Dark matter models and anomalies in B meson decays and the muon g-2

R. Capucha[1,2]

Collaboration: D. Huang[3,4,5], T. Lopes[6], R. Santos[1,2,7]

6 TÉCNICO LISBOA

7 ISEL INSTITUTO SUPERIOR DE ENGENHARIA DE LISBOA

1 CFTC Centro de Física Teórica e Computacional

2 Ciências ULisboa

3 universidade de aveiro

4 NAOC 中国科学院国家天文台 NATIONAL ASTRONOMICAL OBSERVATORIES CHINESE ACADEMY OF SCIENCES

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Email: fc46435@alunos.fc.ul.pt

Introduction

- Most experimental results agree with SM predictions. But there are exceptions**: B meson decays** and **muon's anomalous magnetic moment**, and it is incomplete **- dark matter (DM),** matter-antimatter asymmetry. Need **new Physics (NP).**

- Hints of NP comes from the observed **anomalies in the semileptonic decay rates of the B meson**, which suggests a **violation of lepton flavor universality**:

$$R(K^{(*)}) = \mathcal{B}(B \to K^{(*)}\mu^+\mu^-)/\mathcal{B}(B \to K^{(*)}e^+e^-)$$

LHCb Collaboration

$$R(K) = 0.846^{+0.060+0.016}_{-0.054-0.014}, \qquad q^2 \in [1.1, 6]\ \mathrm{GeV}^2$$

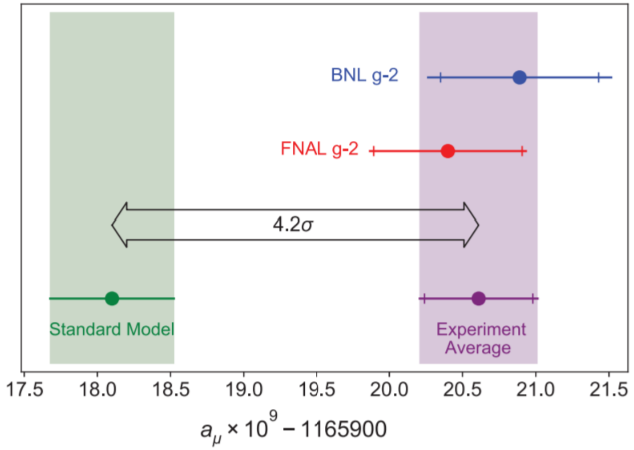
$$R(K^*) = \begin{cases} 0.660^{+0.110}_{-0.070} \pm 0.024, & q^2 \in [0.045, 1.1]\ \mathrm{GeV}^2, \\ 0.685^{+0.113}_{-0.069} \pm 0.047, & q^2 \in [1.1, 6]\ \mathrm{GeV}^2. \end{cases}$$

SM predictions

$$R(K) = 1.0004(8), \qquad q^2 \in [1.1, 6]\ \mathrm{GeV}^2,$$

$$R(K^*) = \begin{cases} 0.920 \pm 0.007, & q^2 \in [0.045, 1.1]\ \mathrm{GeV}^2, \\ 0.996 \pm 0.002, & q^2 \in [1.1, 6]\ \mathrm{GeV}^2. \end{cases}$$

Introduction



- Another NP important hint comes from the measurement of the **(g – 2) of the muon,**

showing a **4.2σ discrepancy** relative to the SM prediction, 10.1103/PhysRevLett.126.141801

$$a_\mu(\mathrm{Exp}) - a_\mu(\mathrm{SM}) = (251 \pm 59) \times 10^{-11}$$

- Further demand for NP arises from the increasing number of experiments pointing to the existence of **dark matter**, whose nature remains a mystery.

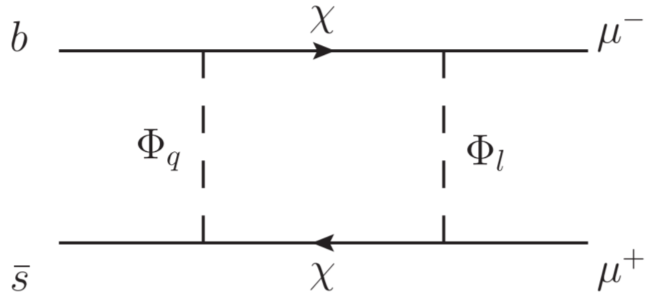
- All three NP issues can be solved with a class of models where **DM** is a **neutral $SU(2)_L$ singlet vectorlike fermion** with a **Z_2 symmetry**. With **two extra scalar fields**, one $SU(3)_c$ colored while the other colorless, anomalies in B meson decays are solved by NP one-loop contributions, Eur. Phys. J. C 79, 517 (2019).

- This model was recently extended by considering different $SU(2)_L$ representations for the newly introduced particles, 10.1103/PhysRevD.102.075009.

The models

- **$SU(2)_L$** representations of new particles are either **singlet, doublet, or triplet**. All particles belong to the **Z_2 odd sector or dark sector**. **Vectorlike fermions** have **electric charge 0 or ±1**. Charges of remaining new fields determined by the Yukawa interaction:

$$\mathcal{L}_{\text{int}}^{\text{NP}} = y_{Q_i} \bar{Q}_{Li} \Phi_q \chi_R + y_{Li} \bar{L}_{Li} \Phi_l \chi_R + \text{H.c.},$$



- The lightest color- and electromagnetically-neutral Z_2 odd particle is the DM candidate.
- In total there are 8 possible models (if we swap the spins 0 ↔ 1/2 for the new particles, we can generate other 8 models). **Model 5** has been studied in detail, 10.1103/PhysRevD.102.075009. Here, we will focus on **model 3**.

TABLE V. Charge assignment for the Z_2-odd fields in Model 5.

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
χ_R	**1**	**2**	−1/2
Φ_l	**1**	**1**	0
Φ_q	**3**	**1**	2/3

TABLE III. Charge assignment for the Z_2-odd fields in Model 3.

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
χ_R	**1**	**1**	−1
Φ_l	**1**	**2**	1/2
Φ_q	**3**	**2**	7/6

Detailed study of model 3

- All **new fields are odd under Z_2**, unlike the SM fields which are even. **Fermionic field χ** is a $SU(2)_L$ **singlet**. Both new **scalar fields ϕ_2 and ϕ_3** are **$SU(2)_L$ doublets**, and ϕ_3 is the colored scalar.

- Dirac mass and **Yukawa couplings** to the fermion χ:

$$\mathcal{L} \supset m_\chi \bar{\chi}_L \chi_R + y_{Q_i} \bar{Q}_{Li} \Phi_3 \chi_R + y_{L_i} \bar{L}_{Li} \Phi_2 \chi_R + \text{H.c.},$$

- The **scalar potential** can be written as:

$$\begin{aligned} V = & - m_{11} \Phi_1^\dagger \Phi_1 + m_{22} \Phi_2^\dagger \Phi_2 + m_{33} \Phi_3^\dagger \Phi_3 + \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \lambda_2 (\Phi_2^\dagger \Phi_2)^2 - \lambda_3 (\Phi_{3,a}^\dagger \Phi_{3,a})(\Phi_{3,b}^\dagger \Phi_{3,b}) \\ & + \lambda_{12} (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_{13} (\Phi_1^\dagger \Phi_1)(\Phi_3^\dagger \Phi_3) + \lambda_{23} (\Phi_2^\dagger \Phi_2)(\Phi_3^\dagger \Phi_3) + \lambda_5 \left[(\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2 \right] \\ & + \lambda'_{12} (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \lambda'_{13} (\Phi_1^\dagger \Phi_3)(\Phi_3^\dagger \Phi_1) + \lambda'_{23} (\Phi_2^\dagger \Phi_3)(\Phi_3^\dagger \Phi_2) \\ & + y_{13} (\Phi_1^T i\sigma_2 \Phi_3)^\dagger (\Phi_1^T i\sigma_2 \Phi_3) + y_{23} (\Phi_2^T i\sigma_2 \Phi_3)^\dagger (\Phi_2^T i\sigma_2 \Phi_3) \,, \end{aligned}$$

with (in the unitary gauge):

$$\Phi_1 = \begin{bmatrix} 0 \\ \frac{1}{\sqrt{2}}(v+h) \end{bmatrix}, \quad \Phi_2 = \begin{bmatrix} \phi_l^+ \\ \frac{1}{\sqrt{2}}(S+iA) \end{bmatrix}, \quad \Phi_3 = \begin{bmatrix} \phi_q^{+5/3} \\ \phi_q^{+2/3} \end{bmatrix}$$

Detailed study of model 3

- The mass spectrum is given by

$$m_h^2 = 2v^2\lambda_1\,, \quad m_S^2 = m_{22} + v^2\,\frac{\lambda_{12}+\lambda'_{12}+2\lambda_5}{2}\,, \quad m_A^2 = m_{22} + v^2\,\frac{\lambda_{12}+\lambda'_{12}-2\lambda_5}{2}\,,$$

$$m_{\phi_l}^2 = m_{22} + v^2\,\frac{\lambda_{12}}{2}\,, \quad m_{\phi_q^{5/3}}^2 = m_{33} + v^2\,\frac{y_{13}+\lambda_{13}}{2}\,, \quad m_{\phi_q^{2/3}}^2 = m_{33} + v^2\,\frac{\lambda'_{13}+\lambda_{13}}{2}\,.$$

- The following parameters are fixed:

$$\lambda_1 = \frac{m_h^2}{2v^2}\,, \quad m_{22} = \frac{2m_{\phi_l}^2 - v^2\lambda_{12}}{2}\,, \quad \lambda'_{12} = \frac{m_S^2 + m_A^2 - 2m_{\phi_l}^2}{v^2}\,,$$

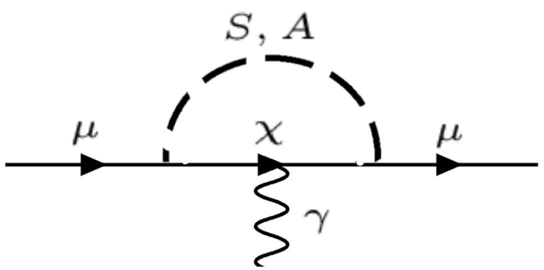
$$m_{33} = \frac{2m_{\phi_q^{5/3}}^2 - v^2 y_{13} - v^2\lambda_{13}}{2}\,, \quad \lambda_5 = \frac{m_S^2 - m_A^2}{2v^2}\,, \quad \lambda'_{13} = \frac{2m_{\phi_q^{2/3}}^2 - 2m_{\phi_q^{5/3}}^2 + v^2 y_{13}}{v^2}\,.$$

- There are **two potential DM candidates**: the neutral scalar **S** or the pseudoscalar **A**. We chose S to be the DM particle. The **Z_2 odd particles only couple to down-quarks of the last two generations** and the **second-generation leptons**, i.e., only y_b, y_s, and y_μ are nonzero.

$$\mathcal{L} \supset y_{d_i}\left(\bar{u}_{Lj} V_{ji} \chi_R^- \,\phi_q^{+5/3} + \bar{d}_{Li}\chi_R^- \phi_q^{+2/3}\right) + y_{e_i}\left(\bar{\nu}_{Li}\phi_l^+ \chi_R^- + \frac{\bar{e}_{Li}\chi_R^-(S+iA)}{\sqrt{2}}\right) + \mathrm{H.c.}$$

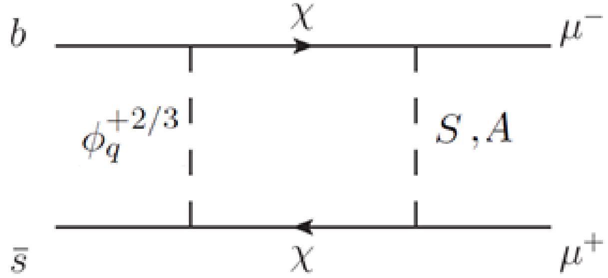
Detailed study of model 3

- **NP contribution to (g-2)** in our model is: J. High Energy Phys. 04 (2017) 043



$$\Delta a_\mu = \frac{m_\mu^2 |y_\mu|^2}{16\pi^2 m_\chi^2}[\tilde{F}_7(x_S) + \tilde{F}_7(x_A)], \quad \tilde{F}_7(x) = \frac{1 - 6x + 3x^2 + 2x^3 - 6x^2 \ln x}{12(1-x)^4}, \quad x_{S(A)} = m_{S(A)}^2 / m_\chi^2.$$

- **NP contribution to B → K$^{(*)}$ μ$^+$μ$^-$ (b → s μ$^+$μ$^-$)** decays:



$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* (C_9^{\text{NP}} \mathcal{O}_9 + C_{10}^{\text{NP}} \mathcal{O}_{10}), \quad \mathcal{O}_9 = \frac{\alpha}{4\pi}[\bar{s}\gamma^\nu P_L b][\bar{\mu}\gamma_\nu \mu], \quad \mathcal{O}_{10} = \frac{\alpha}{4\pi}[\bar{s}\gamma^\nu P_L b][\bar{\mu}\gamma_\nu \gamma^5 \mu]$$

➢ Contributions to the Wilson coefficients $C^{NP}_{9,10}$:

$$C_9^{\text{box}} = -C_{10}^{\text{box}} = \mathcal{N} \frac{y_s y_b^* |y_\mu|^2}{64\pi \alpha m_\chi^2} [F(x_{\Phi_q}, x_S) + F(x_{\Phi_q}, x_A)], \quad x_{\Phi_q,S,A} \equiv m_{\Phi_q,S,A}^2 / m_\chi^2 \quad \mathcal{N}^{-1} = 4G_F V_{tb} V_{ts}^* / \sqrt{2}$$

$$F(x,y) = \frac{1}{(1-x)(1-y)} + \frac{x^2 \ln x}{(1-x)^2(x-y)} + \frac{y^2 \ln y}{(1-y)^2(y-x)}.$$

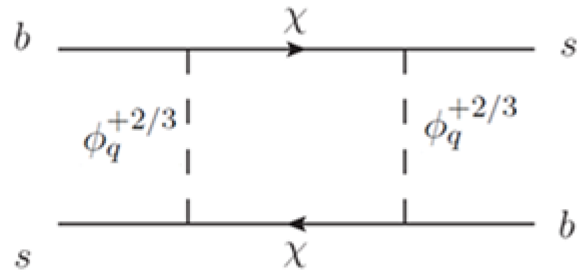
➢ The best fitted value of the Wilson coefficient is **$C^{NP}_9 = -C^{NP}_{10} = -0.53 \pm 0{,}08$**, 10.1016/j.physletb.2019.134858. In our numerical scan, all points must generate Wilson coefficients within the 2σ range.

Detailed study of model 3

- NP contribution to $\mathbf{Bs} - \overline{\mathbf{B}}\boldsymbol{s}$ **mixing,** J. High Energy Phys. 06 (2019) 118:

$$\mathcal{H}_{\text{eff}}^{B\bar{B}} = C_{B\bar{B}} Q_1 \equiv C_{B\bar{B}} (\bar{s}_\alpha \gamma^\mu P_L b_\alpha)(\bar{s}_\beta \gamma^\mu P_L b_\beta) \qquad C_{B\bar{B}}^{\text{NP}} = \frac{(y_s y_b^*)^2}{128\pi^2 m_\chi^2} F(x_{\Phi_q}, x_{\Phi_q}) \qquad F(x,x) = \frac{1 - x^2 + 2x \ln x}{(1-x)^3}$$

$$R_{\Delta M_s} = \frac{\Delta M_s^{\text{exp}}}{\Delta M_s^{\text{SM}}} - 1 = -0.09 \pm 0.08, \qquad R_{\Delta M_s} = \left| 1 + \frac{0.8 C_{B\bar{B}}^{\text{NP}}(\mu_H)}{C_{B\bar{B}}^{\text{SM}}(\mu_b)} \right| - 1$$



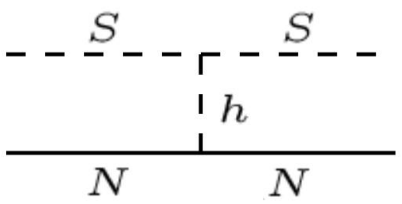
➢ We constrain $\mathbf{C^{NP}}_{\mathbf{B\bar{B}}}$ by requiring $R_{\Delta Ms}$ to lie in its **2σ range**.

- We have included several Z_2 odd particles to the particle spectrum, which induce **corrections to the EW oblique parameters S, T and U at one-loop** (not yet included in the scan).

DM constraints

- **Dark matter direct detection:** dominant signal comes from tree-level diagram with t-channel SM-like Higgs mediation, leading to the DM-nucleon scattering cross section

$$\sigma(SN \to SN) = \frac{(\lambda_{12} + \lambda'_{12} + 2\lambda_5)^2}{4\pi} \frac{f_N^2 m_N^2 \mu_{SN}^2}{m_S^2 m_h^4}$$



- Best experimental upper bound on DM direct detection cross section (for a mass above 6 GeV) comes from **XENON1T** experiment, which we take into account in our scan. Phys. Rev. Lett. 121, 111302 (2018)

- **Higgs invisible decays:** upper bound used is **B(h -> SS) < 0.24**. The invisible decay width in our model is:

$$\Gamma(h \to SS) = \frac{(\lambda_{12} + \lambda'_{12} + 2\lambda_5)^2 v_H^2}{32\pi m_h} \sqrt{1 - \frac{4m_S^2}{m_h^2}}.$$

- **Dark matter relic density:** most accurate measurement provided by the Planck Collaboration with $\Omega_{DM}h^2$ **= 0.1199 ± 0.0022**, Astron. Astrophys. 594, A13 (2016). Assuming freeze-out mechanism, relic abundance of S determined by solving the Boltzmann equation which we numerically solve using **MICROMEGAS**.

$$\frac{dn_S}{dt} + 3Hn_S = -\langle \sigma v \rangle (n_S^2 - n_S^{\text{eq}\,2})$$

Analysis and results

- **Multiparameter random scan** to find parameter regions that satisfy all relevant flavor constraints, the muon anomalous magnetic moment Δa_μ, and the DM constraints. **Results** are yet (very) **preliminary and recent**.

- **Assumptions and constraints:**

➢ y_s and y_b are real with $y_s = -y_b/4$.

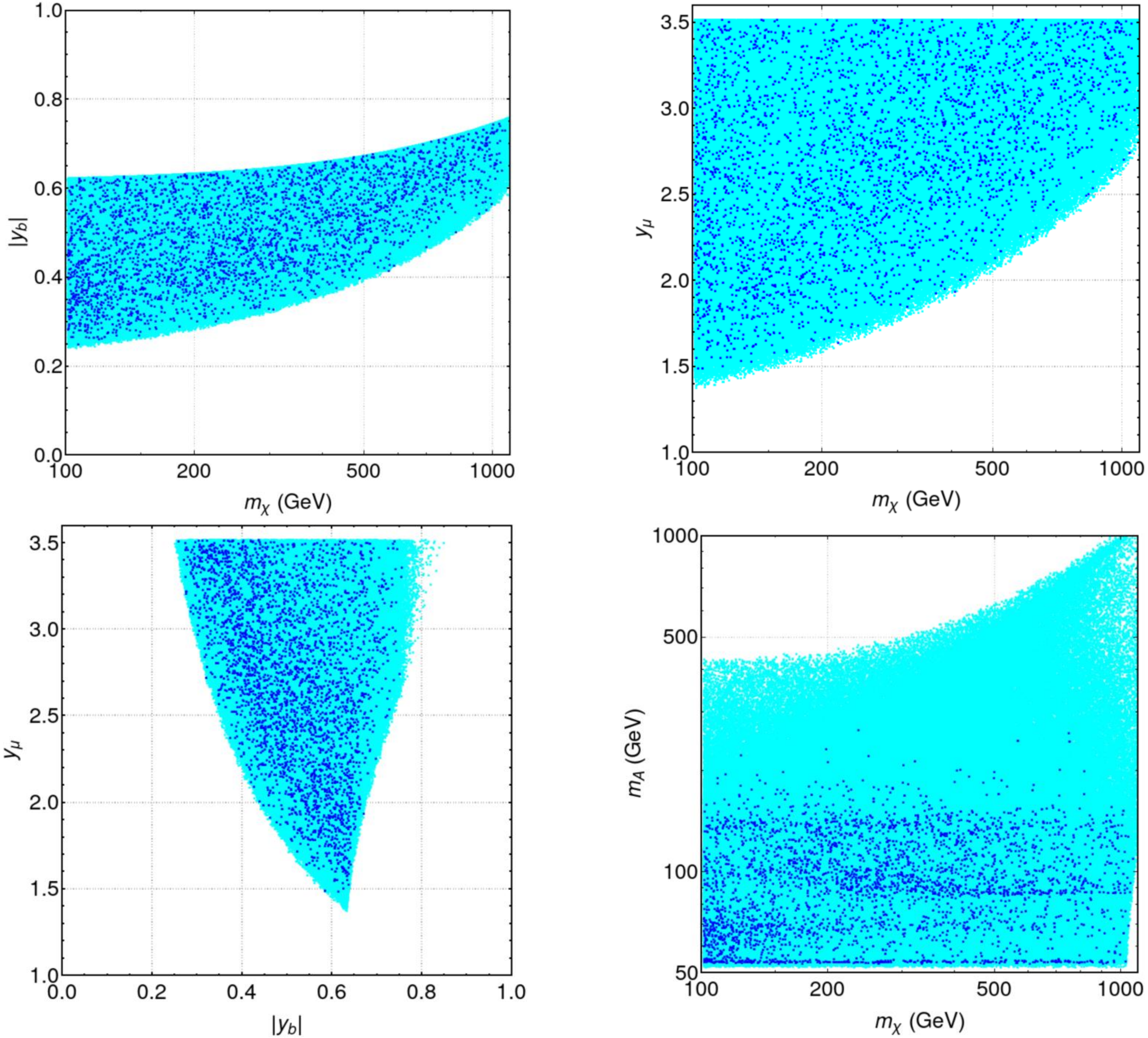
➢ Colored scalars mass: $m_{\phi_q^{5/3}} = m_{\phi_q^{2/3}} = 1.5 \text{ TeV}$

➢ All particles in the dark sector should be at least 10 GeV heavier than the DM candidate S, with 5 GeV ≤ m_S ≤ 1 TeV and $m_{\phi l} > m_Z/2$.

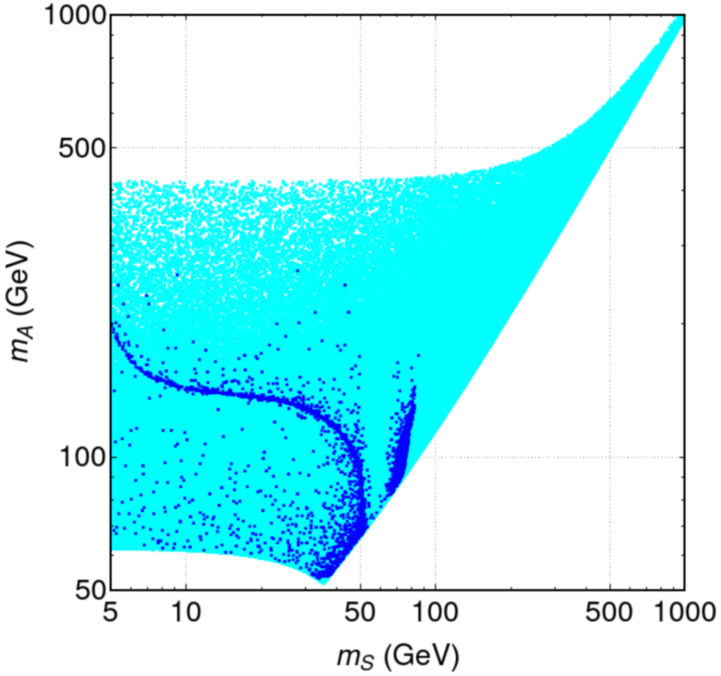
➢ LEP searches for unstable heavy vectorlike charged leptons set lower limit of 101.2 GeV for χ.

➢ Dimensionless couplings: $|y_b| \leq 1$, $0 \leq y_\mu \leq (4\pi)^{1/2}$, $\lambda_5 \leq 4\pi$, $\lambda_{12}' \leq 4\pi$, $\lambda_{12} + \lambda_{12}' + \lambda_5 \leq 1$.

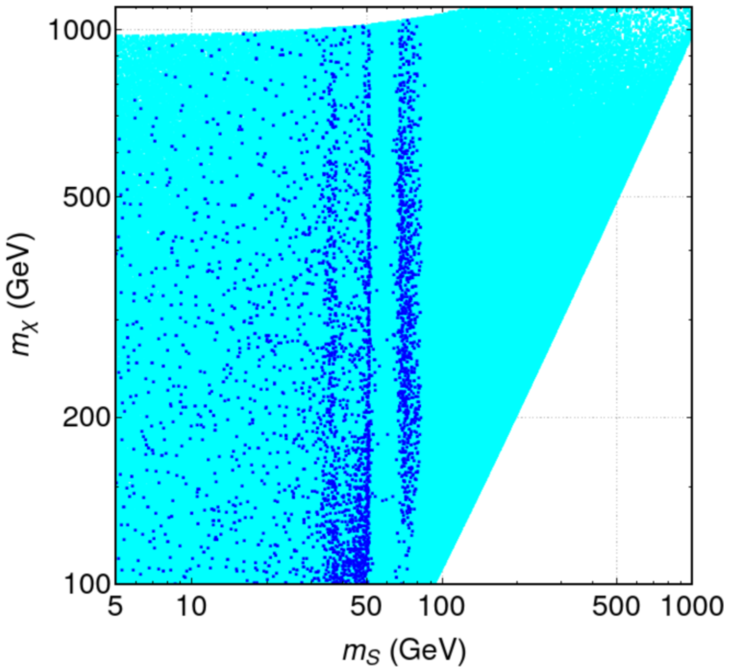
- Color scheme: **all points satisfy** the mentioned **b-physics data within 2σ**. **Cyan points excluded** when considering observed **DM relic abundance**, within 2σ CL. **Blue points cannot satisfy** constraints from **DM searches**. **Green points not allowed by the muon (g − 2)** data within its 3σ range. **Red points** is the common parameter space which can **explain all previous data at the same time**.



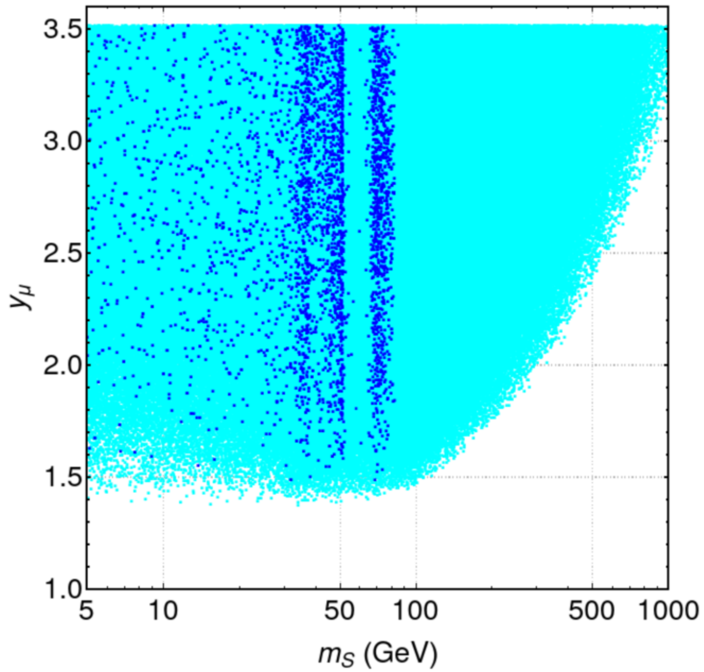
|y_b|
m_χ (GeV)
y_μ
m_χ (GeV)
y_μ
|y_b|
m_A (GeV)
m_χ (GeV)



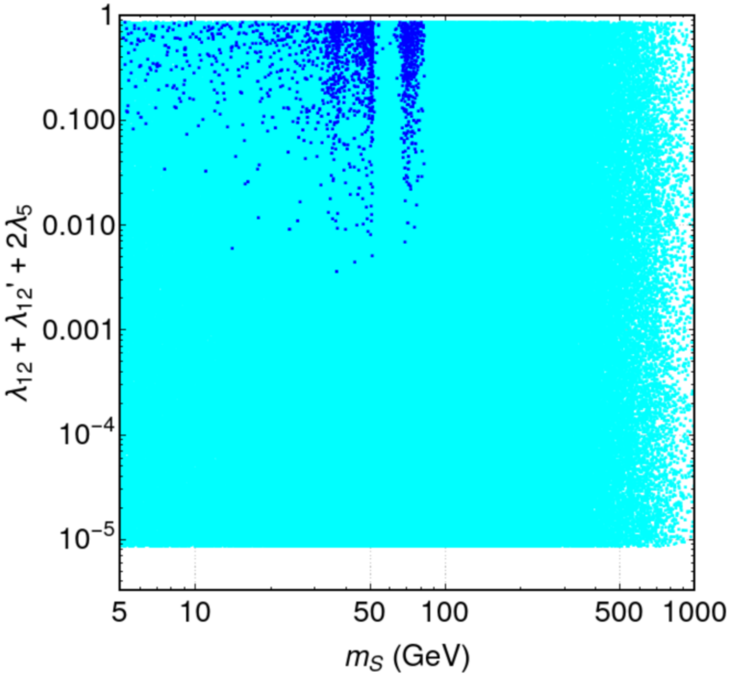
1000
500
100
50
m_A (GeV)
5 10 50 100 500 1000
m_S (GeV)



1000
500
200
100
m_χ (GeV)
5 10 50 100 500 1000
m_S (GeV)

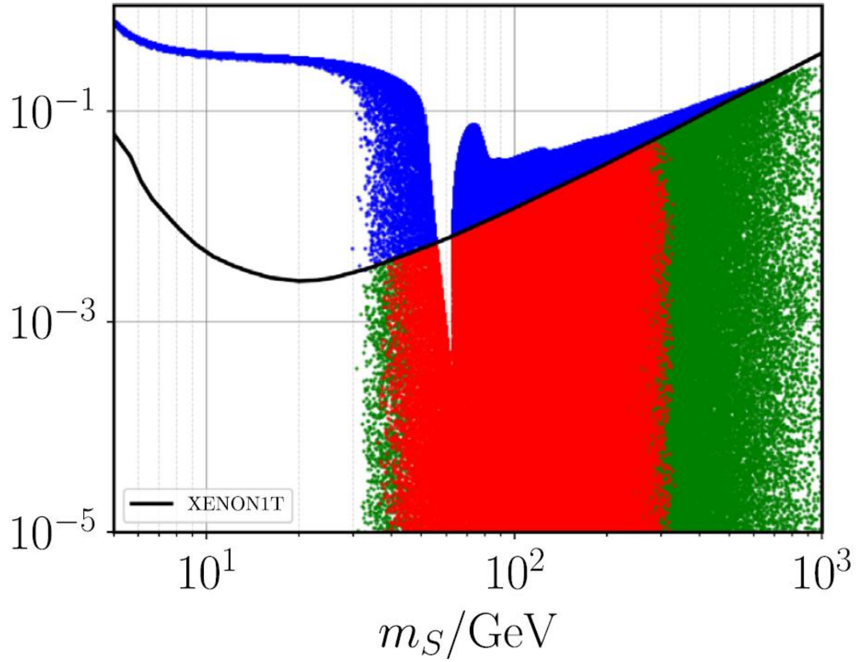


3.5
3.0
2.5
2.0
1.5
1.0
y_μ
5 10 50 100 500 1000
m_S (GeV)



1
0.100
0.010
0.001
10^{-4}
10^{-5}
$\lambda_{12} + \lambda_{12}' + 2\lambda_5$
5 10 50 100 500 1000
m_S (GeV)

from model 5



10^{-1}
10^{-3}
10^{-5}
XENON1T
10^1 10^2 10^3
m_S/GeV

Analysis and results

- First set of plots: **B meson decay data** limits **$|y_b|$** to be around **0.25-0.75** and **y_μ above ~1.4**. Constraints from DM (**DM relic density**) do not have a major impact on the parameter space (similar cyan and blue regions) for these parameters. But they limit pseudoscalar mass: **50 GeV ≤ m_A ≤ 300 GeV.**

- Second set of plots: DM relic density constraint limits **m_S ≤ 100 GeV**, and **$\lambda_{12} + \lambda_{12}' + \lambda_5 \geq 10^{-3}$** (bottom-right plot). There are **no allowed points that also satisfy DM direct detection constraints** (and g-2), **contrary to model 5**.

- Comparing with **model 5**, **flavor** phenomenology and constraints are very **similar**, but **DM** constraints lead to **significant differences in the allowed parameter region**.

Conclusions

- We continued the **study of a class of models** that simultaneously **provides solutions to** the anomalies in **B-meson decays**, to the **muon (g-2)**, and a **DM candidate**.

- In particular, we focused on the flavor and DM physics of a particular model, **model 3**, in which we introduce **two $SU(2)_L$ scalar doublets**, one an **$SU(3)_c$ triplet** and the other colorless, plus a **$SU(2)_L$ singlet vectorlike fermion** with **-1 charge**.

- Performing a random scan over the whole parameter space, we found that the (preliminary) **results related to the B meson decay constraints are similar to what was found in a previous studied model** (model 5), showing that the **Yukawa couplings should be sizeable**. But significant differences were found in the parameter region that obeys DM constraints. Particularly, **there are no points satisfying DM direct detection constraints (and g-2), contrary to model 5**.

- Results still being analysed, in particular, we want to see if scan can be refined in order to allow for a larger parameter space that satisfies DM relic density, as well as the remaining constraints.