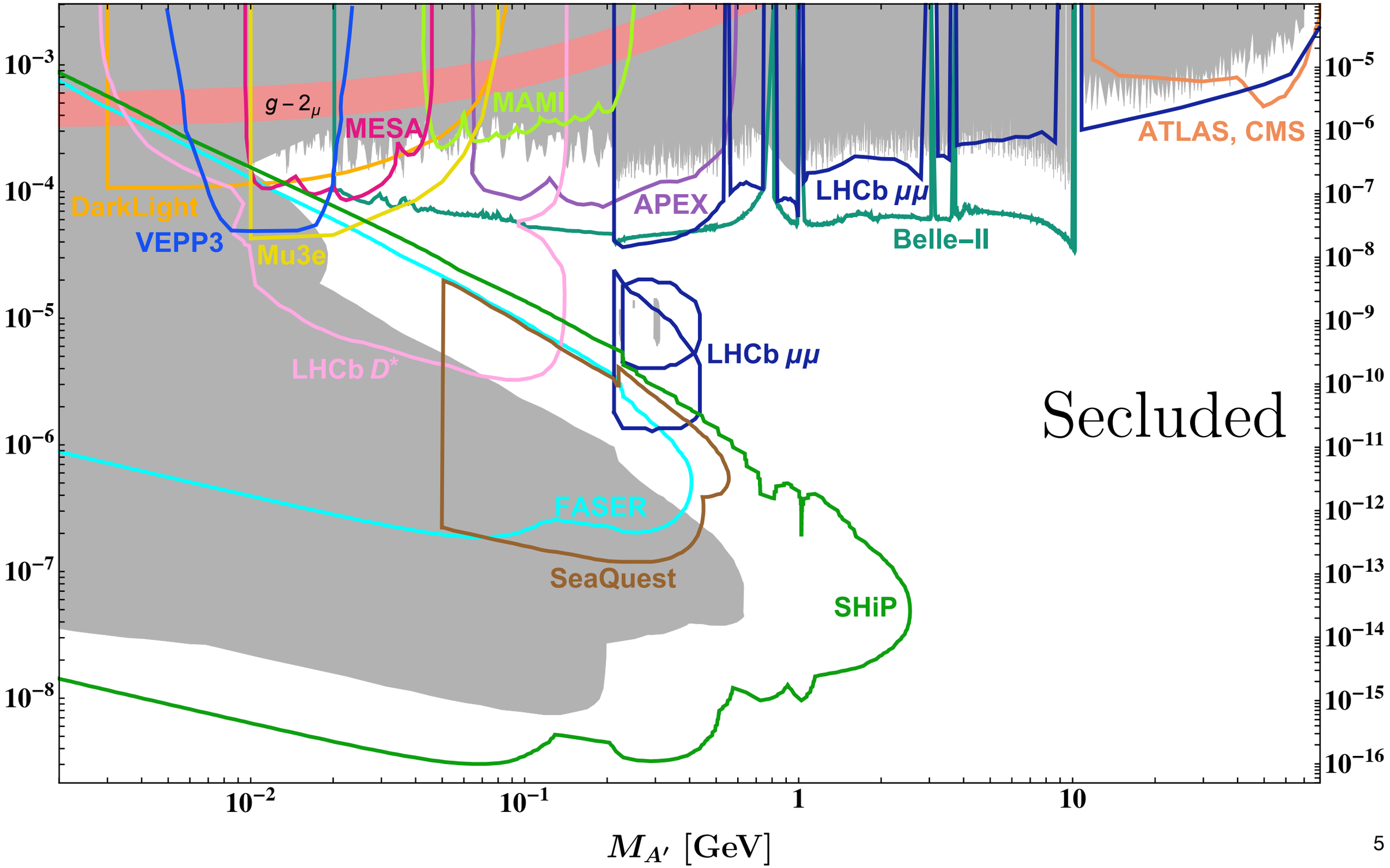
Secluded Hidden Photon

No SM fields are charged under the new U(1) symmetry.

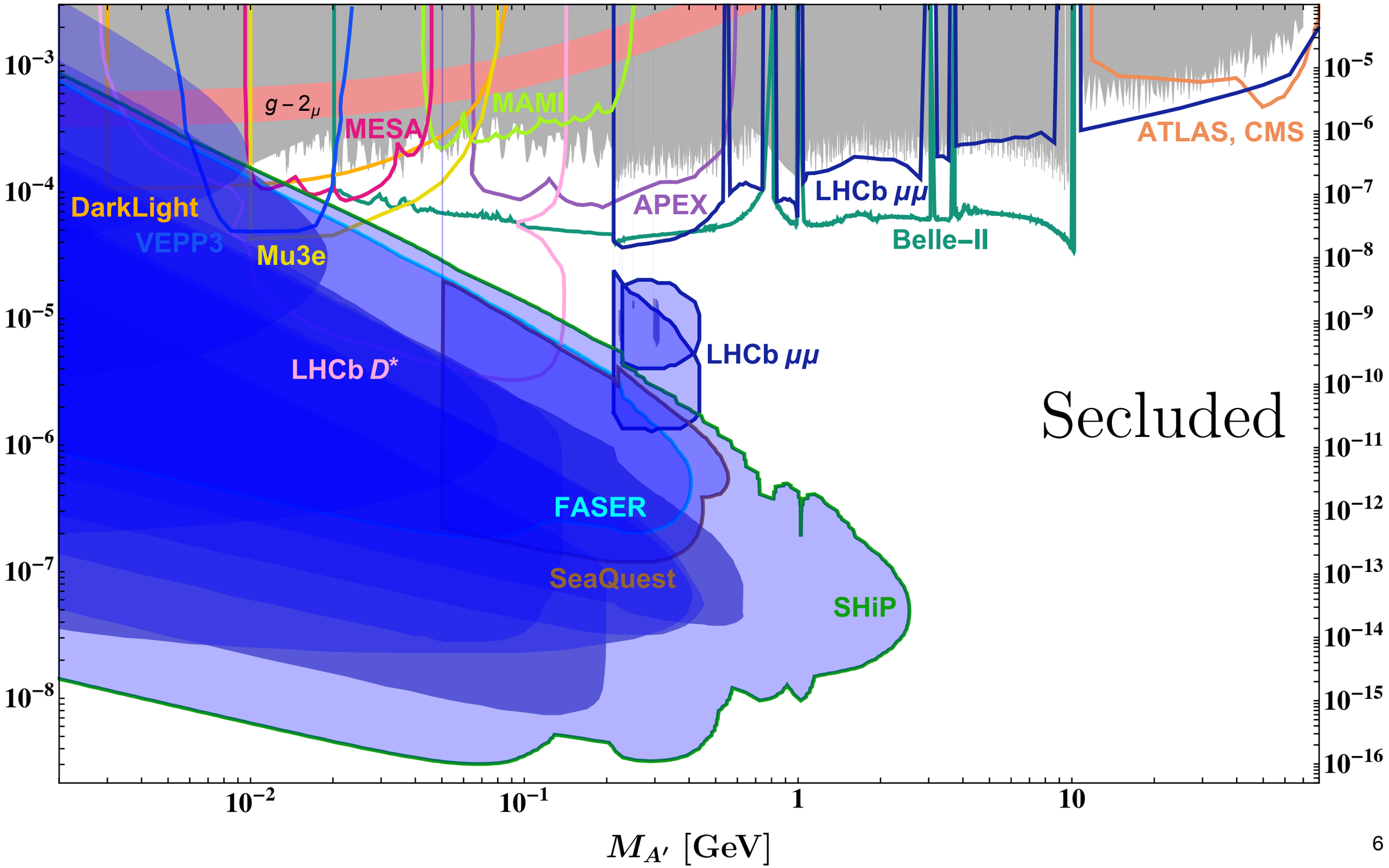
Secluded $U(1)_X$ - current status



Secluded $U(1)_X$ - future sensitivity



Displaced searches (LLPs)



Gauge Boson Mass

- Higgs breaking of new U(1):

$$\mathcal{L} = (D_\mu S)^\dagger D^\mu S = (\partial_\mu + ig' A'_\mu)(f + \xi)(\partial^\mu - ig' A'^\mu)(f + \xi)$$
$$\supset g'^2 f^2 A'_\mu A'^\mu$$

$$\boxed{M_{A'} = g' f}$$

- If A' is light it must also be very weakly coupled → long-lived

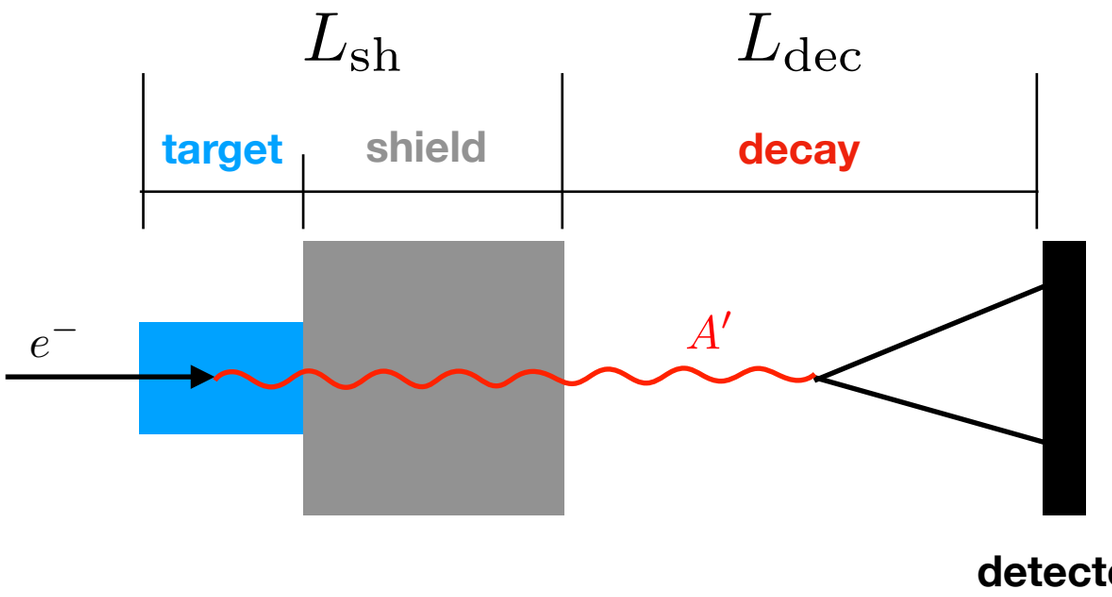
→ A prime candidate for displaced searches!

Beam dumps — ideal HP experiments

A' naturally light and weakly coupled: $M_{A'} = g' f$

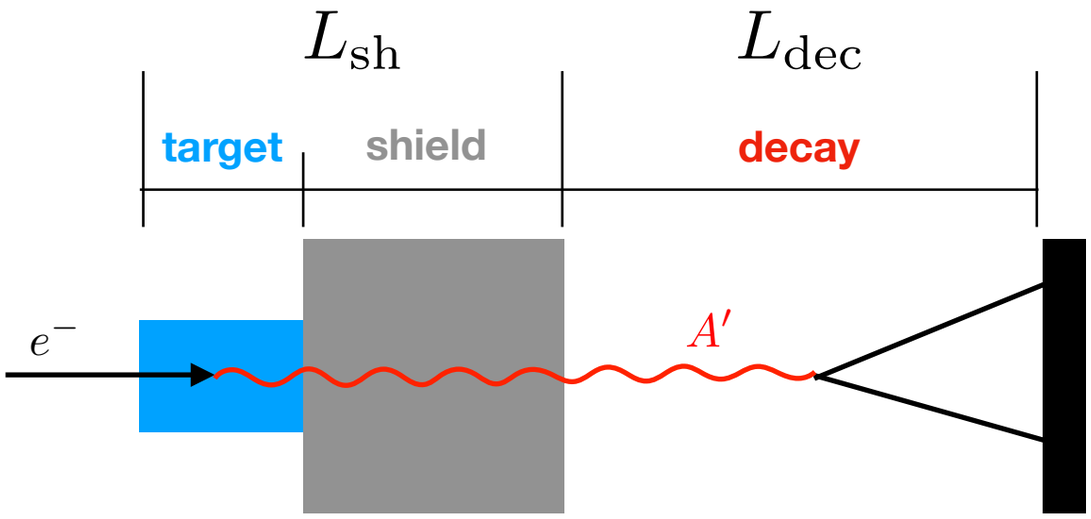
Beam dumps — ideal HP experiments

A' naturally light and weakly coupled: $M_{A'} = g' f$



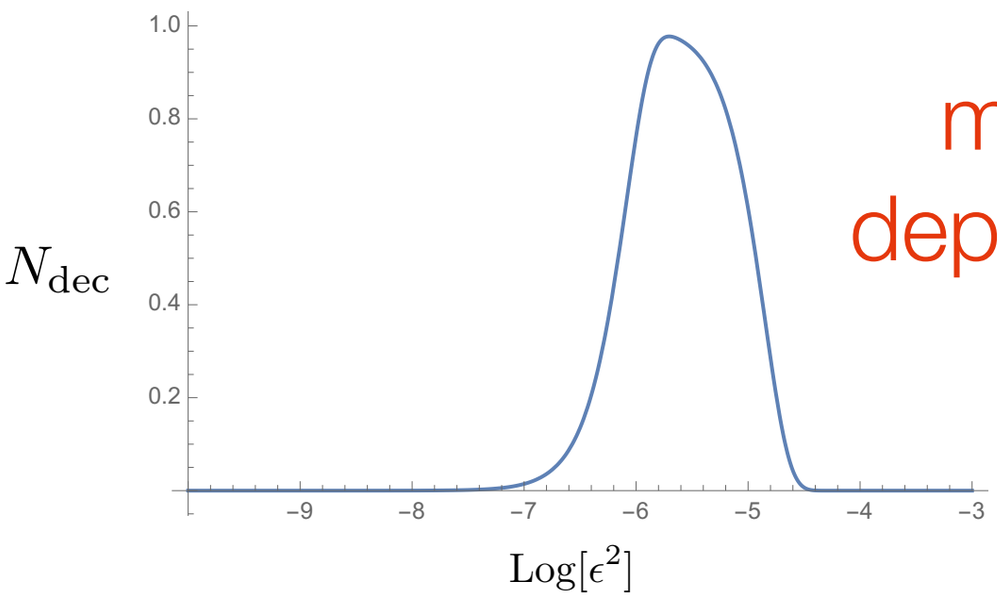
Beam dumps — ideal HP experiments

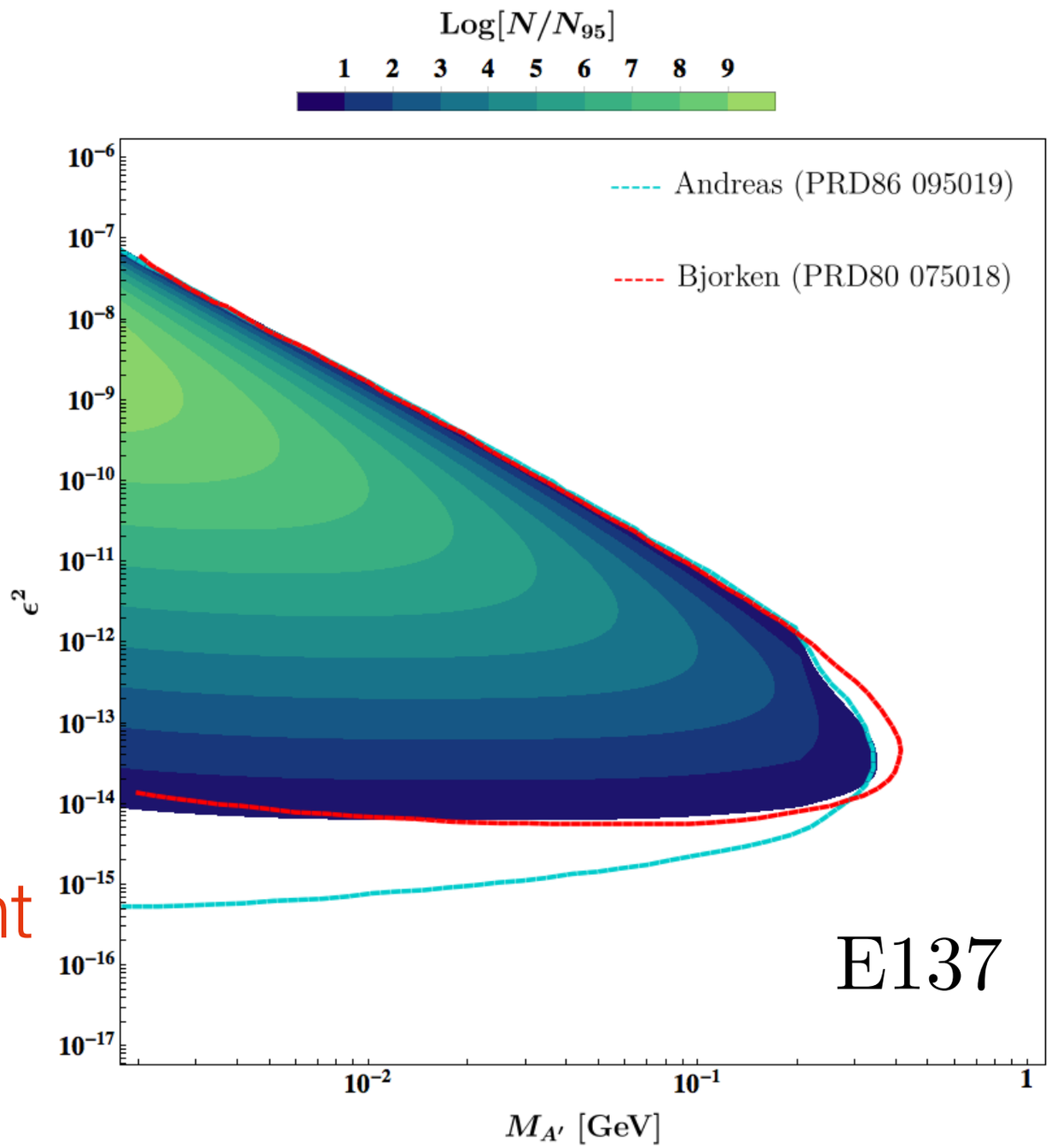
A' naturally light and weakly coupled: $M_{A'} = g' f$



$$N_{\rm dec} \propto e^{-\frac{L_{\rm sh}}{\ell_{A'}}}\left(1 - e^{-\frac{L_{\rm dec}}{\ell_{A'}}}\right)$$

model dependent





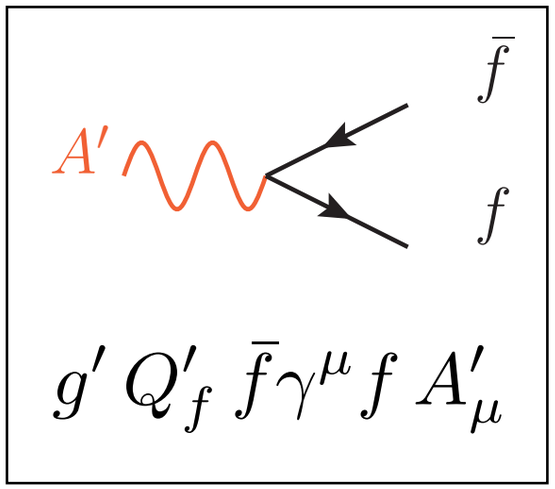
Anomaly-free gauge groups

Some SM fields are charged under the new U(1) symmetry.

Charging SM fields under extra U(1)

- Four extra anomaly-free groups within the SM:

$B - L$	$L_\mu - L_e$	$L_e - L_\tau$	$L_\mu - L_\tau$
charging quarks & leptons	charging 1st & 2nd generation leptons	charging 1st & 3rd generation leptons	charging 2nd & 3rd generation leptons



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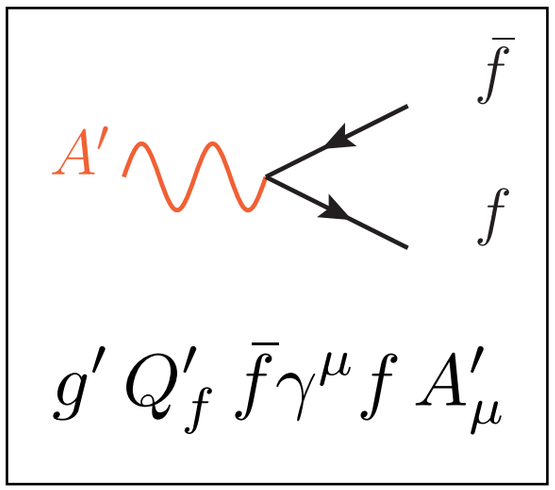
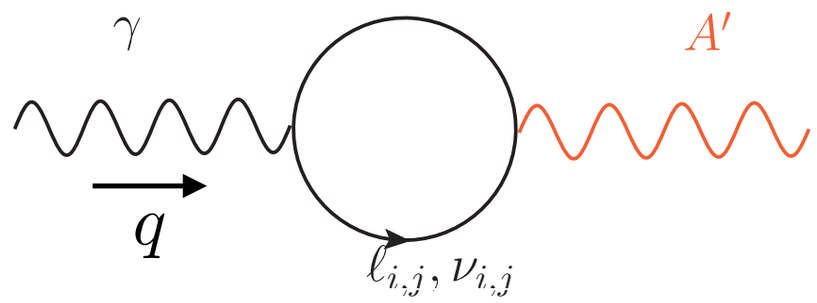


- Loop-induced mixing is unavoidable!
  However, it is finite and calculable for $L_i - L_j$:

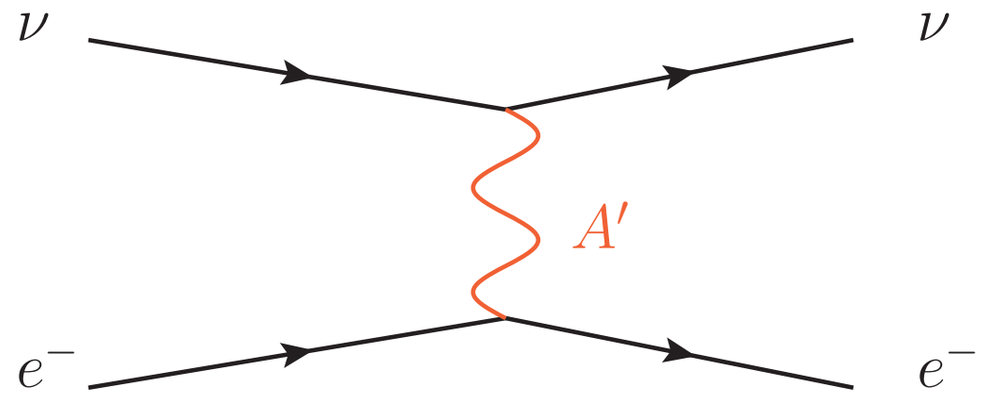


$$\Rightarrow \quad \frac{\epsilon_{ij}(q^2)}{2} F^{\mu\nu} F'_{\mu\nu}$$

$$\epsilon_{ij}(q^2) \simeq \frac{3\, e\, g_{ij}}{4\pi^2} \int_0^1 dx\, x(1-x) \log\left(\frac{m_i^2 + q^2 x(x-1)}{m_j^2 + q^2 x(x-1)}\right)$$

Neutrino scattering experiments

- **Example:** Borexino has measured the elastic scattering rate of solar neutrinos.



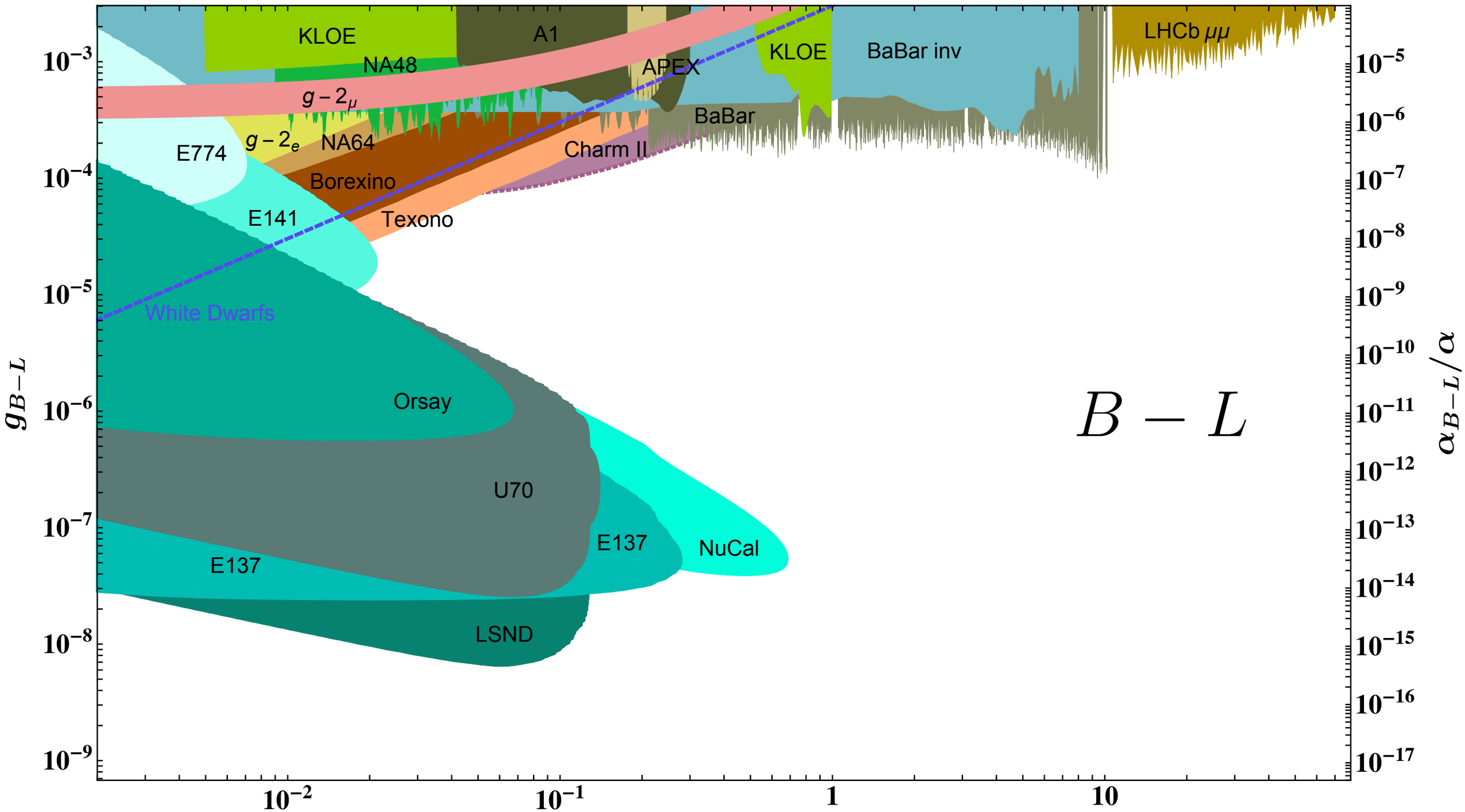
- Solar (electron) neutrinos oscillate on way to earth.

→ All neutrino flavors can contribute to scattering:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E} \propto \sum_{i,j=1}^{3} f_i \ |g' \left(U^\dagger Q_\nu U\right)_{ij}|^2$$

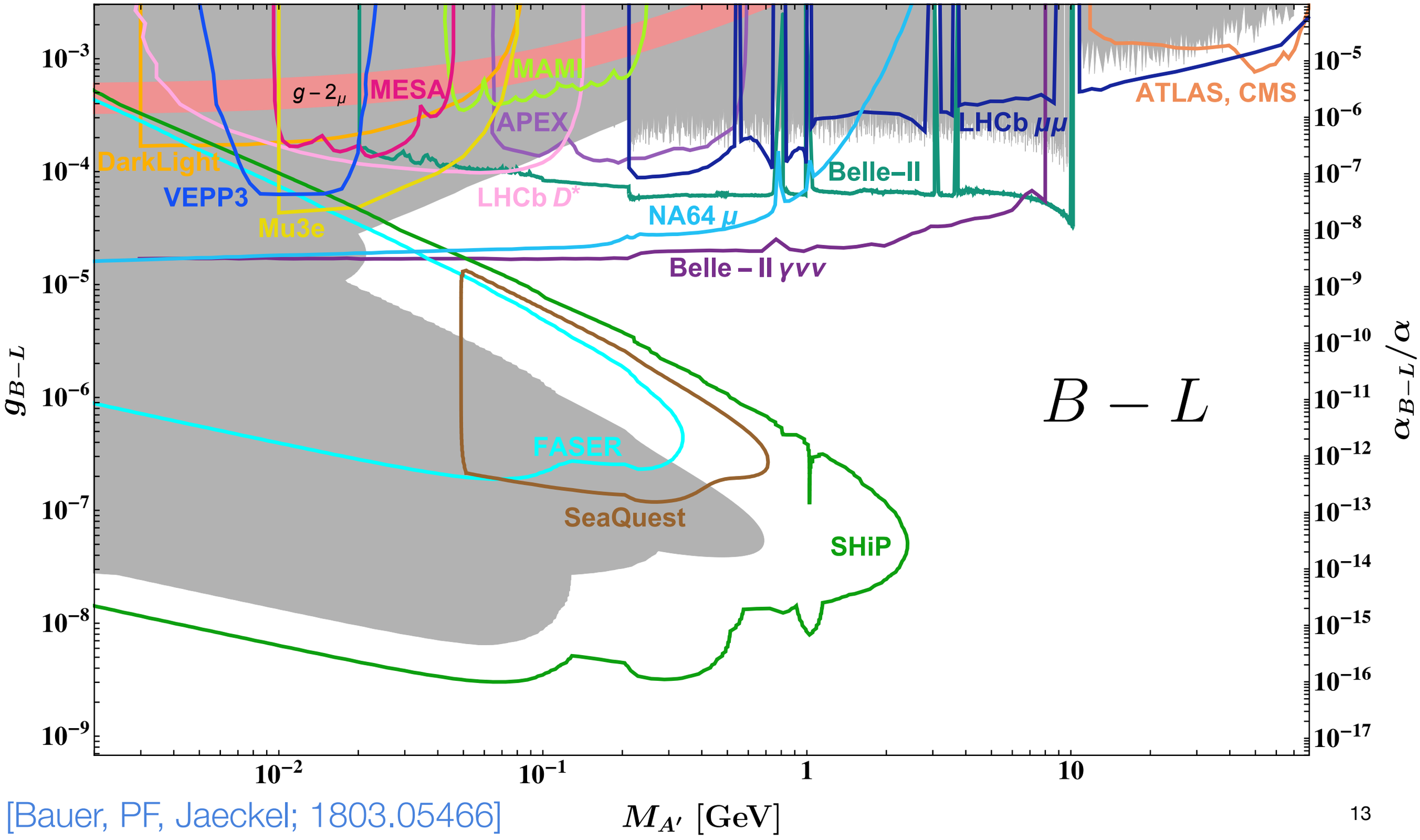
with lepton mixing matrix U, neutrino charge matrix Q_ν and the fraction f_i of the i-th neutrino mass eigenstate at earth.

$B - L$ - current status



[Bauer, PF, Jaeckel; 1803.05466]

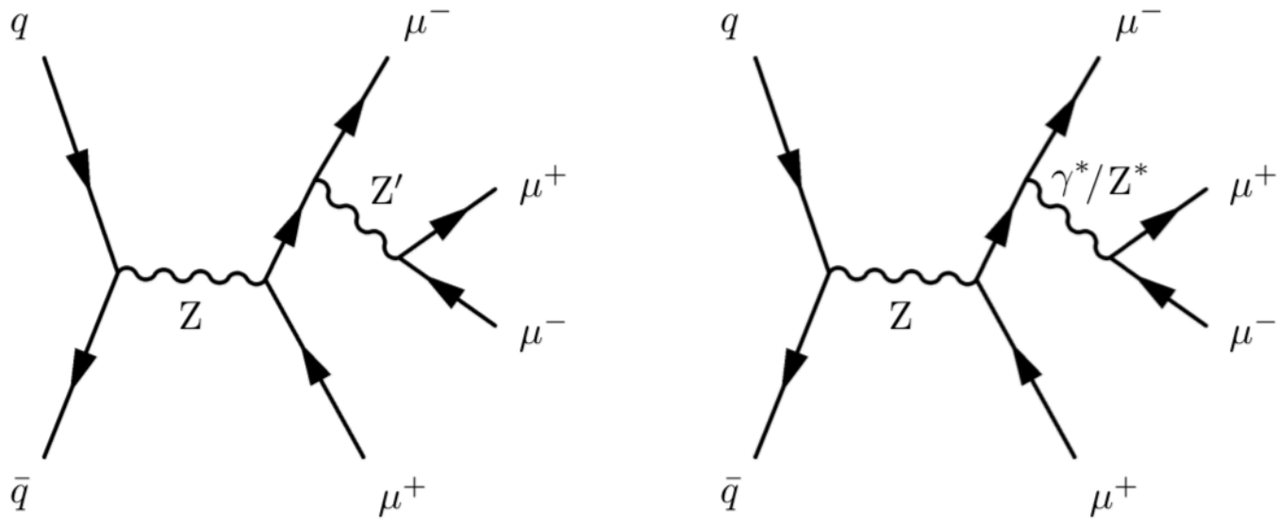
$B - L$ - future sensitivity

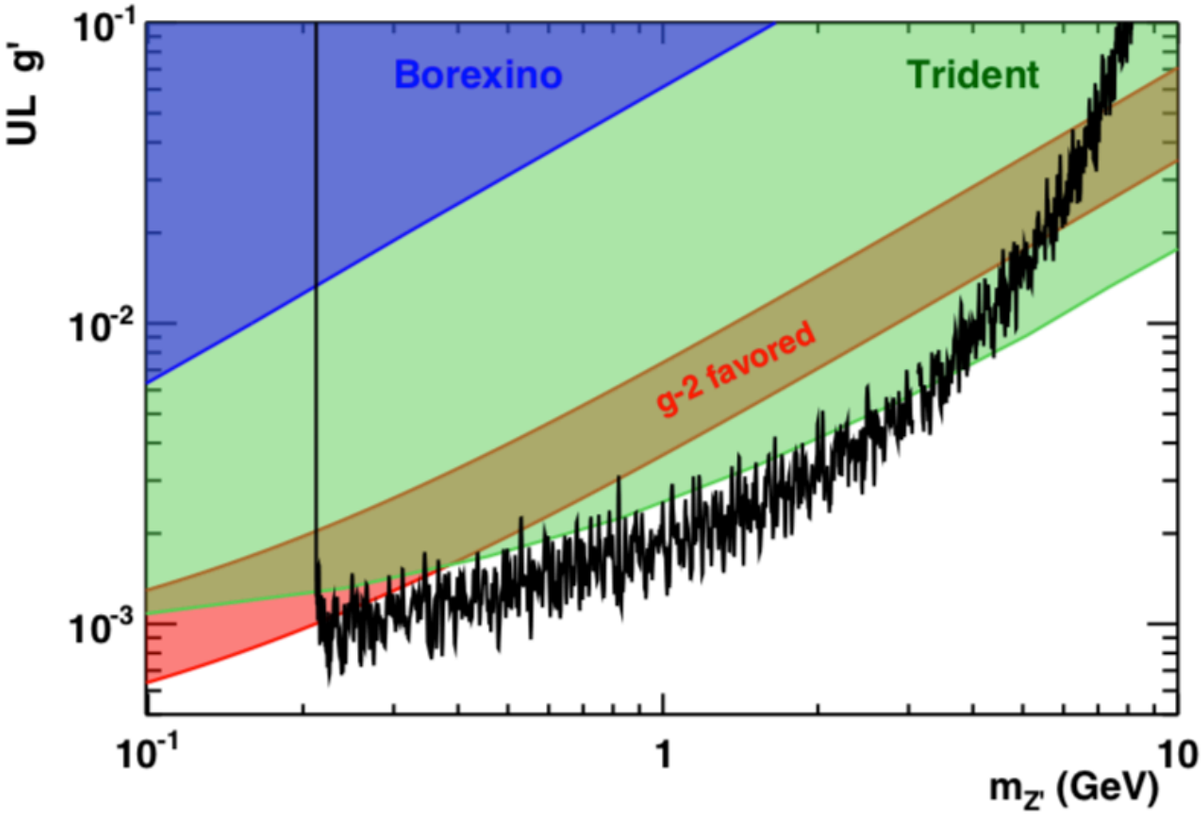


[Bauer, PF, Jaeckel; 1803.05466]

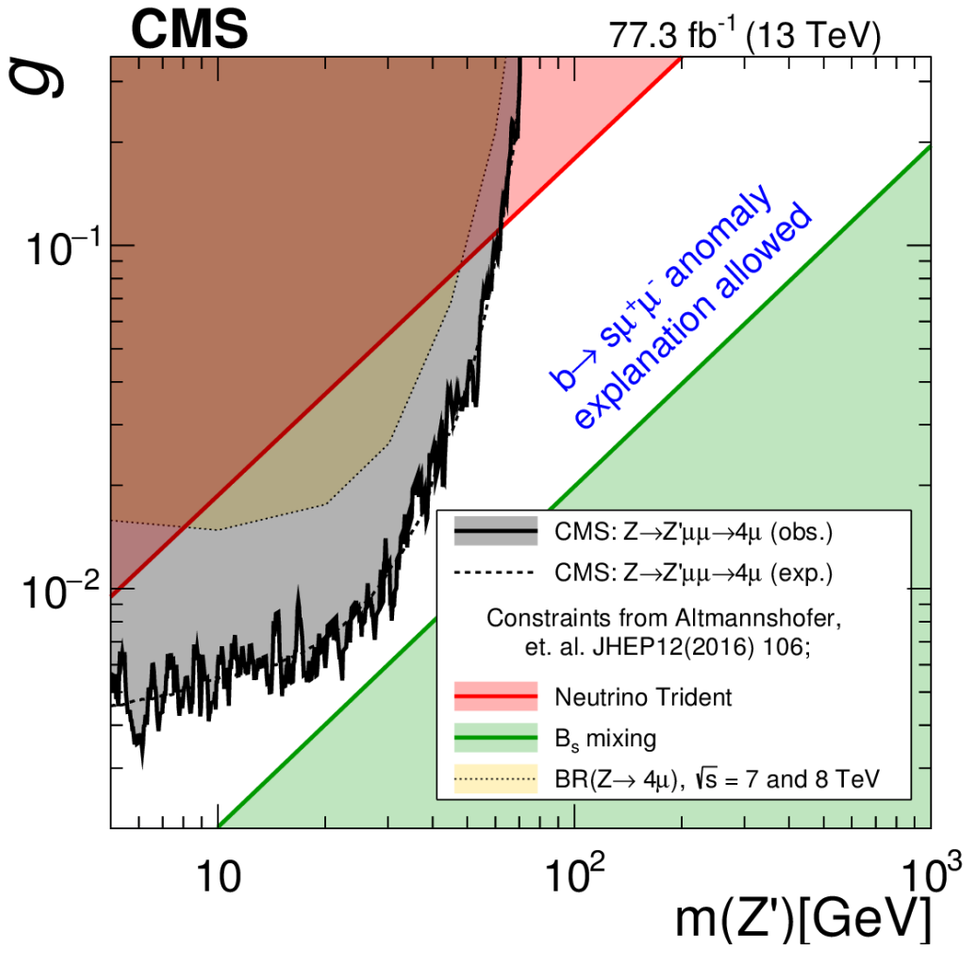
Charging L_μ: Four-muon signature

For charged L_μ the HP contributes significantly to a four-muon final state in colliders





[BaBar PRD **94**, 011102]



[CMS, 1808.03684]

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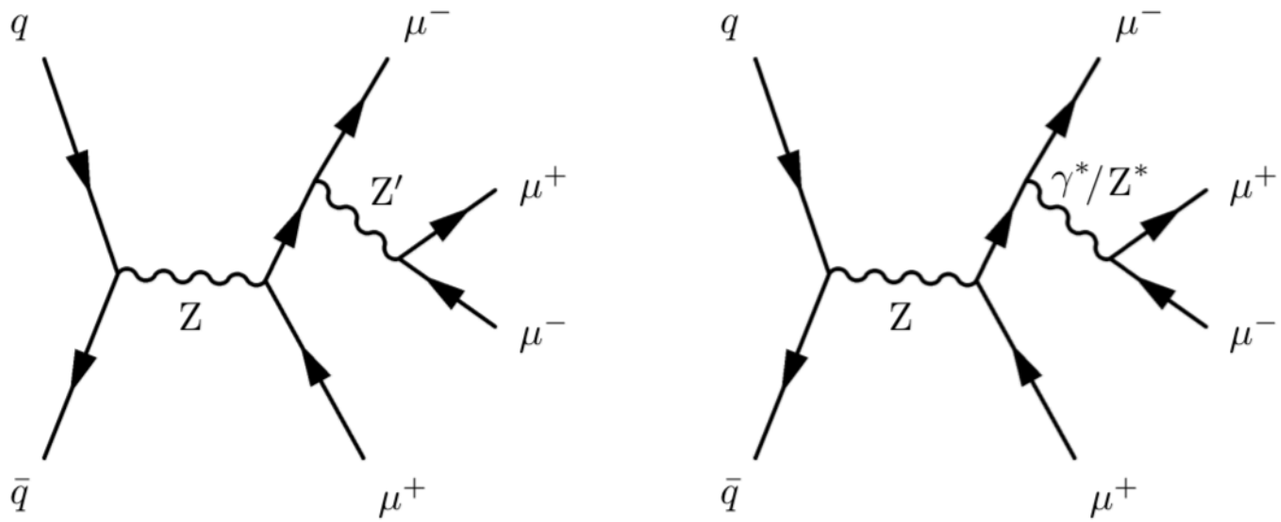
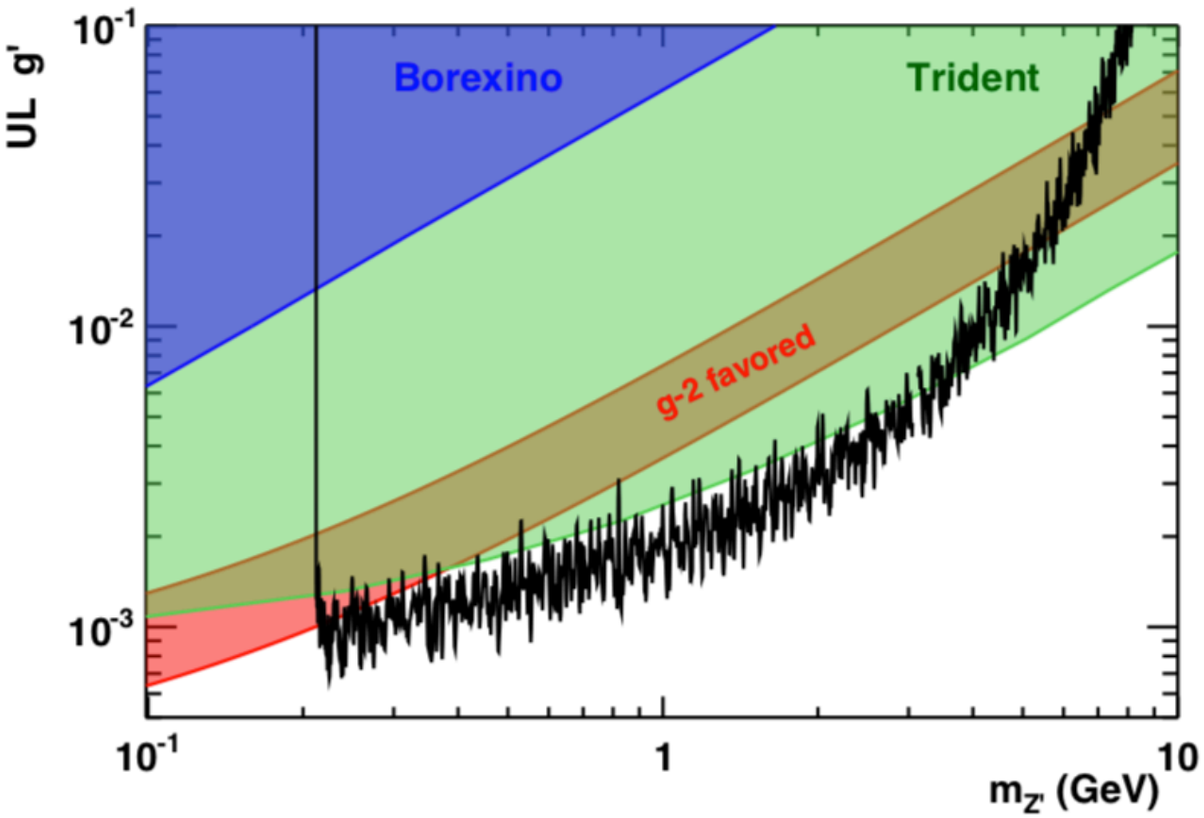
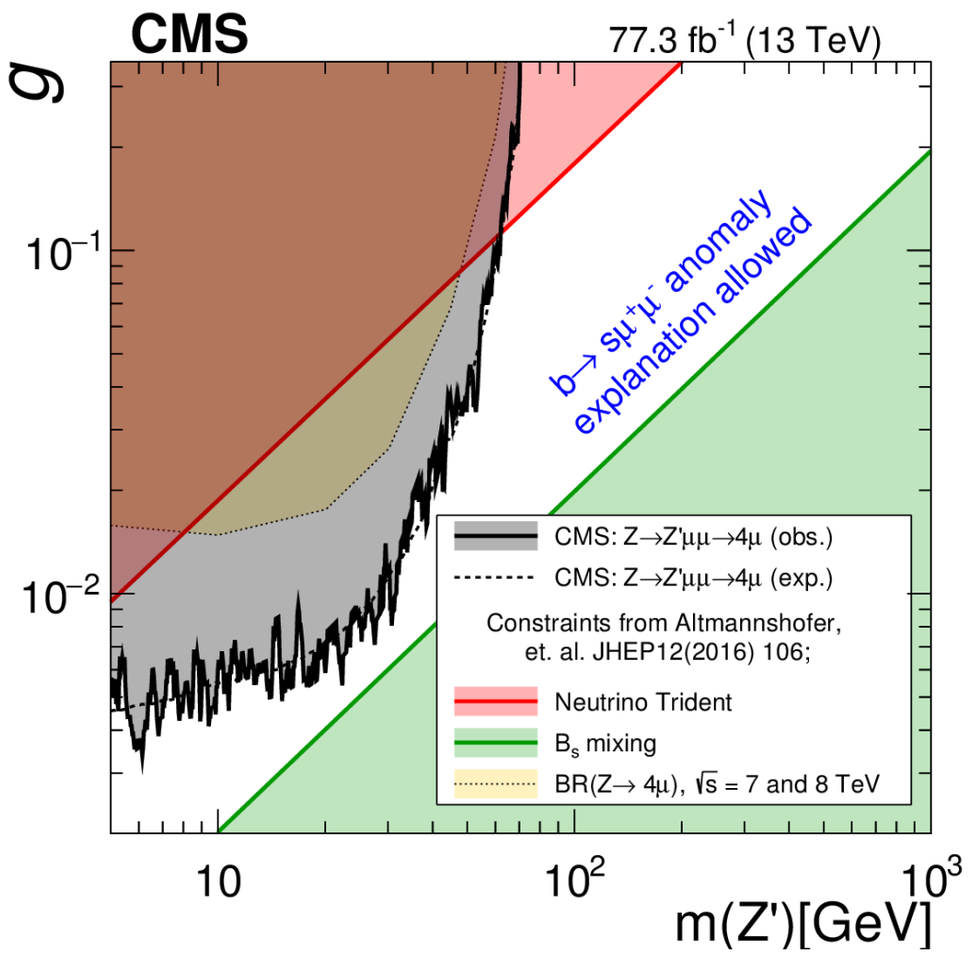


What about 2 displaced muons?

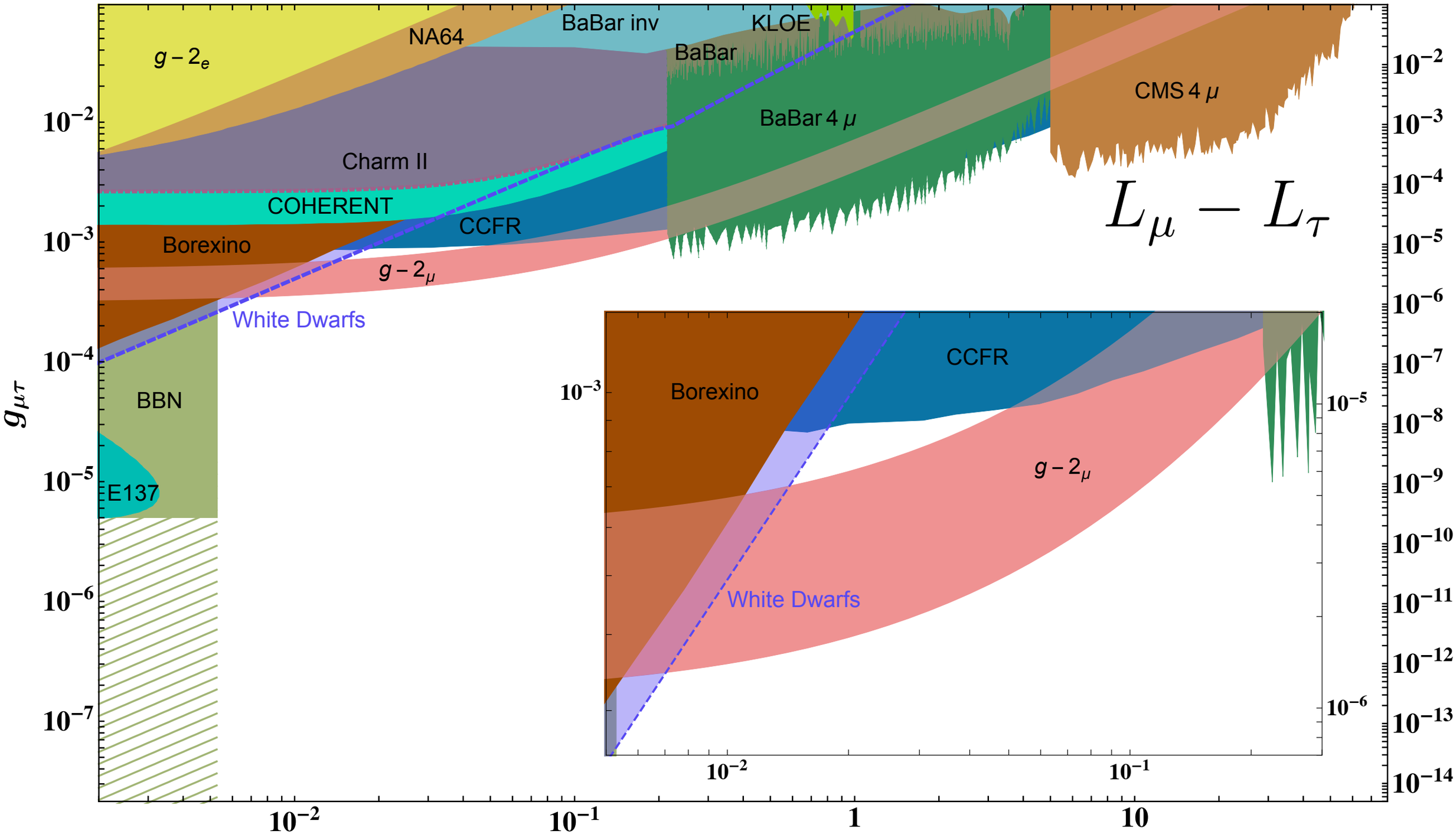


[BaBar PRD **94**, 011102]



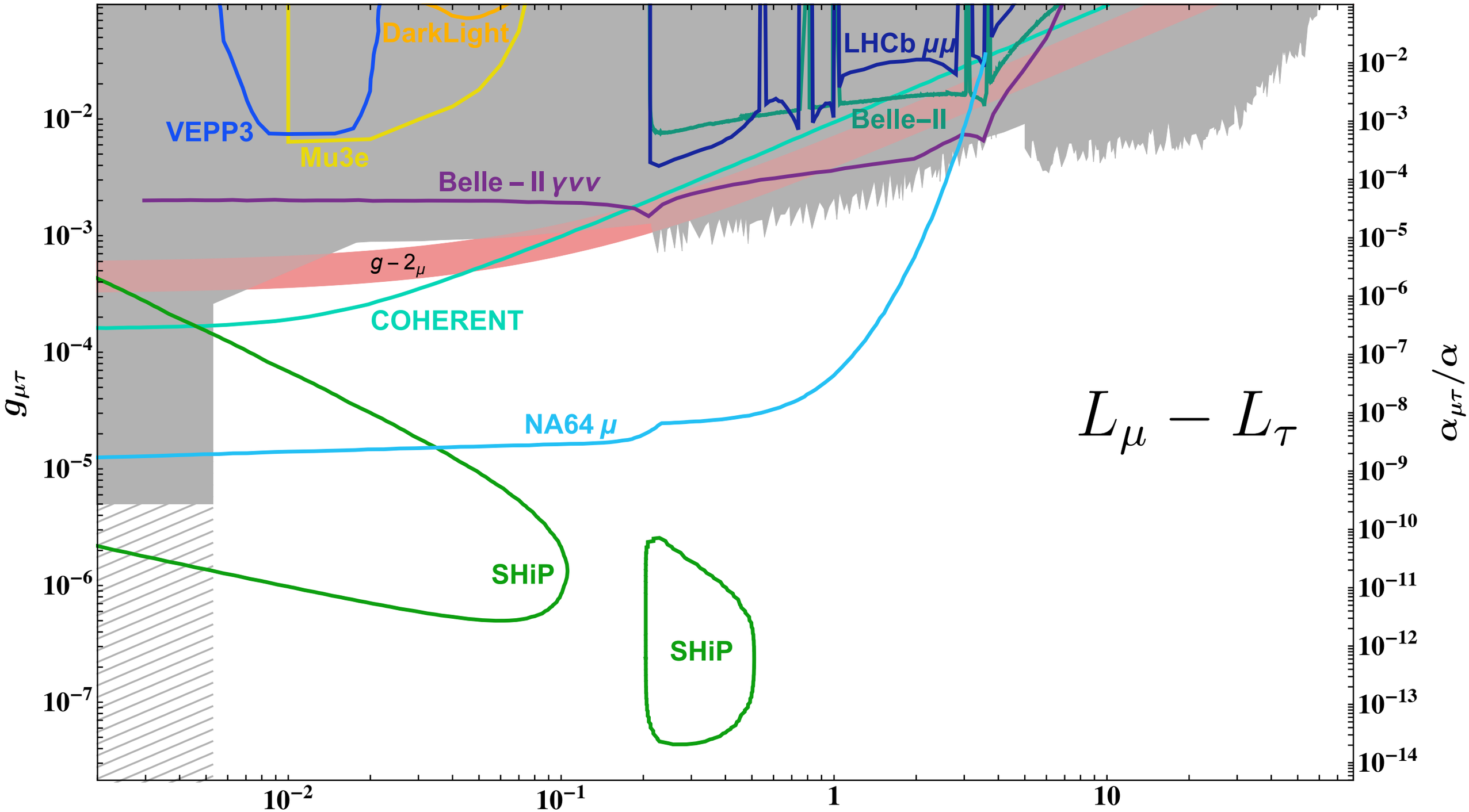
[CMS, 1808.03684]

$L_\mu - L_\tau$ - current status



[Bauer, PF, Jaeckel; 1803.05466]

$L_\mu - L_\tau$ - future sensitivity



[Bauer, PF, Jaeckel; 1803.05466]

Let there be light DM

Augment field content by light vector-like fermion charged under $U(1)_{L_\mu - L_\tau}$.

Vector-like DM within $U(1)_{L_\mu - L_\tau}$

- Add a vector-like fermion: $\mathcal{L} = -g_{\mu\tau}\, Q_\chi\ \bar{\chi}\gamma^\mu\chi\, A'_\mu$

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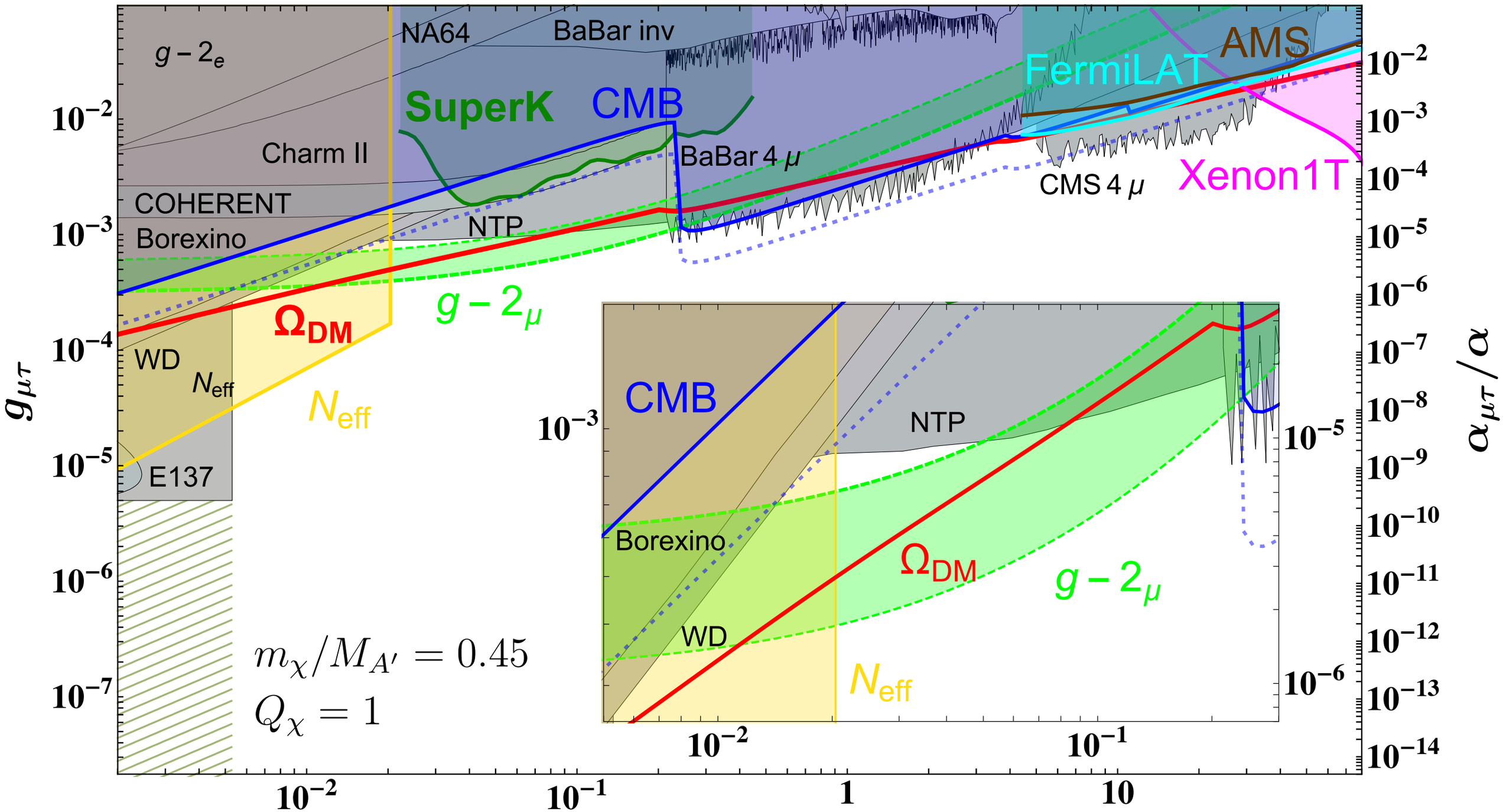
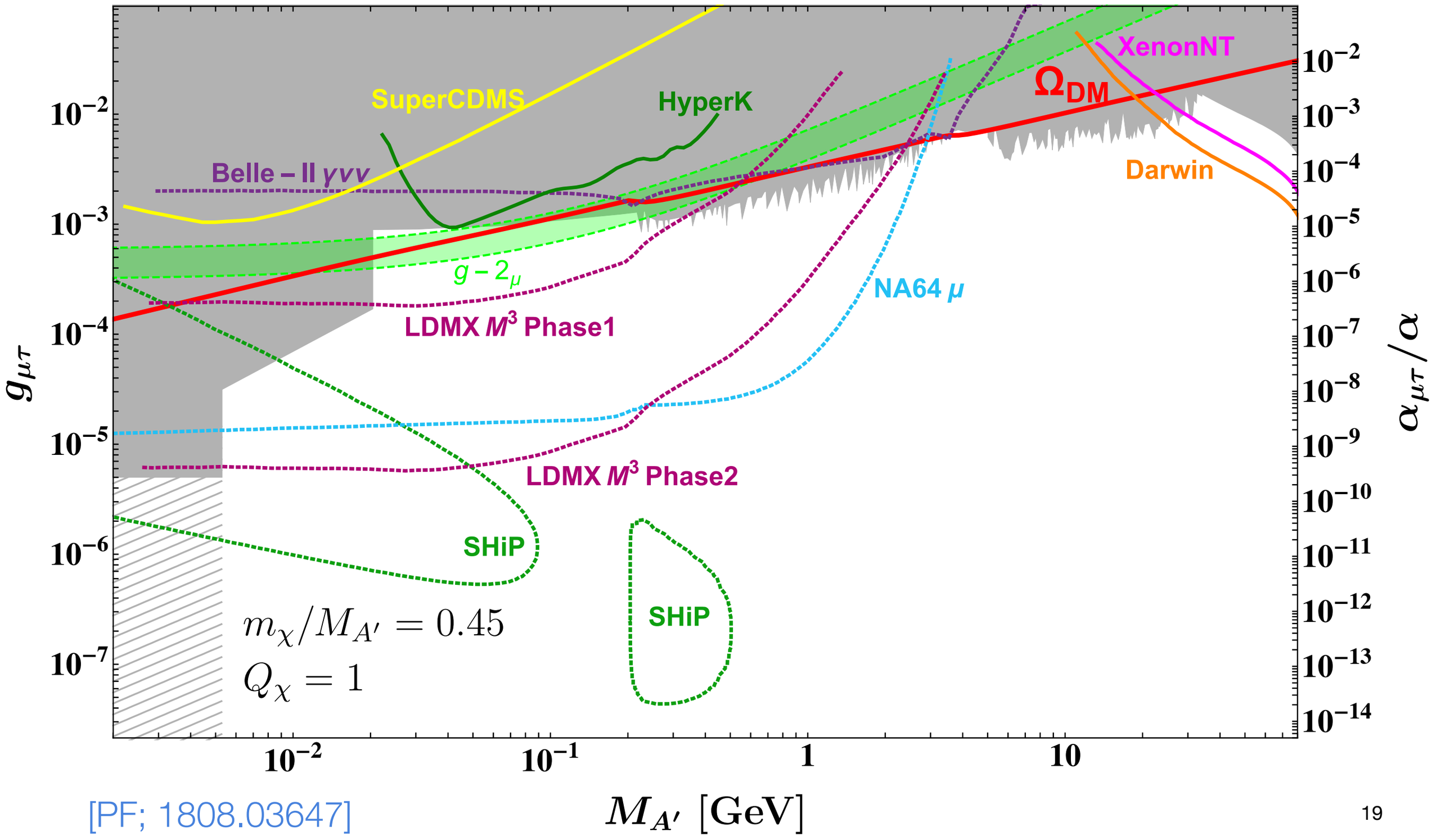


[PF; 1808.03647]

$L_\mu - L_\tau$ DM — future sensitivity

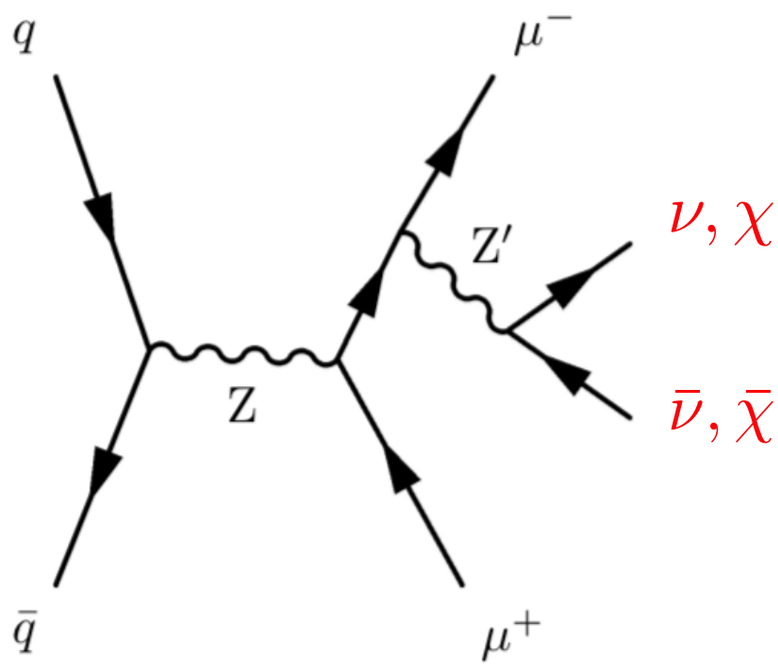


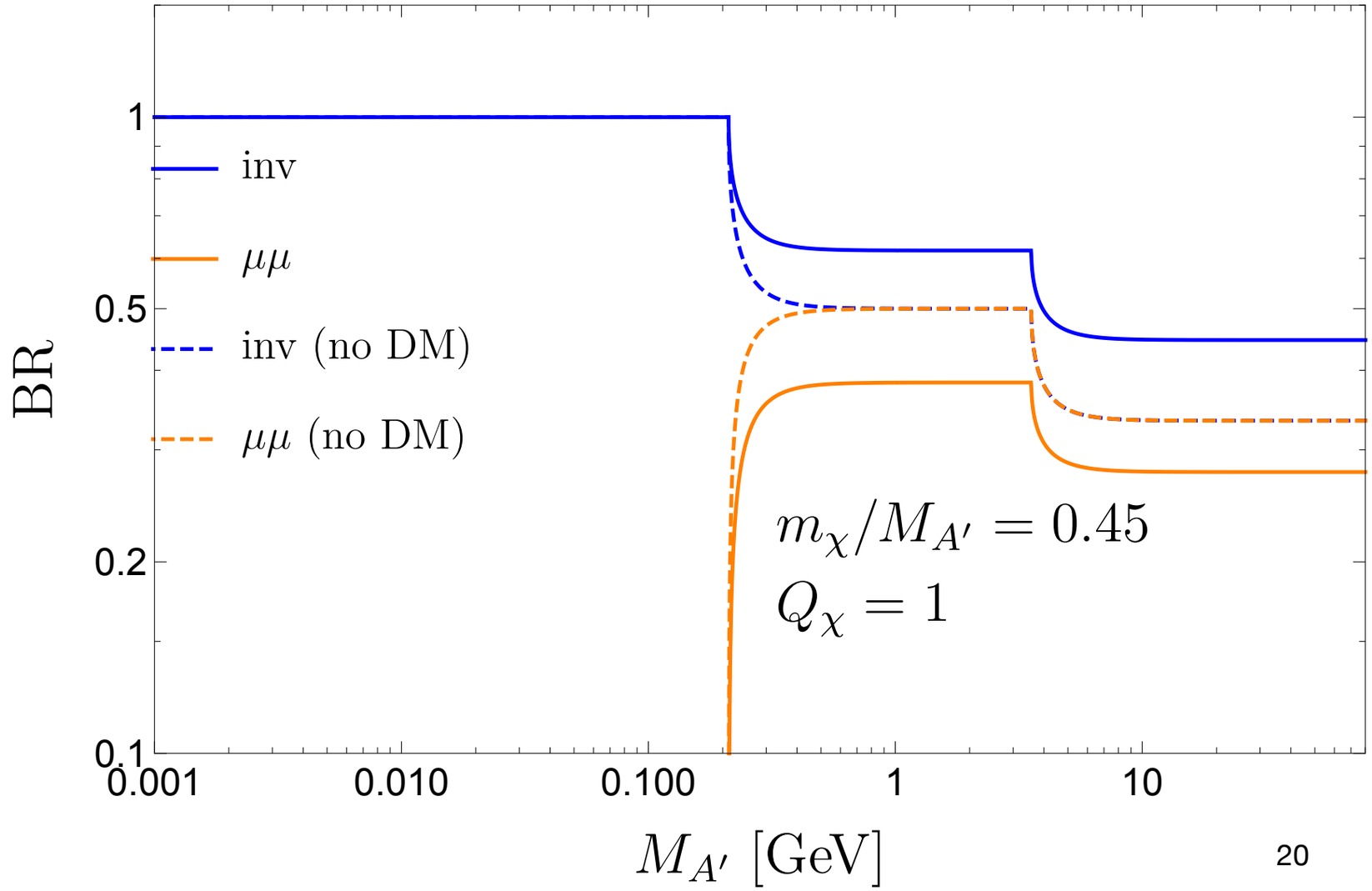
[PF; 1808.03647]

$L_\mu - L_\tau$ DM — Smoking gun ?

- A' has sizable invisible branching fraction!

- Possible smoking gun could be mono-X + MET or
  Dimuon + MET signatures → is this measurable?





Conclusions

- Gauge couplings to SM particles can ***dramatically* reshape** the landscape of **HP constraints**.
  ⟶ Different experiments are sensitive to different scenarios!

- New **white dwarf limit** improved over previous Borexino constraints and **rules out** part of the $(g-2)_\mu$ explanation of $L_\mu - L_\tau$.

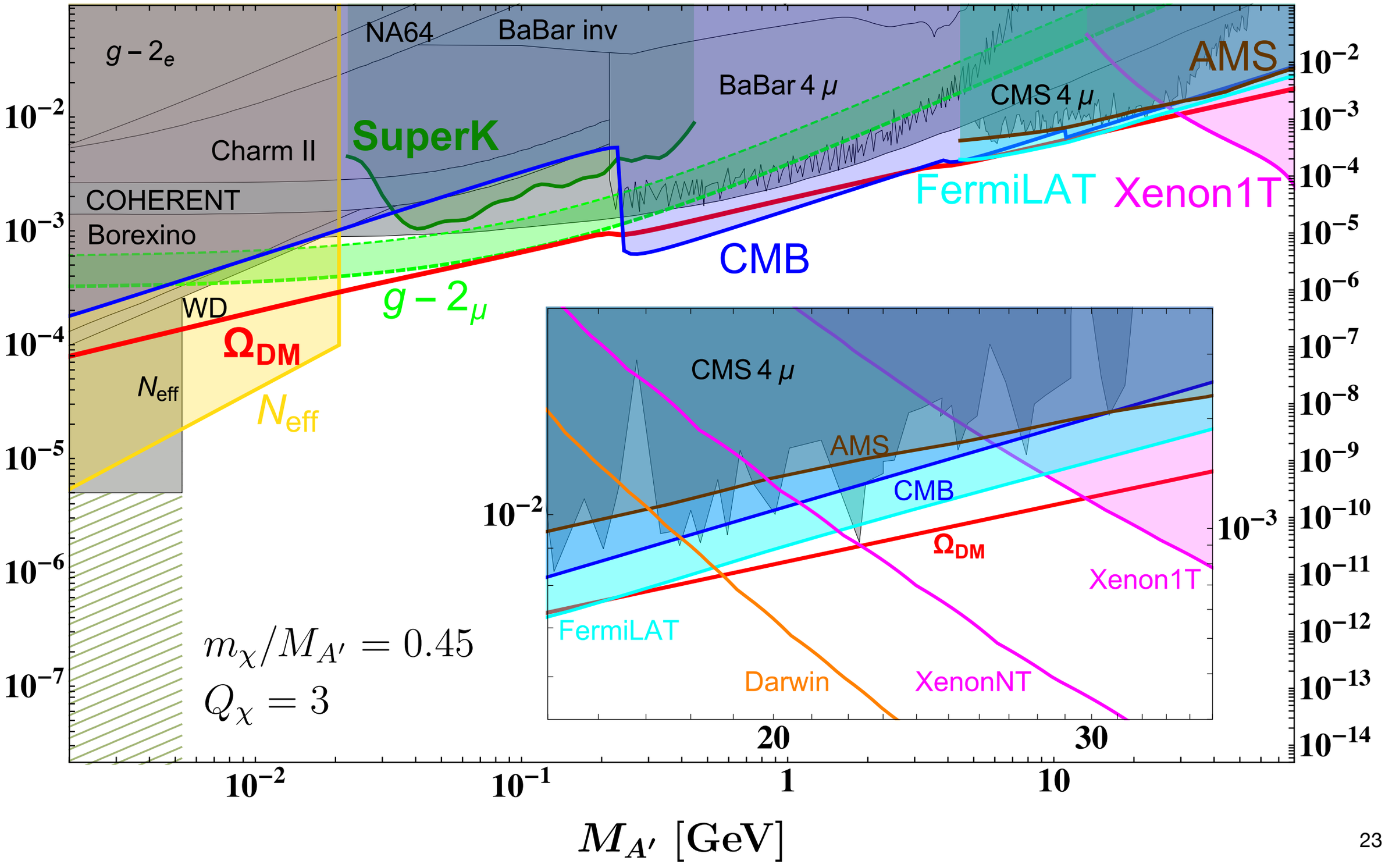
- Future experiments like Belle-II, SHiP and a dedicated muon run of NA64 could rule out large part of parameter space.

- **Simultaneous explanation** of $(g-2)_\mu$ and Ω_{DM} in extended $U(1)_{L_\mu - L_\tau}$.

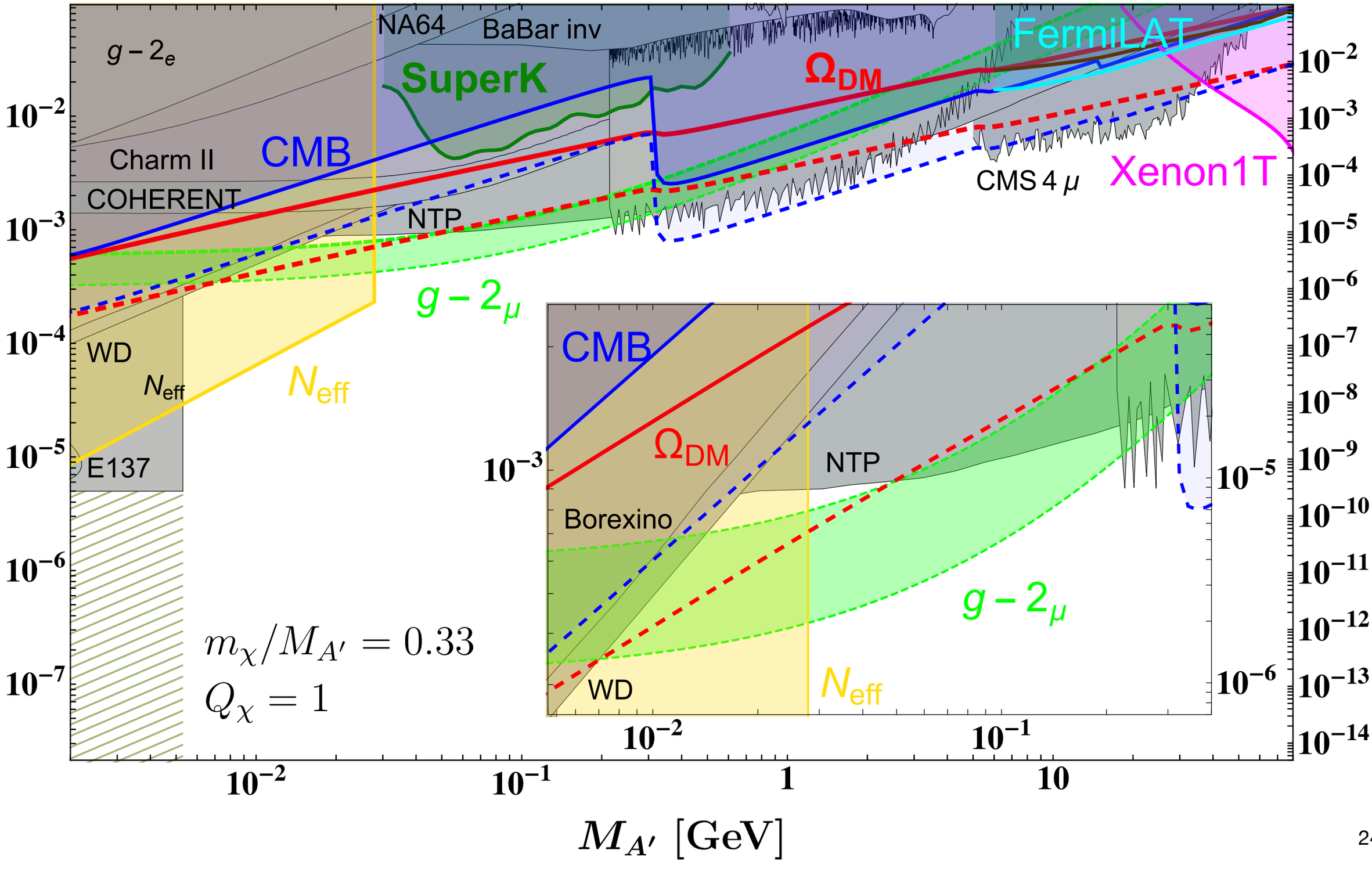
Thank you for your attention!

Backup

$L_\mu - L_\tau$ DM — Non-unit charge

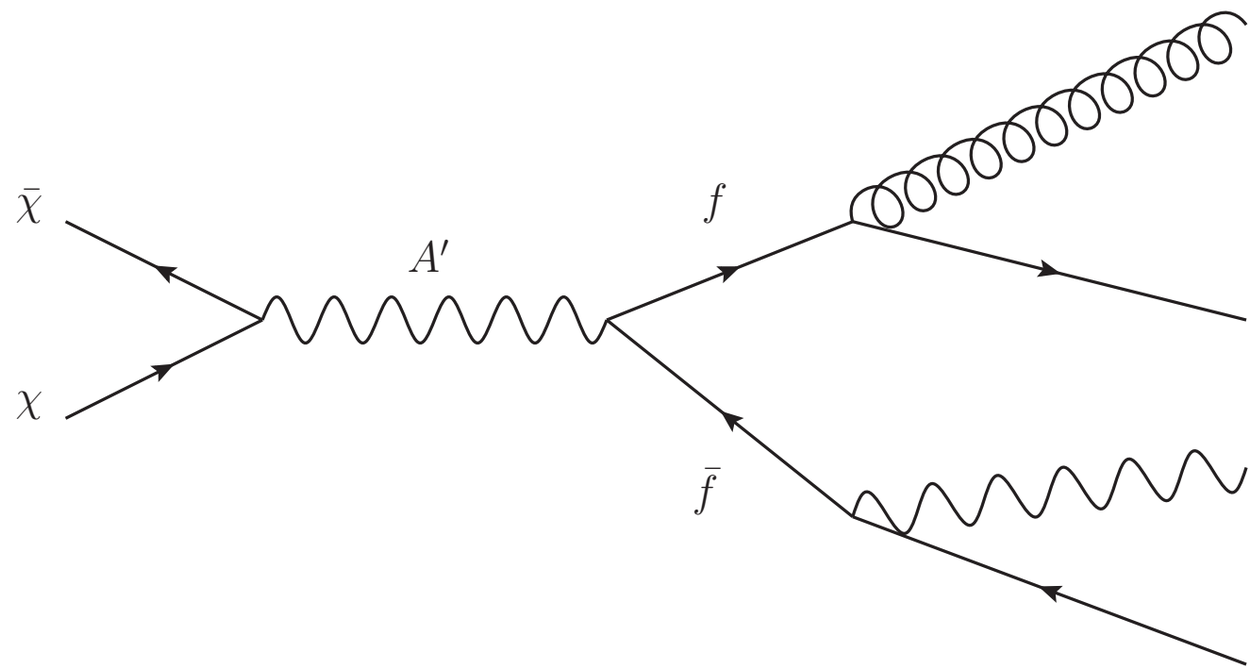


$L_\mu - L_\tau$ DM — Standard Benchmark

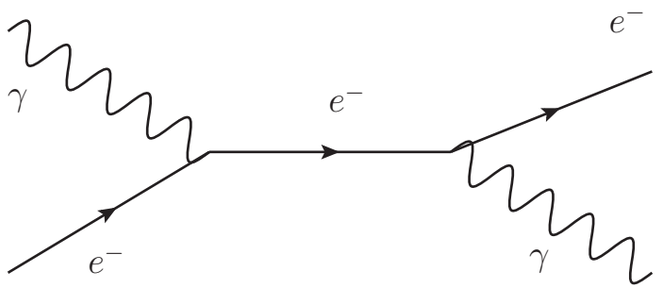


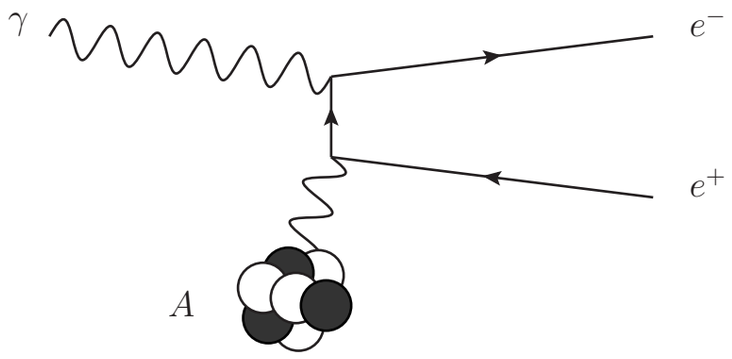
DM annihilation in the early Universe

- DM can inject energy into primordial plasma via cascade decays into secondary $e^{\pm}$, photons and neutrinos



- Secondary particles heat and ionize IGM and alter post-recombination ionization fraction x_e of hydrogen

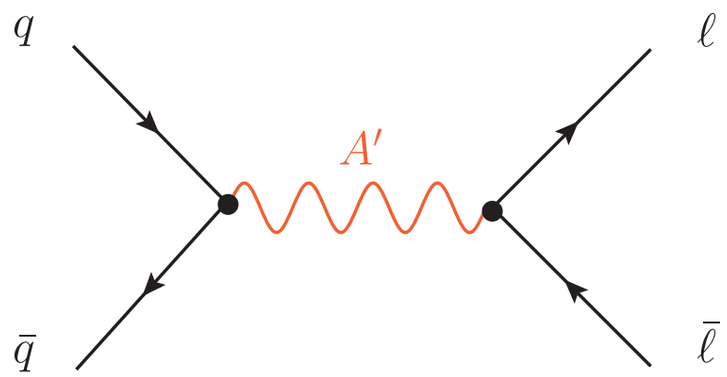




- Extra ionization leads to broadening of last scattering surface of CMB photons ⟶ modification of TT, TE and EE power spectra

Resonance searches

- E.g. at LHC A' can be produced in Drell-Yan.

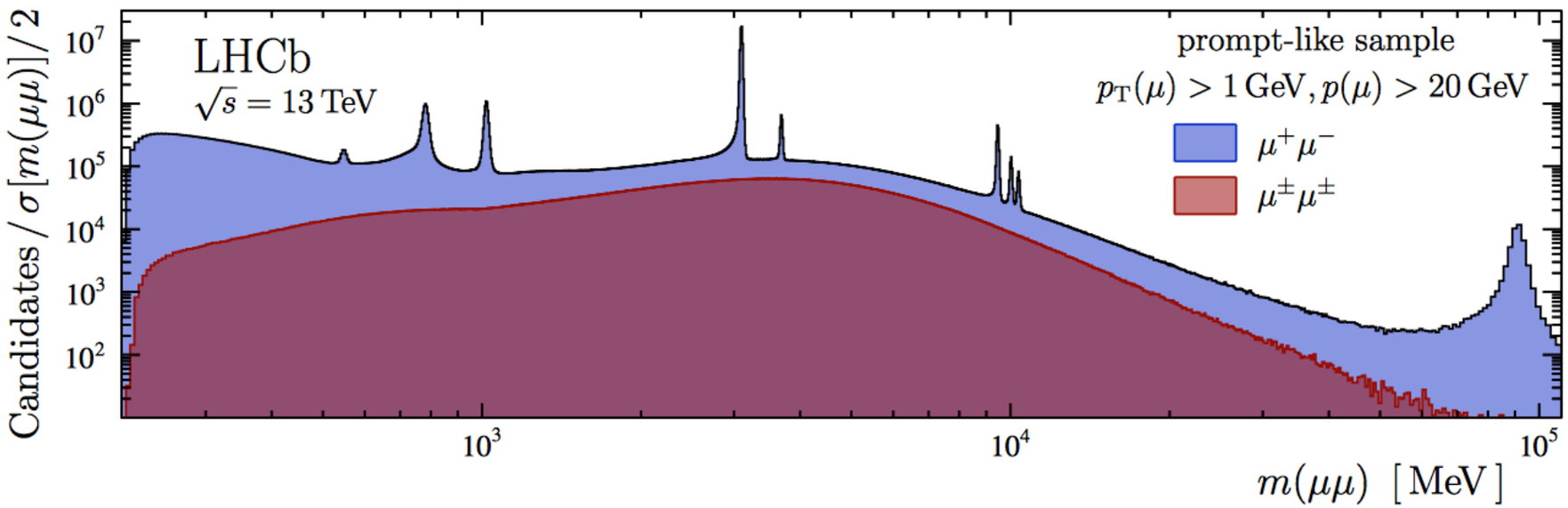


- Number of signal events scales as

$$n_{\mathrm{sig}} \propto \sigma_{\mathrm{prod}} \times BR_{A' \to \ell\ell} \approx \frac{\epsilon^2}{M_{A'}^2} BR_{A' \to \ell\ell}$$

- Obtain upper limit n_{lim} from profile-likelihood of binned dilepton spectrum:

$$\Rightarrow \quad n_{\mathrm{sig}} \leq n_{\mathrm{lim}} \quad @\ 90\%\mathrm{C.L.}$$



[R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **120**, no. 6, 061801 (2018)]

White dwarf cooling

- Hidden photons can modify plasmon decay and generate extra neutrino cooling of white dwarfs.

- A limit can be set on the Wilson coefficient of the operator

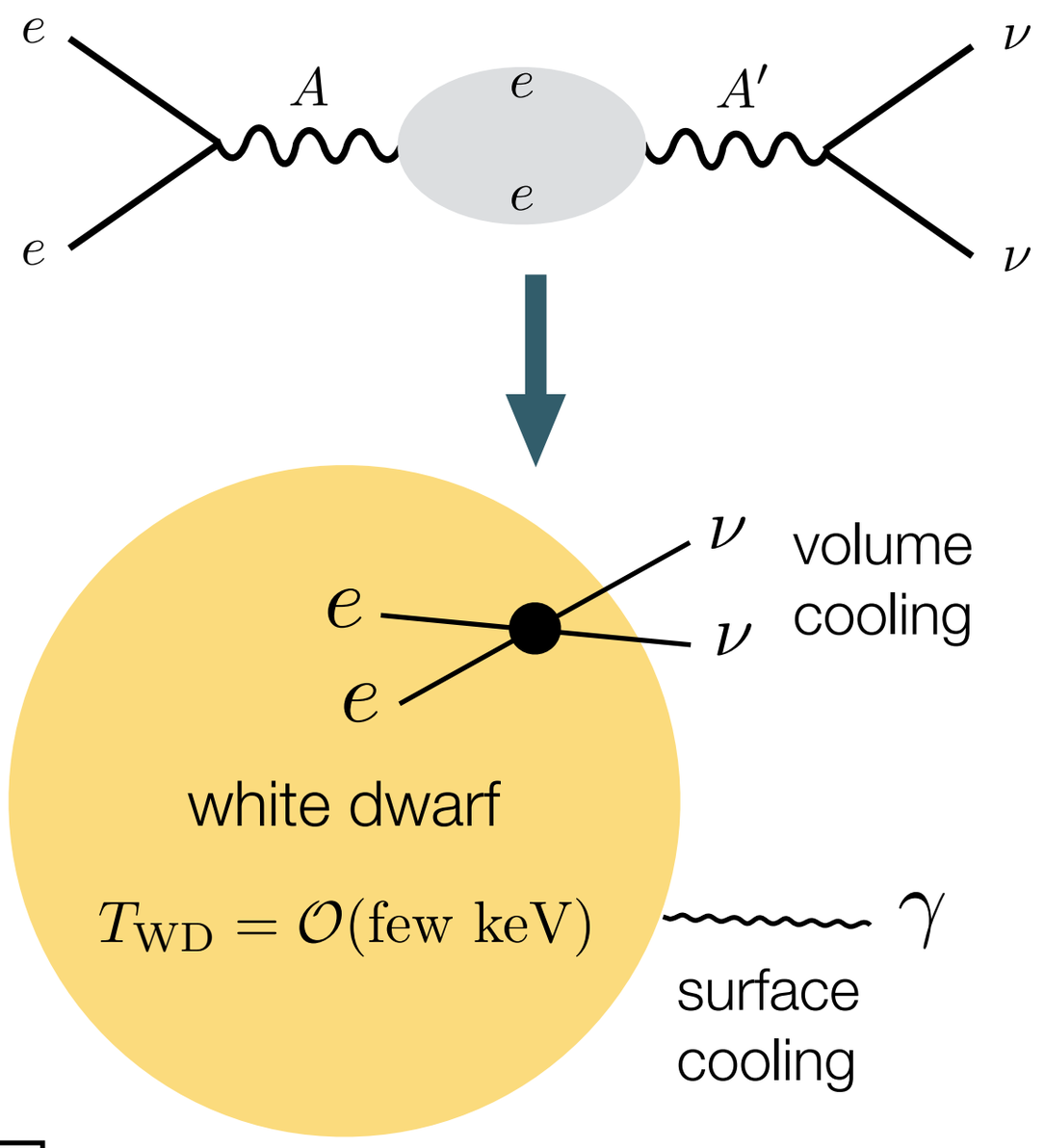
$$\mathcal{L} = C_{\rm WD}\,(\bar{\nu}\gamma_\mu P_L \nu)(\bar{e}\gamma_\mu e)$$

where for a hidden photon

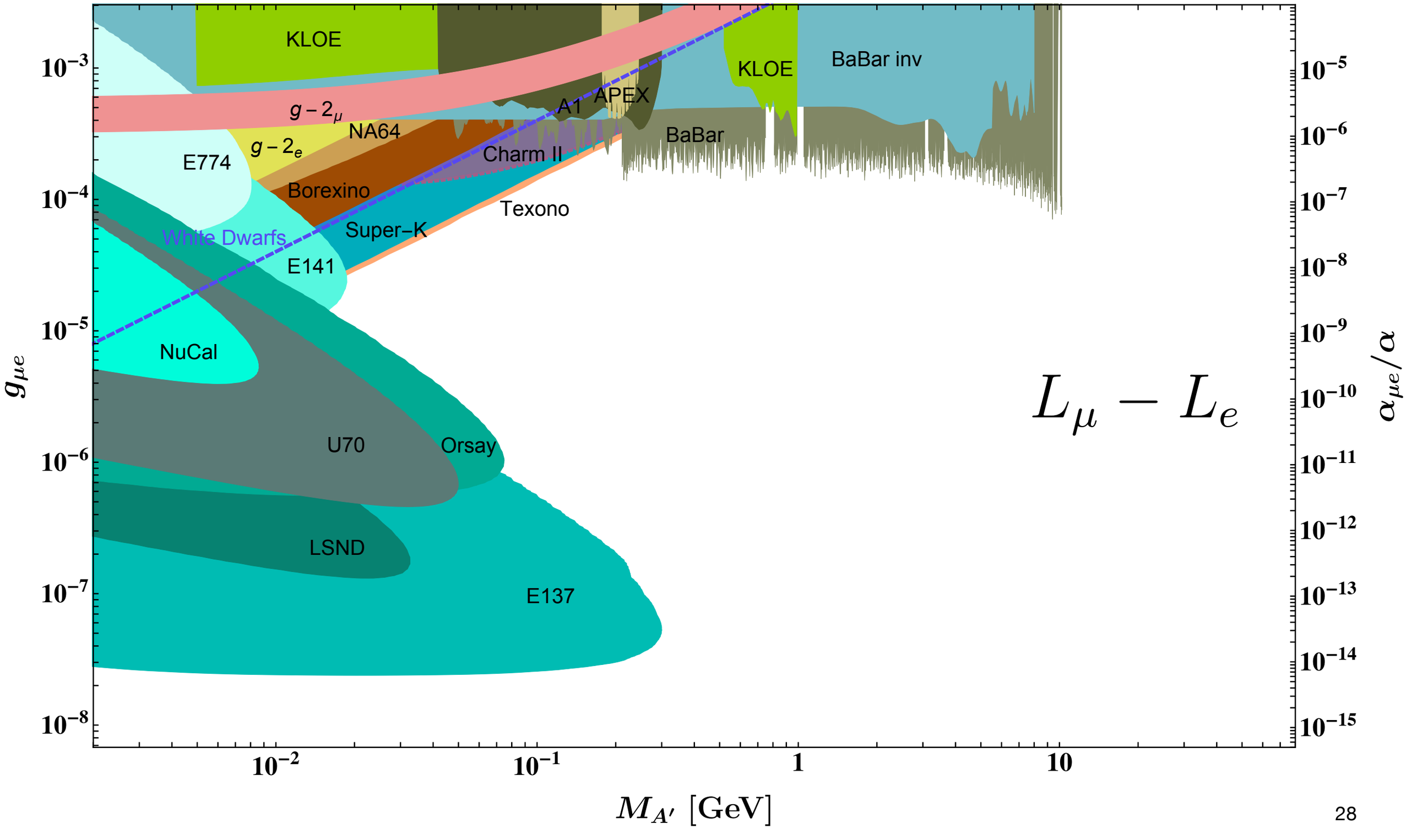
$$C_{\rm WD} = \frac{N_\nu\, 4\pi}{3M_{A'}^2}\,\alpha'\,Q'_e$$

$$\frac{1.12\times10^{-5}}{\rm GeV^2} < C_{\rm WD} < \frac{4.50\times10^{-3}}{\rm GeV^2}$$

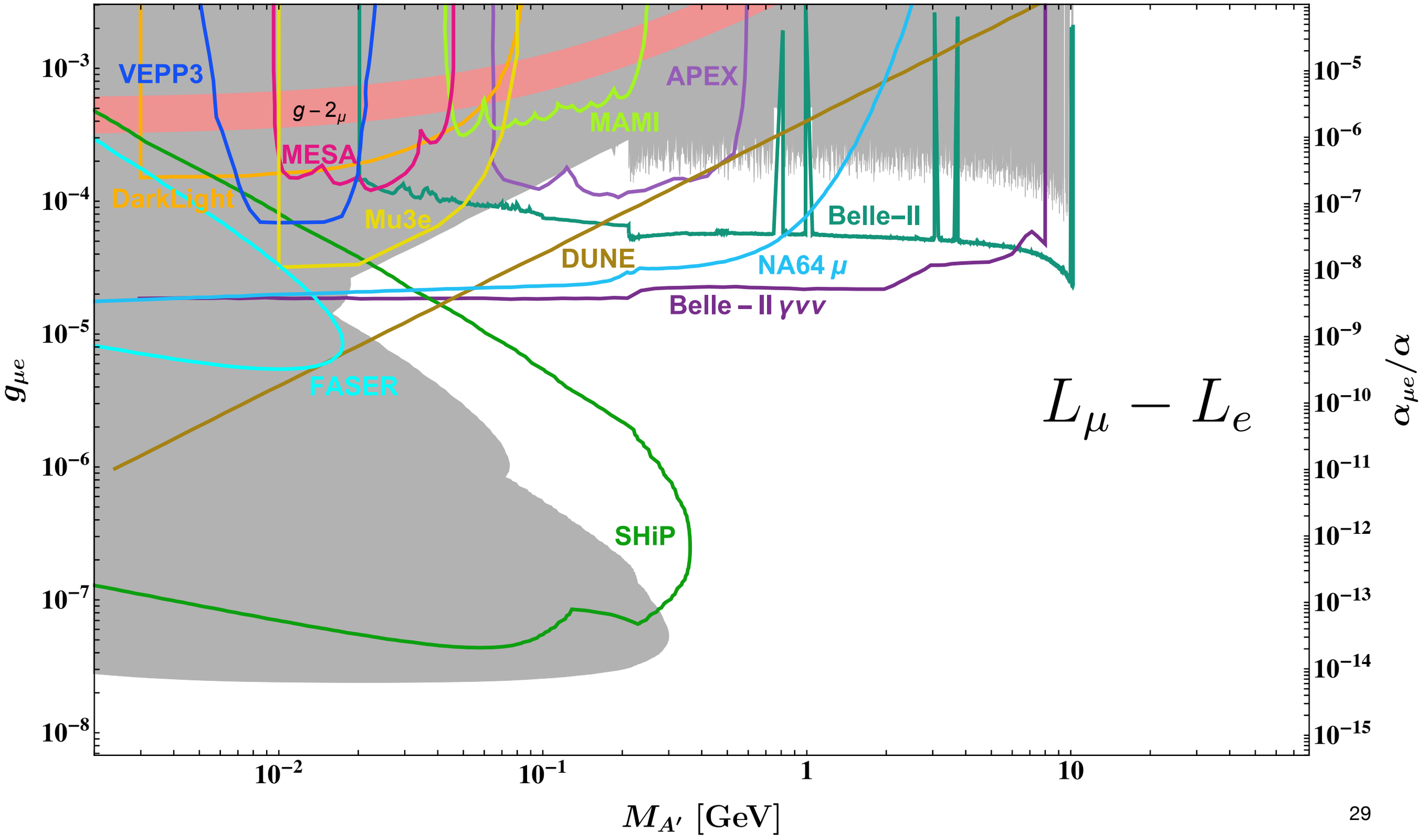
[Dreiner *et al.*, Phys. Rev. D **88**, 043517 (2013)]



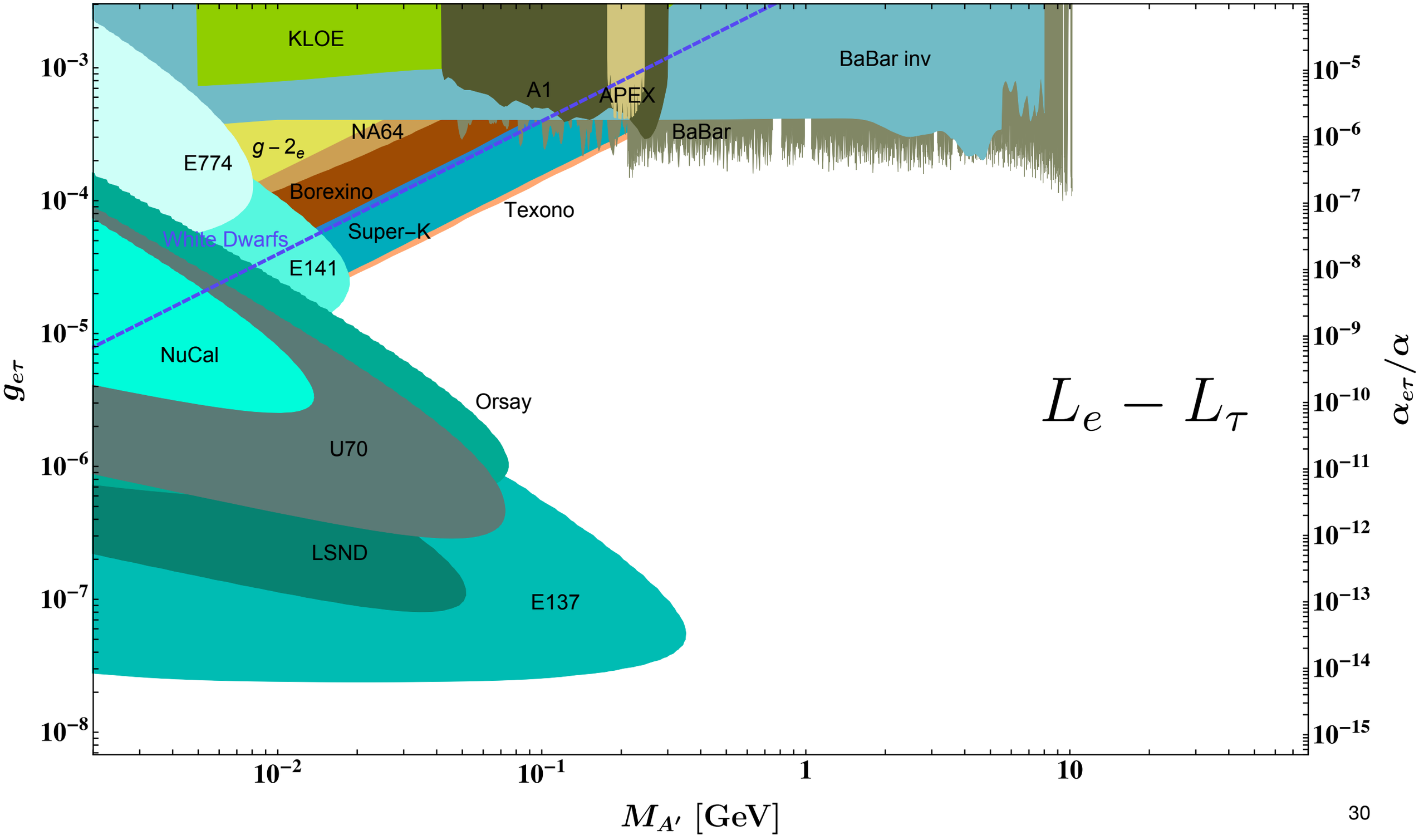
$L_\mu - L_e$ - current status



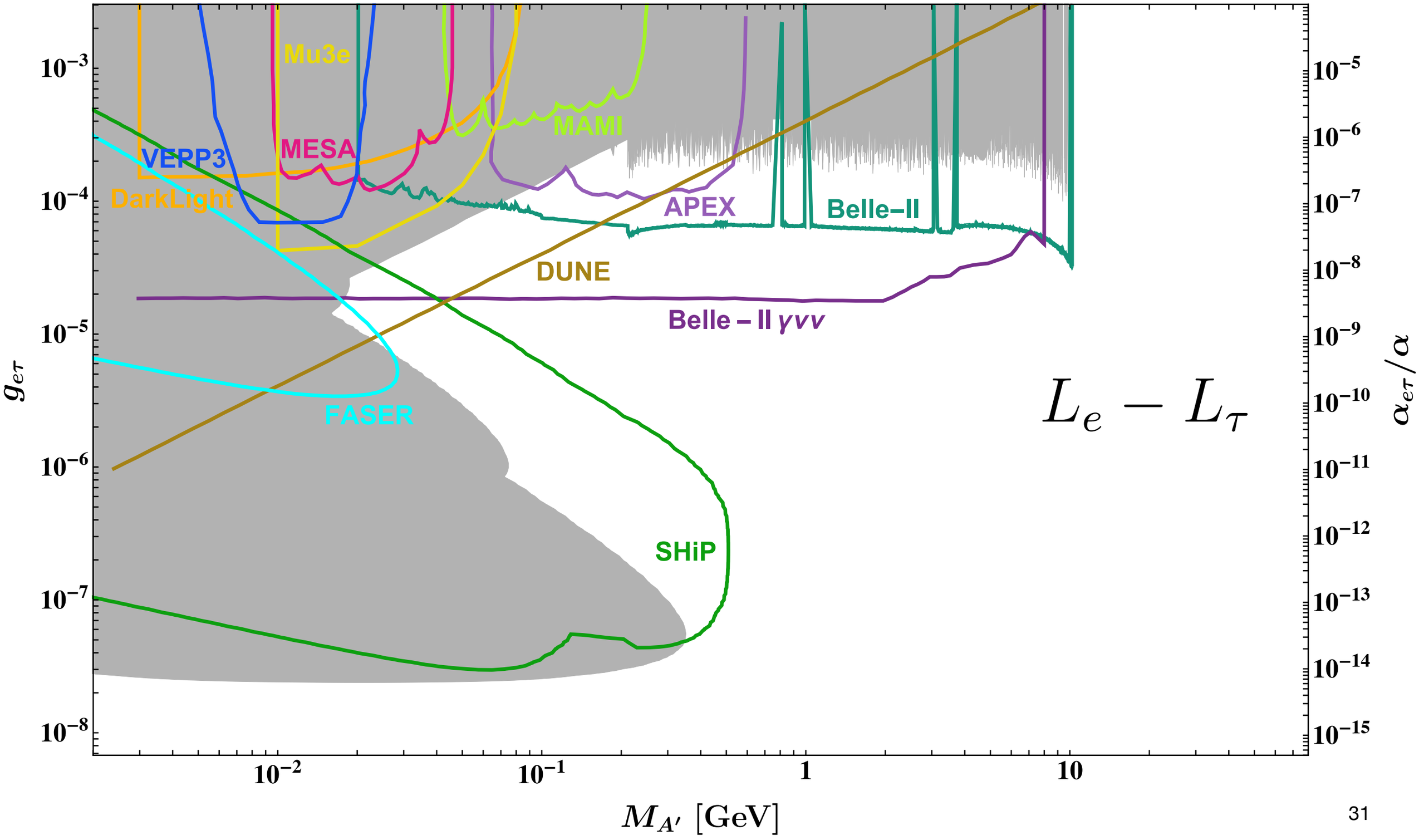
$L_\mu - L_e$ - future sensitivity



$L_e - L_\tau$ - current status



$L_e - L_\tau$ - future sensitivity



Remark: GUT

Why these four groups?

- Study scenarios where U(1) can be remainder of broken flavor group

$$G_{\mathrm{GUT}} \to G_{SM} \times \cdots \times G_F$$

$$\left(\text{E.g.:} \quad SO(10) \to SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \right)$$

[Mohapatra, Valle; PRD **34**, 1642]

- Broken kinetic term will be diagonal

$$\mathcal{L}_{\mathrm{kin}} \propto X^I_{\mu\nu} X^{I,\mu\nu} \to G^a_{\mu\nu} G^{a,\mu\nu} + \cdots + B_{\mu\nu} B^{\mu\nu} + F'_{\mu\nu} F'^{\mu\nu}$$

- Kinetic mixing generated **only radiatively** after symmetry breaking!