Explaining the anomalies with dark loops

work with Pablo Escribano, Avelino Vicente
arXiv: 2209.02730

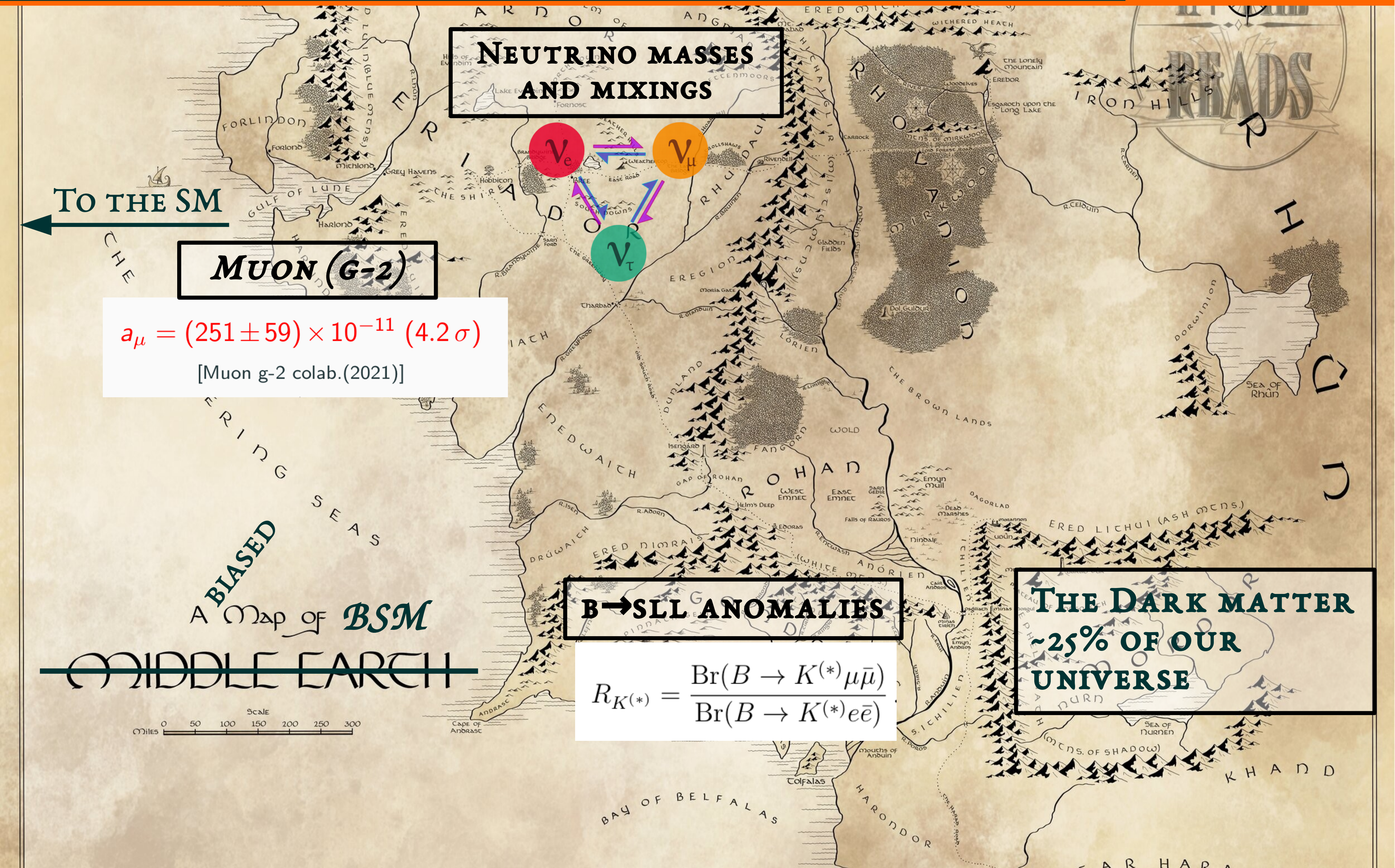
Ricardo Cepedello

University of Würzburg

Desy Theory Workshop

29th September 2022

Motivation



Neutrino masses and mixings

ν_e ν_μ ν_τ

To the SM

Muon (g-2)

$a_\mu = (251 \pm 59) \times 10^{-11}$ $(4.2\,\sigma)$

[Muon g-2 colab.(2021)]

A BIASED Map of BSM ~~Middle Earth~~

B→sll anomalies

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

The Dark matter ~25% of our universe

Motivation (a model to fit them all)

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*(and in the **dark loops** bind them)*

Neutrino masses and mixings

Viable dark matter candidate

Dark loops

Fullfil all experimental constraints

Flavor anomalies in the b→sll

Muon (g-2) anomaly

[Some works on 1-loop b→sll and some of the other anomalies:
Da Huang et al 2020; Arcadi et al 2021; Becker et al 2021;
Freitas et al 2022; Capucha et al 2022]

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

← *Dark Matter!*

← *Scalar Leptoquark* $S = \left(S_{2/3}\ S_{-1/3}\right)$

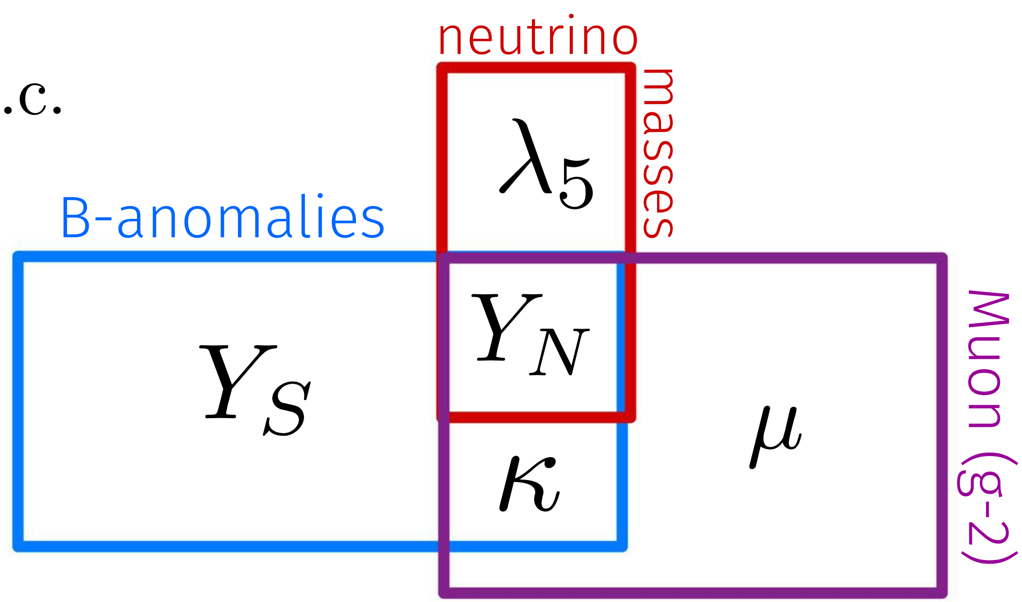
* *One massless neutrino*

[Scenario of Arnan et al 2017]

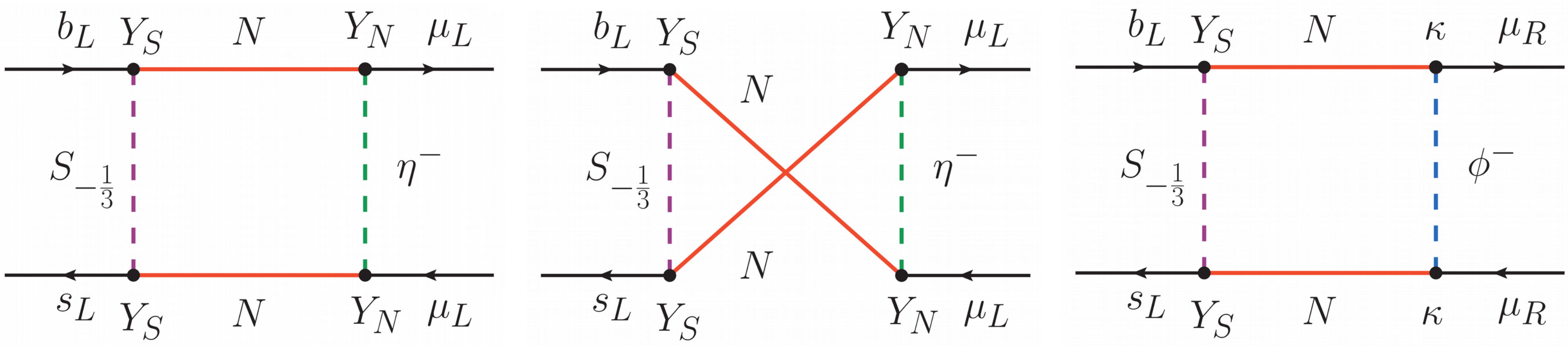
$$-\mathcal{L}_{\rm NP} = Y_N\, \overline{N}\, \ell_L\, \eta + Y_S\, \overline{q}_L\, S\, N + \kappa\, \overline{N^c}\, e_R\, \phi^\dagger + \frac{1}{2}\, M_N\, \overline{N^c}\, N + \text{h.c.}$$

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

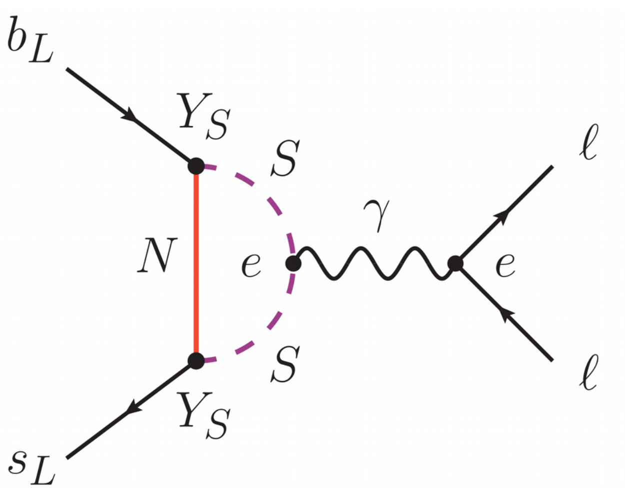
*Of course, there are new couplings, but **linked** through the observables*



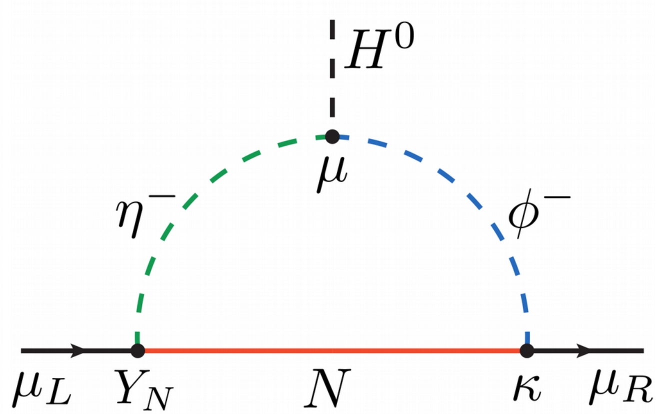
Flavor non-universal $b \to s\ell\ell$



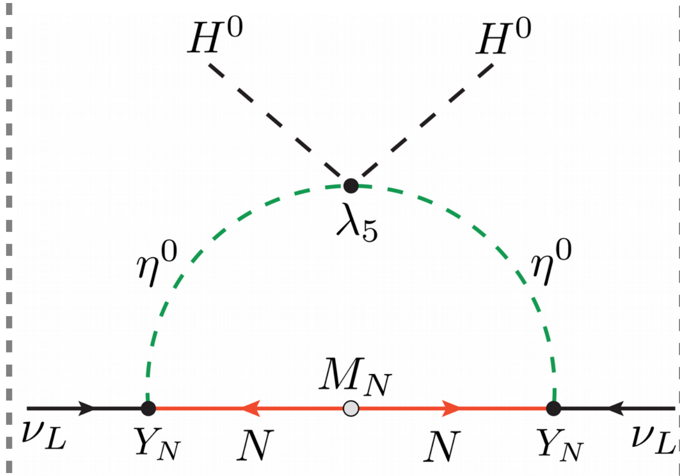
Flavor universal $b \to s\ell\ell$



Muon (g-2)



Neutrino masses



$b \to sll$ anomalies

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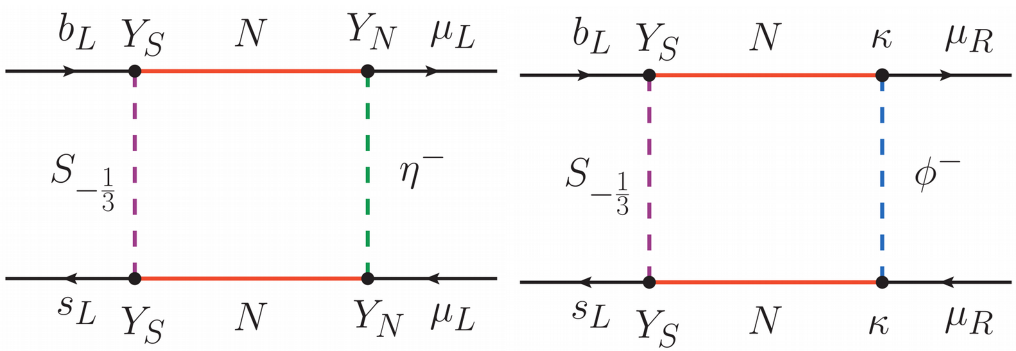
Box contributions to LFUV C_9 and C_{10}



+ crossings

Problem *with 1-loop boxes: unavoidable large B_s mixing*

Solution*: the Majorana nature of the N singlets can be used to suppress the mixing in the limit of (nearly) degenerate NP masses with the crossed diags.* [Arnan et al 2019]

Always the combination: $(Y_S)_2 \times (Y_S)_3$

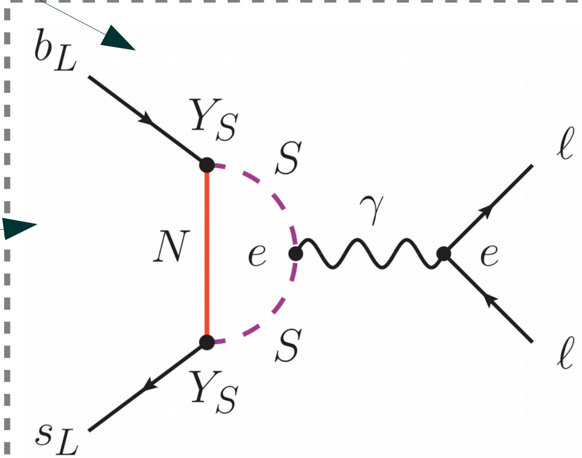
$$\mathcal{O}_9 = \frac{\alpha_{EM}}{4\pi}(\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)$$

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

Problem*: contribution to the magnetic operators O_7 and O_8 i.e. $b \to s\gamma$*

$\Rightarrow (Y_S)_2 \times (Y_S)_3$ *will have an upper bound*

Universal penguin



Neutrino masses

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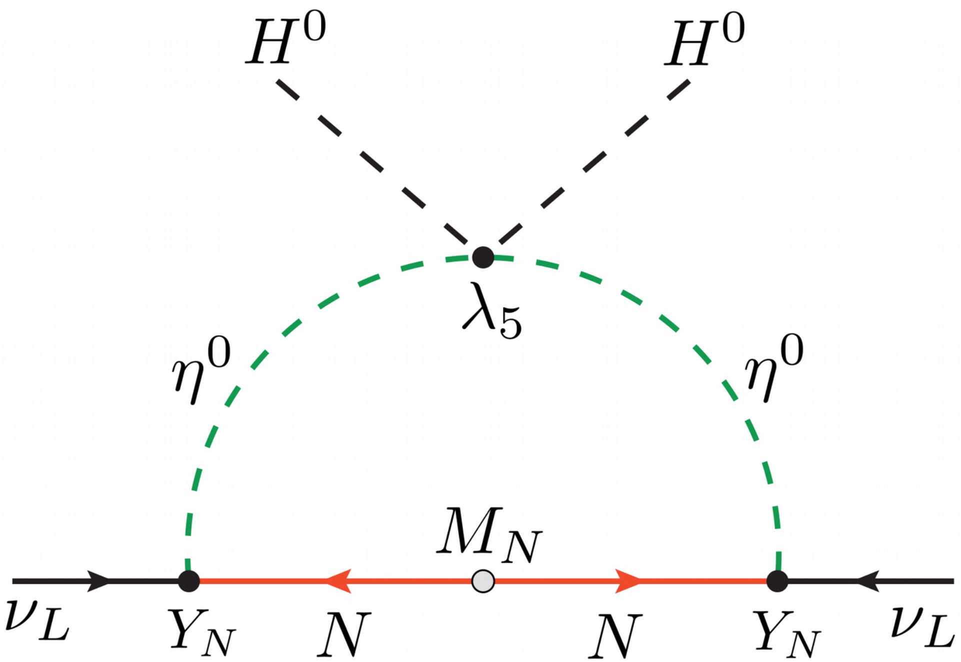
***Tree-level** forbidden by the Z_2 symmetry* → ***naturally light masses** via one-loop suppression*



(Scotogenic mechanism)

[Ma 2006]

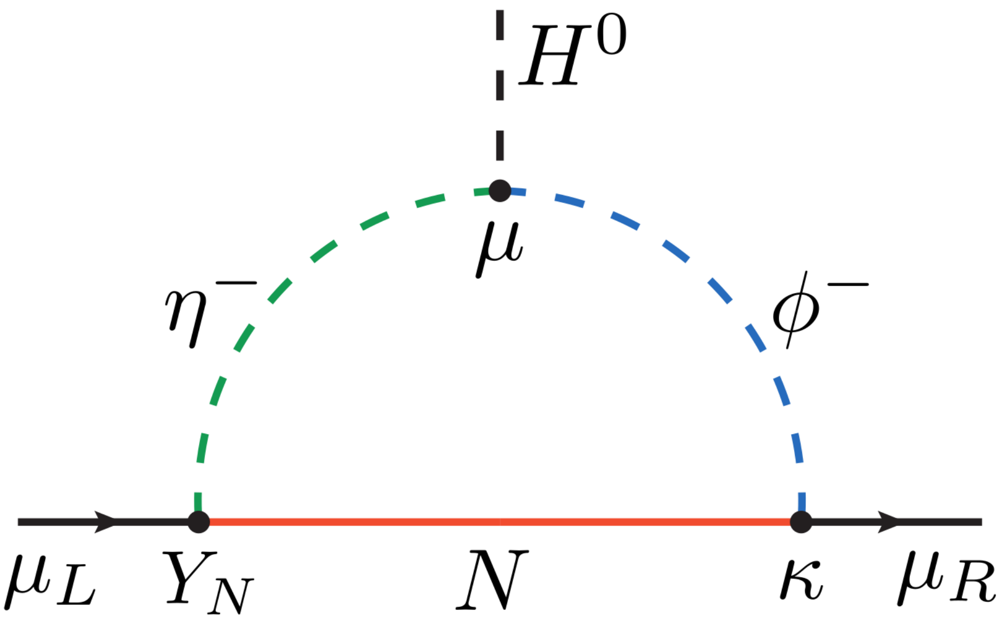
unusual number of generations:

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

Only two light neutrino masses

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

The anomalous magnetic moment



EM dipole moment operator:

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

Diagonal: (g-2)
Off-diagonal: cLFV

[see e.g. Crivellin et al 2018]

- *N couples to left and right-handed leptons:* ***dominant contribution proportional to M_N***
- *Contributes also to charged lepton flavor violating processes like $\mu \to e\gamma$*
- *Y_N fits neutrino oscillation data and **κ** participates in C_9 and C_{10} boxes*

Dark matter

The lightest particle odd under Z_2 is stable ⟶ ***dark matter candidate***

Fermionic dark matter: *singlet N*

- *Pure singlet: produced only via Yukawa Y_N*
- *Underproduced unless Y_N is large*
- *Potential problems with lepton flavor violation*

[Vicente, Yaguna 2015]

Scalar dark matter: *doublet η_a*

- *Similar to the well-studied Inert Doublet Model*
- *Interacts also via gauge*
- *Relic density: mass around 500-600 GeV*

[for example,
Honorez et al 2007;
Honorez, Yaguna 2010;
Aurelio Diaz et al 2016]

Analysis

- *We aim to accommodate **all the anomalies** while being consistent with **neutrino oscillation data***
- *We built a χ^2-function the Wilson coeff. and the muon (g-2)*
- *m_η = 550 GeV (DM), the rest close to 1 TeV and nearly degenerate (B_s mixing)*

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 2022]

Experimental constraints

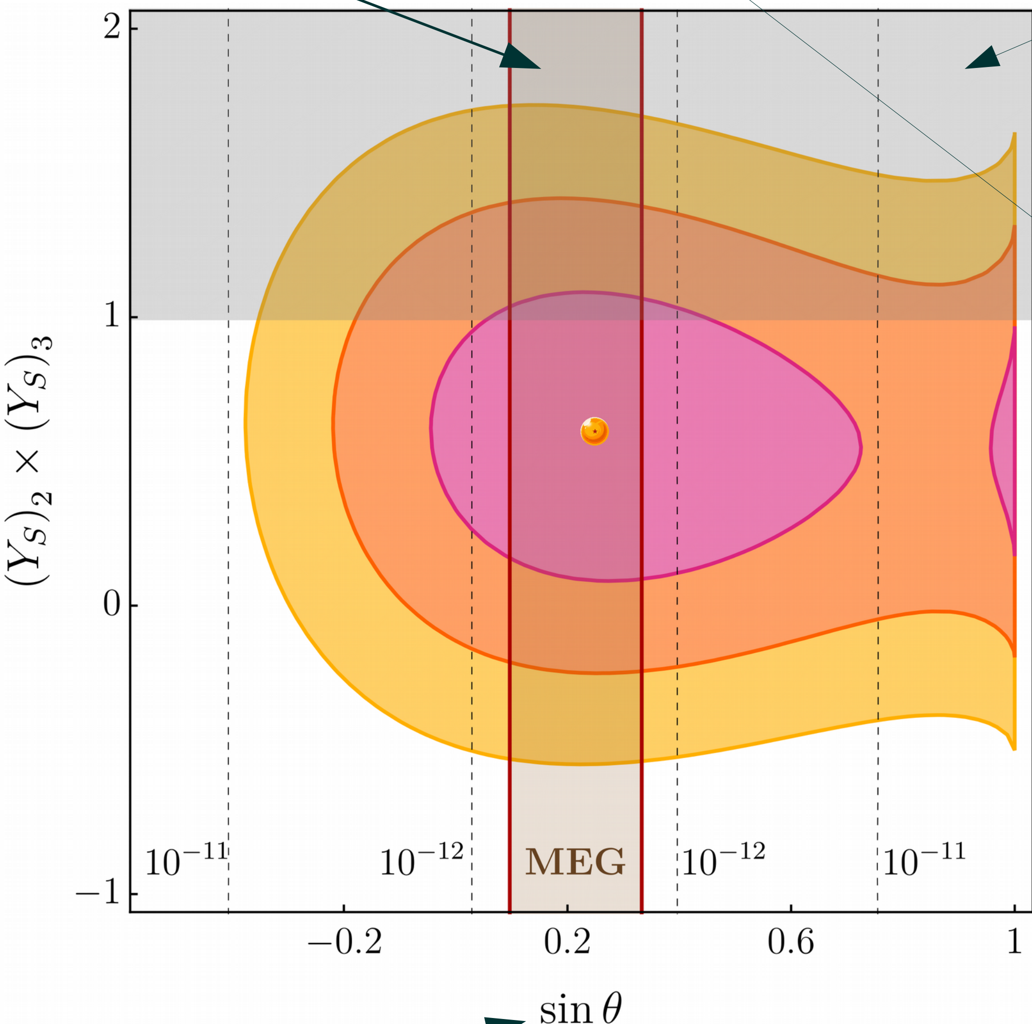
- *Charged lepton flavor violation: very stringent bounds on $\mu \to e\gamma$*
- *B_s mixing inevitable at 1-loop and very constraining*
- *$b \to s\gamma$ yield strong constraints on the coefficients of dipole operators*
- *$B \to K^{(*)} \nu\nu$ unavoidable if a contribution to $R_{K(*)}$ exists:* $R_K^{\nu\bar{\nu}} < 3.9,\ R_{K^*}^{\nu\bar{\nu}} < 2.7$

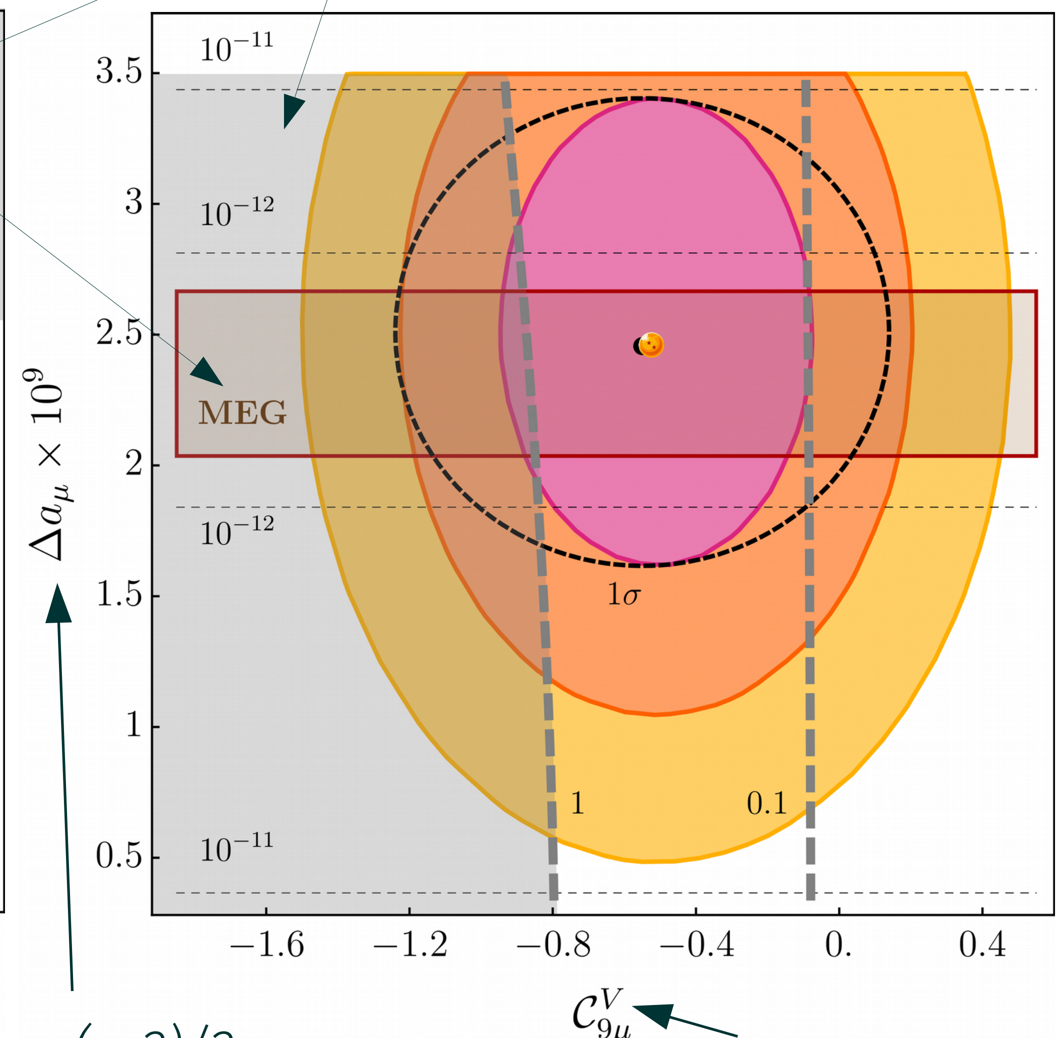
Results

arXiv: 2209.02730

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

$\mathrm{BR}(b \to s\gamma) = (3.49 \pm 0.19) \times 10^{-4}$





Only free parameter in Y_N

(R matrix angle)

Muon (g-2)/2

Coefficient of
$(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$

Conclusions

- *Novel model that accommodates the existing deviations in **b → sll** and the **muon g-2**, induces **neutrino masses** and provides a **dark matter** candidate*

- *The dark sector participates in the observables of interest at the 1-loop level (**dark loops**)*

- *We get a minimum of* $\chi^2_{\rm min} = 1.52$ *a considerable **improvement** with respect to the SM* $(\Delta\chi^2 = \chi^2_{\rm SM} - \chi^2_{\rm min} = 21.23)$

- *BSM fields may be produced at **colliders**, but decay always via missing energy. For example,* $S \to j\, N \to j\, \ell\, \not{E}_T$ *where the jet can be 2nd or 3rd gen quark*

Thank you!!


DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY HAMBURG
GEGRÜNDET 1959
80
DEUTSCHE BUNDESPOST
1984

Backup

Neutrino fit

Neutrino oscillation data from global fit (link)

[de Salas et al 2021]

Apply ***Casas-Ibarra parametrization*** *to get the Yukawa* Y_N *in terms of the oscillation data:*

[Casas, Ibarra 2001]

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

Defined by:

$$m_\nu = Y_N \cdot \Sigma \cdot Y_N$$

and diagionalized by V

(D_X) Diagonal form of the matrix X

Complex orthogonal matrix

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

Parameters

To prove that our model can accommodate the anomalies and simplify the analysis, we fixed several parameters before minimizing the χ^2-function.

- m_η = 550 GeV (DM), the rest close to 1 TeV and nearly degenerate (B_S mixing)
- The 2x2 λ_5 is taken diagonal, i.e. $\lambda_5 = \lambda_5^0 \cdot$ Identity, with $\lambda_5^0 = 2 \times 10^{-10}$
- $\mu_1 = -\mu_2 = -1.0$ TeV
- $\kappa_1 = 0$, $\kappa_2 = 0.04$

The smallness of λ_5 is technically natural and protected against radiative corrections since in the limit $\lambda_5 \to 0$ lepton number is restored. ['t Hooft 1979]

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

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