Neutrino masses, flavor anomalies and muon g-2 from dark loops

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In collaboration with

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[arXiv:2209.02730]

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1. Introduction

Several anomalies are hinting at the presence of new physics effects in the lepton sector of the Standard Model (SM)

- Experimental observation of neutrino flavor oscillations

- Hints observed in $b \to s$ transitions ⟶ Deviation in $\mathrm{Br}\left(B_s \to \mu\bar{\mu}\right)$

  ⟶ Possible LFUV in B-meson decays

$$R_{K^{(*)}} = \frac{\mathrm{Br}\left(B \to K^{(*)}\mu\bar{\mu}\right)}{\mathrm{Br}\left(B \to K^{(*)}e\bar{e}\right)}$$

- Muon anomalous magnetic moment ⟶ $\Delta a_\mu = a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (2.51 \pm 0.59) \times 10^{-9}\ (4.2\sigma)$
- What is the nature of the dark matter (DM) of the Universe

2. The Model

	gen	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
η	2	$\mathbf{1}$	$\mathbf{2}$	$1/2$	$-$
S	1	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$-$
ϕ	1	$\mathbf{1}$	$\mathbf{1}$	-1	$-$
N	1	$\mathbf{1}$	$\mathbf{1}$	0	$-$

Doublet leptoquark ← S

$$S = \begin{pmatrix} S_{\frac{2}{3}} \\ S_{-\frac{1}{3}} \end{pmatrix}$$

⇨ This economical scenario takes into account all the unresolved issues mentioned before

Lagrangian

$$-\mathcal{L}_{\rm NP} = Y_N \overline{N} \ell_L \eta + Y_S \bar{q}_L S N + \kappa \overline{N^c} e_R \phi^\dagger + \frac{1}{2} M_N \overline{N^c} N + \text{ h.c.}$$

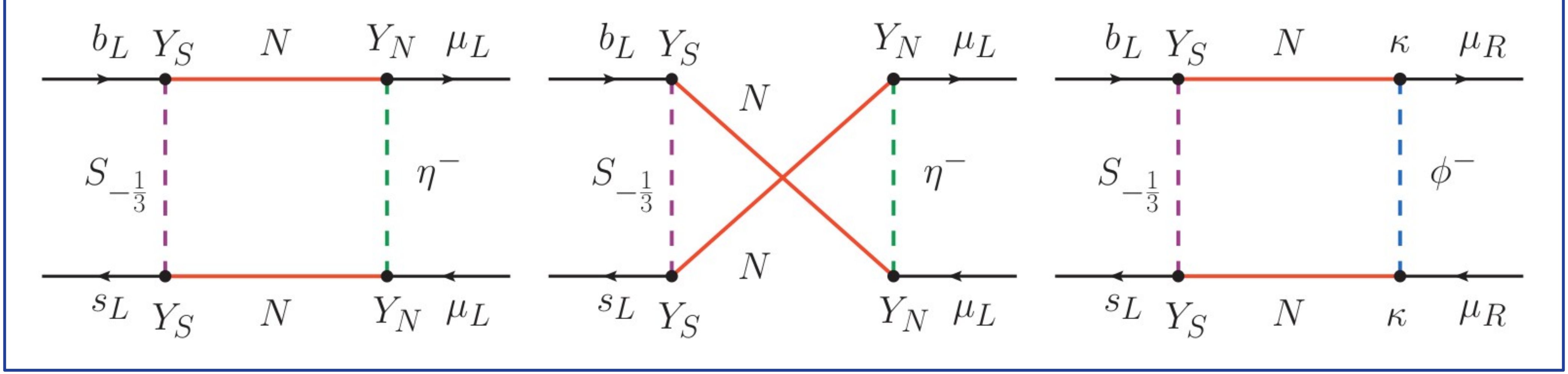
$$\mathcal{V}_{\rm NP} \supset \frac{\lambda_5}{2} \left(H^\dagger \eta\right)^2 + \mu H \eta \phi + \text{ h.c.}$$

Only the SM scalar doublet H acquires a non-zero vev

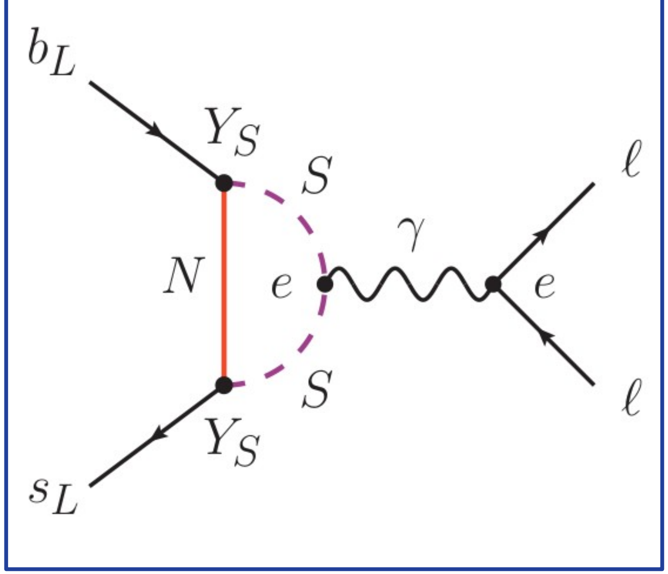
⇨ The EW symmetry gets broken in the standard way preserving the Z_2 parity

3. Dark loops

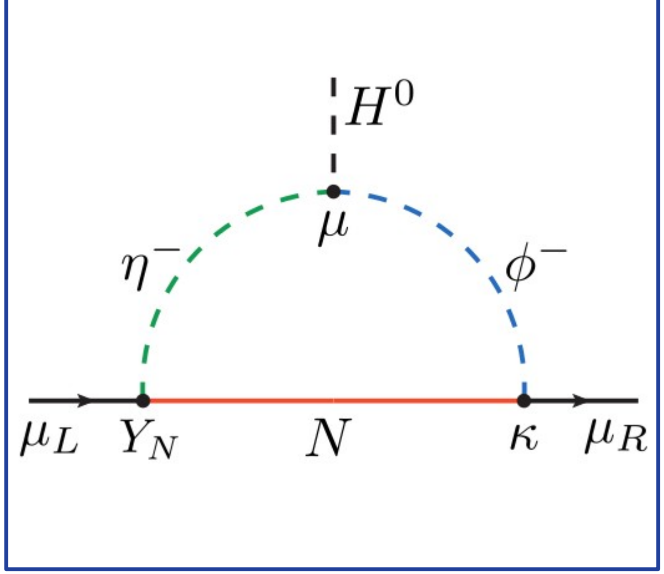
Flavor non-universal $b \to s\ell\ell$



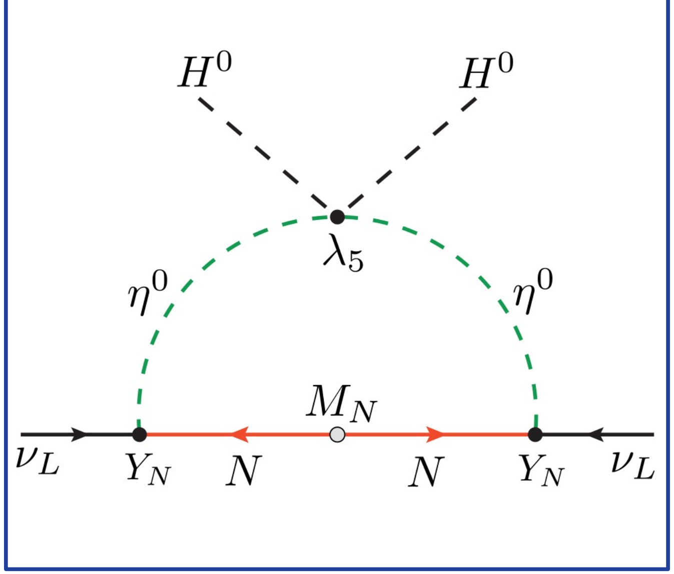
Flavor universal $b \to s\ell\ell$



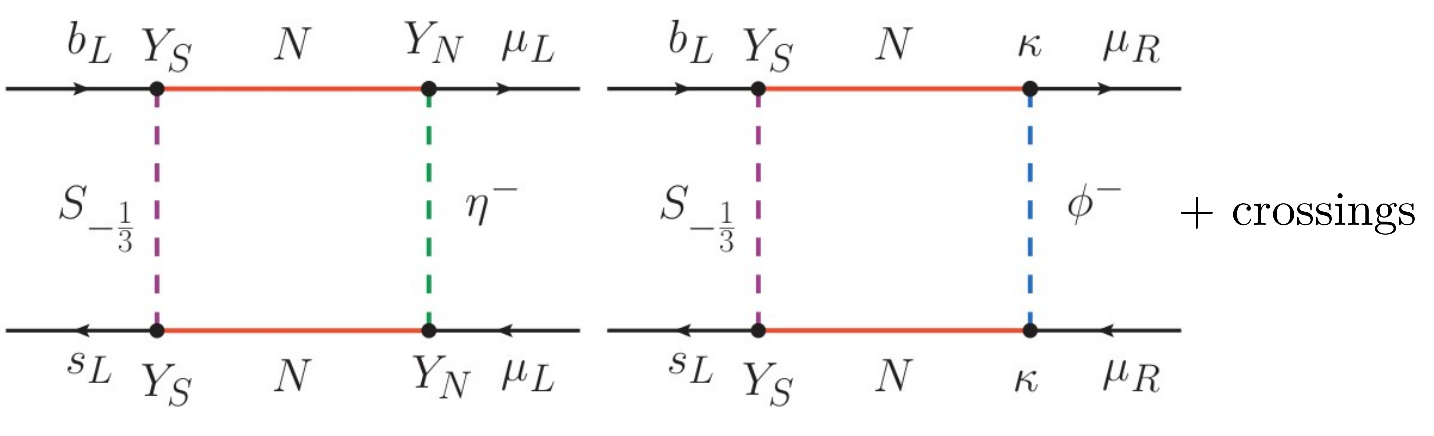
Muon g-2



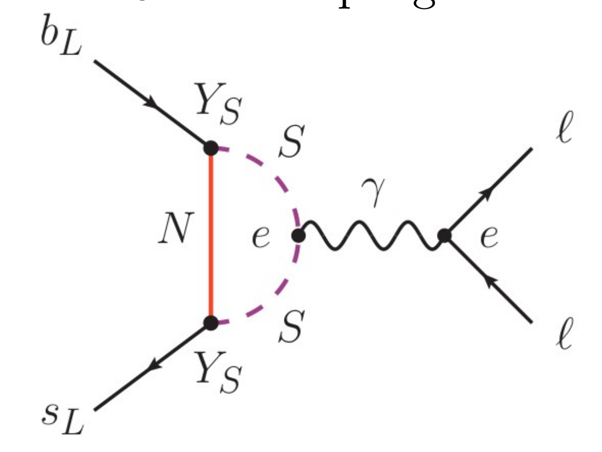
Neutrino masses



Box contributions



Universal penguin



- Box diagrams responsible for LFUV contributions, important to explain the R_K ratio

$$R_{K^{(*)}} = \frac{\text{Br}\left(B \to K^{(*)}\mu\bar{\mu}\right)}{\text{Br}\left(B \to K^{(*)}e\bar{e}\right)}$$

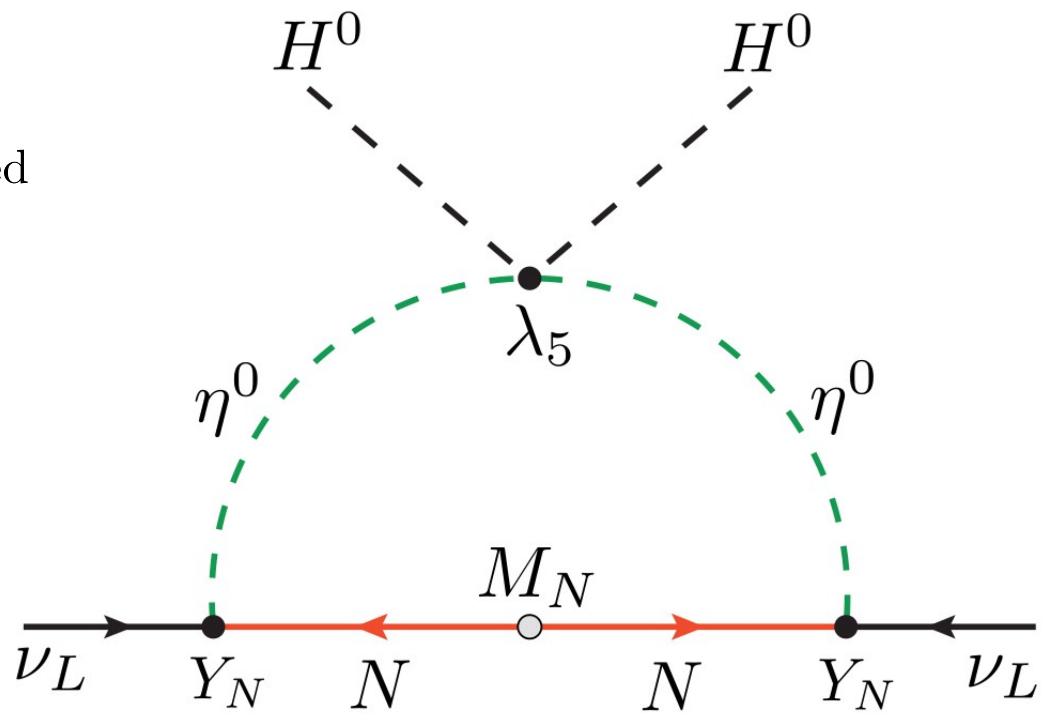
- Penguin diagrams responsible for LFU contributions

- The presence of the crossed diagrams is used to cancel unavoidable large B_s mixing in the limit of (nearly) degenerate NP masses

Arnan, Crivellin, Fedele, Mescia 1904.05890

$$\mathcal{O}_9 = \frac{\alpha_{EM}}{4\pi}\left(\bar{s}\gamma_\mu P_L b\right)\left(\bar{\mu}\gamma^\mu \mu\right)$$
$$\mathcal{O}_{10} = \frac{\alpha_{EM}}{4\pi}\left(\bar{s}\gamma_\mu P_L b\right)\left(\bar{\mu}\gamma^\mu \gamma_5 \mu\right)$$

- Tree-level contributions forbidden
- Majorana neutrino masses are induced at 1-loop level



Scotogenic mechanism

Ma hep-ph/0601225

⇨ But with unusual number of generations:

$$n_N = 1 \quad n_\eta = 2$$

Escribano, Reig, Vicente 2004.05172

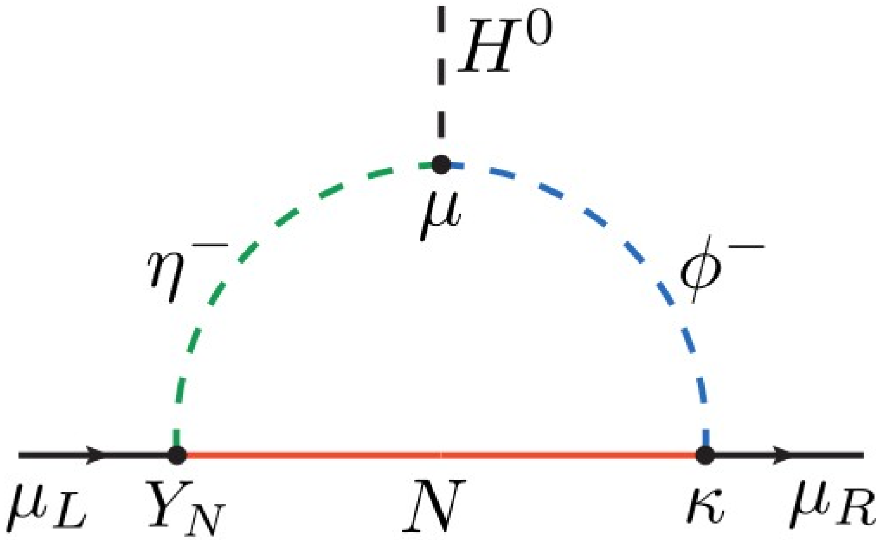
⇨ Only two light neutrino masses!

$$(m_\nu)_{\alpha\beta} \approx \frac{1}{32\pi^2} v^2 \sum_{a,b} (Y_N)_{\alpha a} (Y_N)_{\beta b} \lambda_5^{ab} \frac{M_N}{m_b^2 - M_N^2} \left[\frac{m_b^2}{m_a^2 - m_b^2} \log \frac{m_a^2}{m_b^2} - \frac{M_N^2}{m_a^2 - M_N^2} \log \frac{m_a^2}{M_N^2} \right]$$

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (2.51 \pm 0.59) \times 10^{-9} \ (4.2\sigma)$$

Muon g-2 Collaboration hep-ex/0602035, 2104.03281

Aoyama et al 2006.04822



EM dipole moment operator

$$c_R^{\alpha\beta} \overline{\ell}_\alpha \sigma_{\mu\nu} P_R \ell_\beta F^{\mu\nu}$$

- N couples to left- and right-handed leptons, there's no chirality flipping suppression
- This diagram contributes also to charged lepton flavor violating processes like $\mu \to e\gamma$

3. Dark loops. Dark matter

- The lightest neutral Z_2-odd state is stable and it is a potentially valid DM candidate

- Two possibilities:
  - **Fermion** dark matter: singlet N
  - **Scalar** dark matter: doublet η_a

4. Numerical results

- We want our model to accommodate all the anomalies while being consistent with neutrino oscillation data and all the experimental constraints
- We built a χ^2 function with the four Wilson coefficients and the AMM of the muon
- $m_\eta = 550\,GeV$ (DM) , $m_{NP} \approx 1\,TeV$

Global fit (Scenario 5)

$$\mathcal{C}_{9\mu}^{V} = -0.55^{+0.44}_{-0.47}$$
$$\mathcal{C}_{10\mu}^{V} = 0.49^{+0.35}_{-0.41}$$
$$\mathcal{C}_{9}^{U} = \mathcal{C}_{10}^{U} = -0.35^{+0.42}_{-0.38}$$

Algueró et al 2104.08921

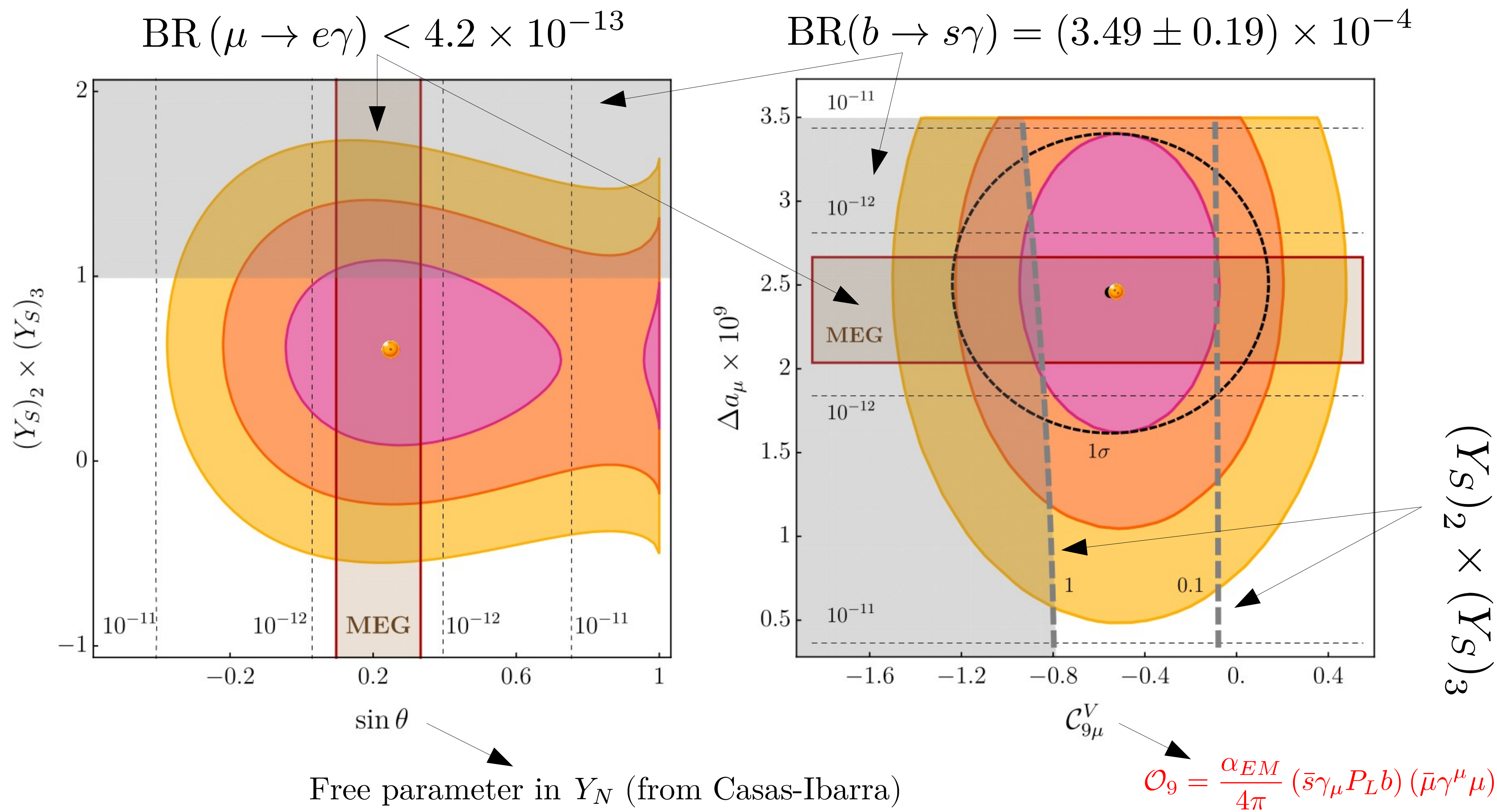
Experimental constraints

- Charged lepton flavor violating processes are potentially dangerous, such as $\mu \to e\gamma$

  MEG: $\mathrm{BR}\,(\mu \to e\gamma) < 4.2 \times 10^{-13}$ MEG Collaboration 1605.05081

- Processes with mesons:
  - $b \to s\gamma$: Yields strong constraints on the coefficients of dipole operators
  - $B \to K^{(*)}\nu\bar{\nu}$: Unavoidable if a contribution to $R_{K^{(*)}}$ exists: $R_K^{\nu\bar{\nu}} < 3.9$, $R_{K^*}^{\nu\bar{\nu}} < 2.7$

    Belle Collaboration 1702.03224
  - $B_s \to \overline{B}_s$: inevitable at 1-loop and typically very constraining



- The parameters can deviate from their best-fit values without affecting χ^2 notably
- We don't need too large Yukawas to accommodate the anomalies

5. Conclusions

- This novel model can accommodate the existing deviations in b $\to$ sll and in the muon g-2. Simultaneously induces neutrino masses and has a dark matter candidate

- This is achieved thanks to a dark sector contributing to the observables of interest at the 1-loop level

- We obtained a region of the parameter space with a minimum of $\chi^2_{\rm min} = 1.52$, improving the SM prediction $\left(\Delta\chi^2 = \chi^2_{\rm SM} - \chi^2_{\rm min} = 21.23\right)$

- The BSM particles, which are odd under the new dark parity, can be produced in pairs at colliders, decaying always with missing energy due to the production of the dark matter particles.

  Example: $S \to jN \to j\ell \not{E}_T$

Thanks for your attention!

Backup

Neutrino fit

- We used the neutrino oscillation data from the global fit (link) de Salas et al 2006.11237

- Applying an adapted Casas-Ibarra parametrization, ge are able to get the Yukawa Y_N in terms of the oscillation data

Casas, Ibarra hep-ph/0103065

$$Y_N^T = V D_{\sqrt{\Sigma}} R D_{\sqrt{m_\nu}} U^\dagger_{\mathrm{PMNS}}$$

$D_{\sqrt{\Sigma}}$ is defined by $m_\nu = Y_N \cdot \Sigma \cdot Y_N$ and is diagonalized by V

R is a general orthogonal matrix defined as

$$R = \begin{pmatrix} 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix}$$

Finally, D_X represents the diagonal form of the matrix X

Parameters

To simplify the analysis, we fixed several parameters before minimizing the χ^2 function

$$m_\eta = 550\, GeV \text{ DM} \ , \ m_{\text{BSM}} \sim 1\, TeV \text{ with } m_N \approx m_S$$

The 2×2 λ_5 matrix is taken diagonal, that is $\lambda_5 = \lambda_5^0 \times \mathcal{I}_2$ with $\lambda_5^0 = 2 \times 10^{-10}$

$$\mu_1 = -\mu_2 = -1.0\, TeV$$

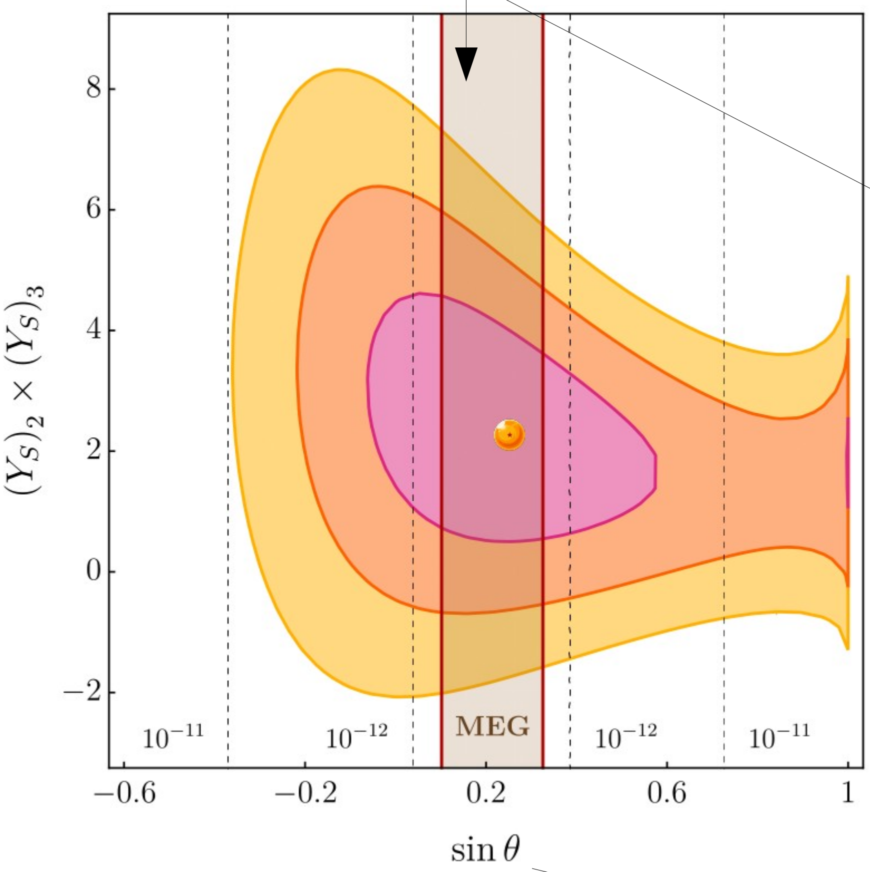
$$\kappa_1 = 0 \, , \, \kappa_2 = 0.04$$

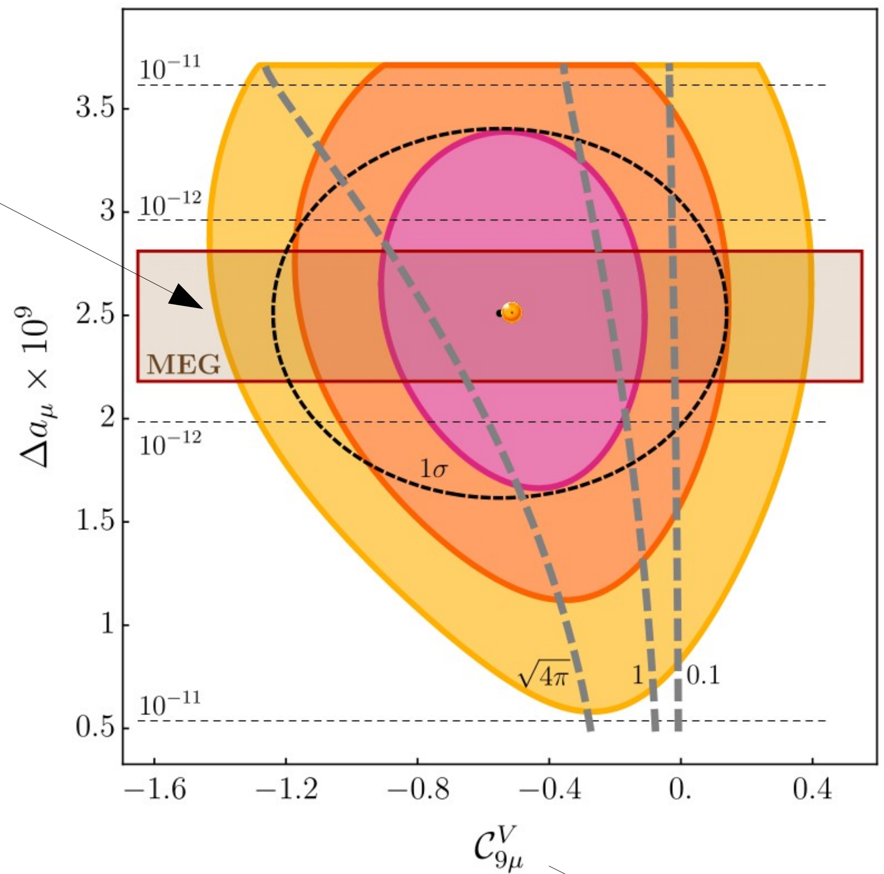
The minimum of the χ^2 function was found for:

$$(Y_S)_2 \times (Y_S)_3 = 0.6 \quad , \quad \sin\theta = 0.25$$

4. Numerical results. M_{BSM} = 600 GeV

$$\mathrm{BR}\,(\mu \to e\gamma) < 4.2 \times 10^{-13}$$





Free parameter from Casas-Ibarra

$$\mathcal{O}_9 = \frac{\alpha_{EM}}{4\pi}\,(\bar{s}\gamma_\mu P_L b)\,(\bar{\mu}\gamma^\mu \mu)$$