Impact of SU(2) representation in models for B and g–2 anomalies from Dark Loops

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Find out more: Huang, Morais and Santos, PhysRevD.102.075009, Capucha, Huang, Lopes and Santos, arXiv:2207.11556

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Overview

- In 2012, a new scalar particle with a mass close to 125 GeV, later identified as the **Higgs boson**, **was discovered at the Large Hadron Collider (LHC)**. Electroweak symmetry breaking confirmed and **SM completed**.

- Most experimental results agree with the SM predictions, but there are exceptions: **B meson decays** and **muon's anomalous magnetic moment**. Also, the **SM cannot be the final theory** – no explanation for **dark matter (DM)**, not enough CP-violation to explain **matter-antimatter asymmetry**.

- We must explore **new physics beyond the SM** to address these issues. **Models for B and $(g\text{-}2)_\mu$ anomalies from dark loops:**

- ➢ Motivation;
- ➢ Theoretical framework;
- ➢ Flavor, DM and EW constraints;
- ➢ Results;
- ➢ Conclusions.

Motivation

- Hints of NP come from the observed **anomalies in the semileptonic decay rates of the B meson**:

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

LHCb Collaboration JHEP08(2017)055, Nature Phys. 18, 277 (2022)

$$R(K) = 0.846^{+0.042+0.013}_{-0.039-0.012}\,, \qquad q^2 \in [1.1, 6]\mathrm{GeV}^2$$

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

SM predictions Hiller et al., PhysRevD.69.074020
Bordone et al., Eur. Phys. J. C 76, 440 (2016)

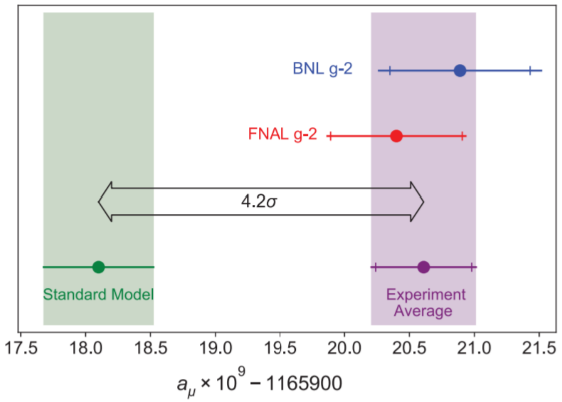
$$R(K) = 1.0004(8), \qquad q^2 \in [1.1, 6]\ \mathrm{GeV}^2,$$

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

- 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:

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

Muon g−2 Collaboration, PhysRevLett.126.141801



- Further demand for NP arises from several observations pointing to the existence of **dark matter** (galaxy rotation curves, galaxy clusters, CMB, gravitational lensing, structure formation, others), whose nature remains a mystery.

Theoretical framework

- All three previous issues can be solved by a class of models with several new particles: **one vectorlike fermion** (**χ**), and **two extra scalar fields**, one $SU(3)_c$ colored (**Φ_3**) and the other colorless (**Φ_2**). Anomalies in B meson decays and g-2 solved by one-loop contributions involving these fields, one of which is the **DM candidate**.

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

$$\mathcal{L}_{Yuk}^{NP} = y_{Q_i}\overline{Q}_{Li}\Phi_3\chi_R + y_{L_i}\overline{L}_{Li}\Phi_2\chi_R + H.c.$$

- In total there are 8 possible models. We will study **Model 3**, and compare it to the previously studied **Model 5** Huang, Morais and Santos, PhysRevD.102.075009

Model 3

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
χ_R	1	1	-1
Φ_2	1	2	1/2
Φ_3	3	2	7/6

Model 5

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
χ_R	1	2	-1/2
Φ_2	1	1	0
Φ_3	3	1	2/3

Theoretical framework

- The **Higgs potential** for Model 3 is:

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

- **Scalar fields** (in the unitary gauge):

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

- **Two potential DM candidates**: the neutral scalars S and A. We chose **S** as the **DM particle** (results unchanged if we chose A, as S and A have same quantum numbers apart from CP). Same choice made in Model 5.

- The **Z_2 odd particles** only couple to down-quarks of the last two generations and second-generation leptons (only y_b, y_s and y_μ are relevant), to suppress the strong flavor constraints on the first-generation of quarks and leptons and simplify the analysis.

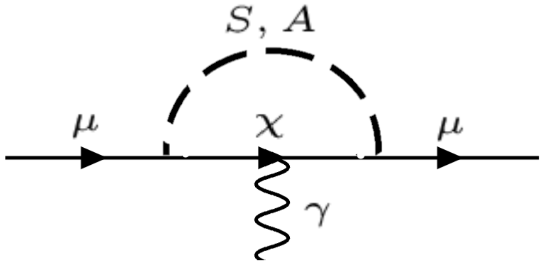
$$
\mathcal{L} = y_{di}(\overline{u}_{Lj}V_{ji}\chi_R^-\phi_q^{+5/3} + \overline{d}_{Li}\chi_R^-\phi_q^{+2/3}) + y_{Li}(\overline{\nu}_{Li}\chi_R^-\phi_l^+ + \frac{\overline{e}_{Li}}{\sqrt{2}}\chi_R^-(S+iA)) + H.c.
$$

Flavor, dark matter and electroweak constraints

- **Model 3 contribution** to **(g-2)** (same as Model 5):

  Arnan, Crivellin, Hofer and Mescia, JHEP04(2017)043

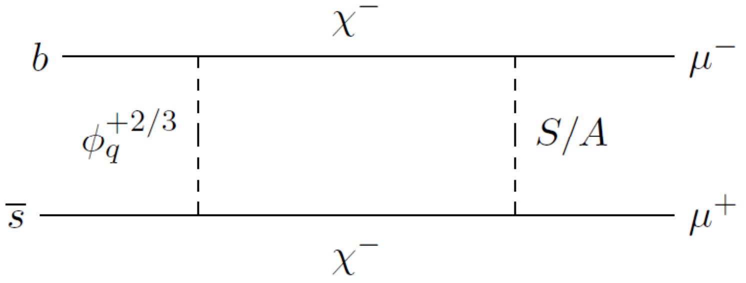
$$\Delta a_\mu = \frac{m_\mu^2 |y_\mu|^2}{16\pi^2 m_\chi^2}\left(\tilde{F}_7(x_S) + \tilde{F}_7(x_A)\right)$$



- **Model 3 contribution** to **B → K$^{(*)}$ $\mu^+\mu^-$ (b → s $\mu^+\mu^-$) decays** (same as Model 5):

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

$$C_9^{NP} = -C_{10}^{NP} = \frac{\sqrt{2}}{4G_F V_{tb}V_{ts}^*}\frac{y_s y_b^* |y_\mu|^2}{64\pi\alpha m_\chi^2}\left(F(x_{\phi_q^{+2/3}}, x_S) + F(x_{\phi_q^{+2/3}}, x_A)\right)$$



➢ **C^{NP}_9 = −C^{NP}_{10} = [-0.59, -0.30]**, Algueró et al., Eur. Phys. J. C 82, 326 (2022). In our numerical scan, all points must generate these Wilson coefficients within their 2σ range.

- **Model 3 contribution** to **$\mathrm{Bs} - \overline{\mathrm{B}}s$ mixing** (same as Model 5):

$$C_{B\overline{B}} = \frac{(y_s y_b^*)^2}{128\pi^2 m_\chi^2} F(x_{\phi_q^{+2/3}}, x_{\phi_q^{+2/3}}) \qquad R_{\Delta M_s} = \frac{\Delta M_s^{Exp}}{\Delta M_s^{SM}} - 1 = -0.09 \pm 0.08 \qquad R_{\Delta M_s} = |1 + \frac{0.8 C_{B\overline{B}}(\mu_H)}{C_{B\overline{B}}^{SM}(\mu_b)} - 1|$$

➢ We constrain C_{BB} by requiring $R_{\Delta M_s}$ to lie in its 2σ range. Arnan, Crivellin, Fedele and Mescia, JHEP06(2019)118

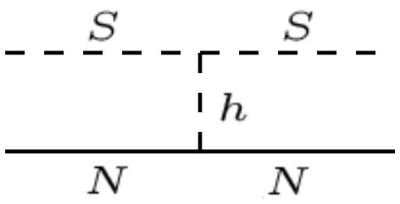
Flavor, dark matter and electroweak constraints

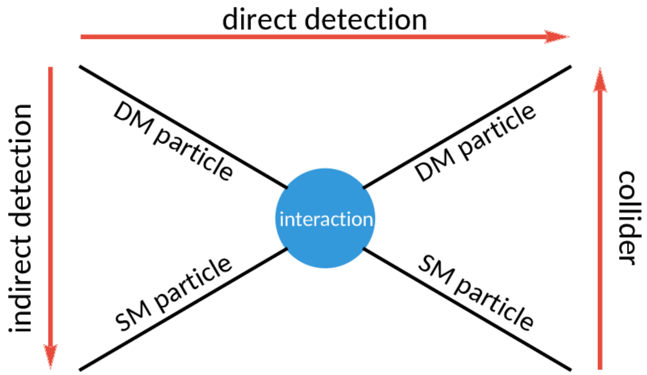
- **DM relic density**: **$\Omega_{DM}h^2 = 0.120 \pm 0.001$,** Planck Collaboration et al., A&A 641, A6 (2020). Assuming the **freeze-out** mechanism, the relic abundance is determined by solving the Boltzmann equation which we do numerically using **MICROMEGAS**.

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

- **Dark matter direct detection:**

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





➢ Best experimental upper bounds come from the **LZ**, **PandaX-4T** and **XENON1T** experiments.

LZ Collaboration, arXiv:2207.03764, PandaX-4T Collaboration, PhysRevLett.127.261802, XENON Collaboration, PhysRevLett.121.111302

- **Collider searches:** upper bound for **Higgs to invisible decays** is **B(h -> SS) < 0.11**. PDG, Zyla et al., PTEP 2020, 083C01 (2020)

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

Flavor, dark matter and electroweak constraints

- **Model 3 contribution** to **EW oblique parameter T**:

➢ The contribution to T in Model 3 is the same as in the **Inert Doublet Model**:

$$T = \frac{g^2}{64\pi^2 m_W^2 \alpha}[F(m_{\phi_l}^2, m_S^2) + F(m_{\phi_l}^2, m_A^2) - F(m_S^2, m_A^2)] \qquad F(A,B) = \begin{cases} \frac{A+B}{2} - \frac{AB}{A-B}\ln\frac{A}{B}, & \text{if } A \neq B. \\ 0, & \text{A} = \text{B}. \end{cases}$$

Grimus, Lavoura *et al., J. Phys. G: Nucl. Part. Phys.* 35 075001 (2008)

➢ **Colored scalars do not contribute** to the T parameter since we chose them to have **equal mass**.

➢ **T = 0.03 ± 0.12**. We require T to be within its 2σ range.

➢ **Contributions to T in Model 5 are zero** at the one-loop order, because the scalar fields are SU(2) singlets, and both components of the doublet vectorlike fermion χ have the same mass (T in the SM is proportional to T ∝ $m_t^2 - m_b^2$).

Results

- **Multiparameter random scan** to find parameter regions that satisfy all relevant flavor constraints, the muon anomalous magnetic moment, the DM constraints and the corrections to the EW oblique parameter T.

- **Final constraints:**

➢ y_s and y_b are real with $y_s = -y_b/4$, $|y_b| \leq 1$, $1 \leq y_\mu \leq 4\pi$.

➢ Colored scalars mass: $m_{\phi l}{}^{5/3} = m_{\phi l}{}^{2/3} = 1.5$ TeV.

➢ All particles in the dark sector at least (most) 10 GeV (1 TeV) heavier than S, with $5\ \text{GeV} \leq m_S \leq 1\ \text{TeV}$.

➢ **LEP constraints:**

  ❑ $m_S + m_{\phi l} > m_W$, $m_A + m_{\phi l} > m_W$, $m_S + m_A > m_Z$, $2m_{\phi l} > m_Z$, $m_{\phi l} > 70$ GeV; A. Pierce and J. Thaler, JHEP08(2007)026

  ❑ $m_S < 80$ GeV + $m_A < 100$ GeV + $m_A - m_S > 8$ GeV region excluded; Lundström et al., Physical Review D 79 (2009)

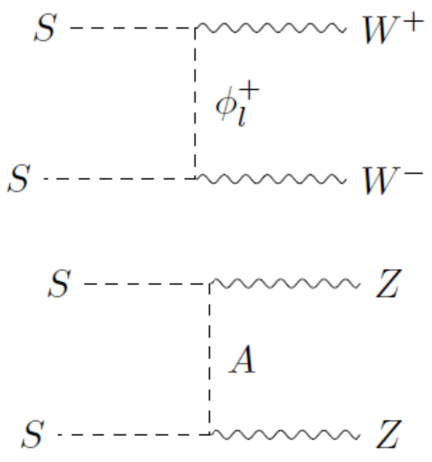
  ❑ $m_\chi > 101.2$ GeV. Achard et al., Physics Letters B 517, 75 (2001)

➢ Higgs portal coupling: $10^{-7} \leq |\lambda_{hs}| \leq 10^{-2}$.

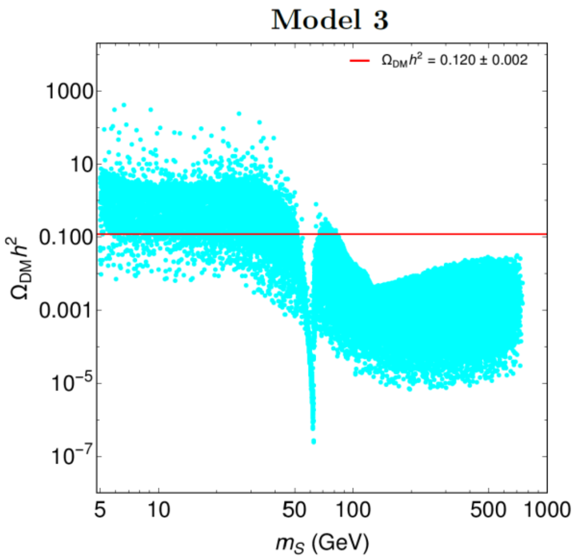
- Color scheme: **all points satisfy B-physics constraints** within 2σ. **Cyan points** excluded when considering **DM relic abundance**, within 2σ CL. **Blue points** cannot satisfy **DM searches**. **Green points** not allowed by the **muon (g − 2)** within its 3σ range. **Red points** are the common parameter space which **explain all previous constraints**.

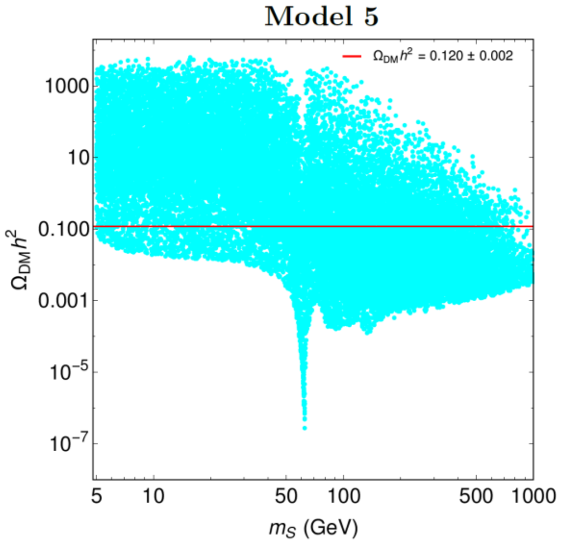
Results

- In both models, there are regions of the parameter space satisfying all the constraints, but differences exist. The main one is related to the **DM's relic density** distribution, which forces **m_S < 80 GeV for Model 3**. This occurs because in **Model 3**, the scalar fields are **SU(2) doublets** and can couple to gauge bosons, unlike for **Model 5** where they are **singlets**.



Model 3 only!





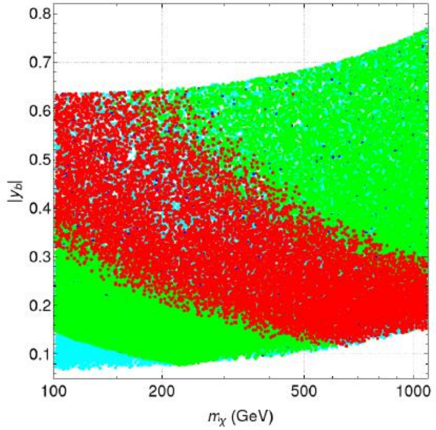
- Some fine-tuning is necessary to keep the **Higgs portal coupling** small enough in Model 3 to verify the direct detection constraints.

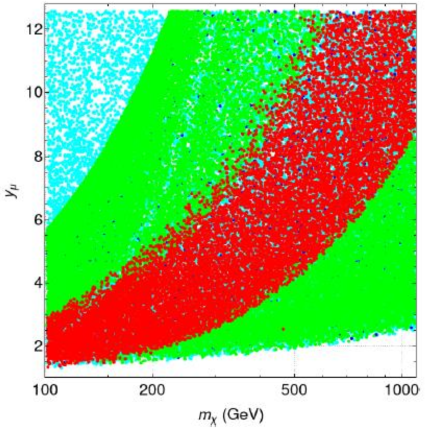
$$\lambda_{hS} = \lambda_{12} + \lambda'_{12} + 2\lambda_5 = \lambda_{12} + 2\,(m_S^2 - m_{\phi_l}^2)/v^2 \qquad \lambda_{12} \approx -2\,(m_S^2 - m_{\phi_l}^2)/v^2$$

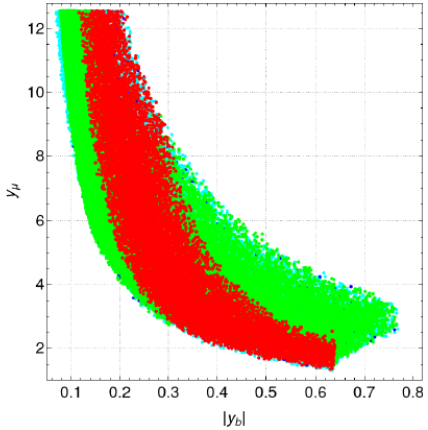
Capucha, Huang, Lopes and Santos, arXiv:2207.11556

Results

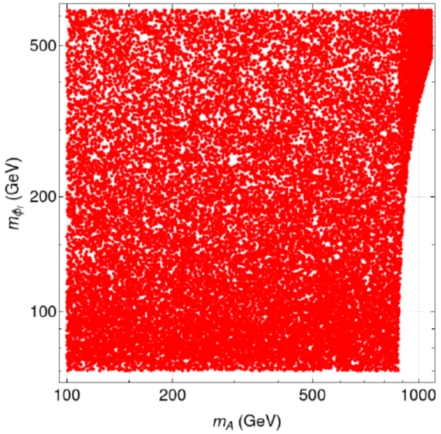
- **Sizeable Yukawa couplings** with similar limits as the ones in Model 5, as expected since the flavor physics is the same, with **$y_\mu > 1.3$** and **$0.11 < y_b < 0.65$** when all constraints are taken into account, and $m_\chi < 1076$ GeV.





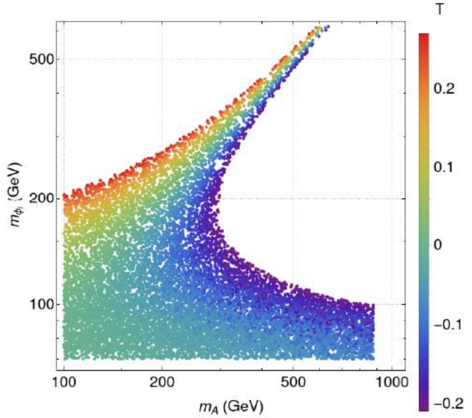


- **Corrections from EW oblique parameters**: upper limit for **m_A** slightly lower (1070 GeV to **870 GeV**), and for heavier masses ($m_{\phi l} > 200$ GeV and $m_A > 300$ GeV), a significant part of the previously allowed parameter space is now excluded.



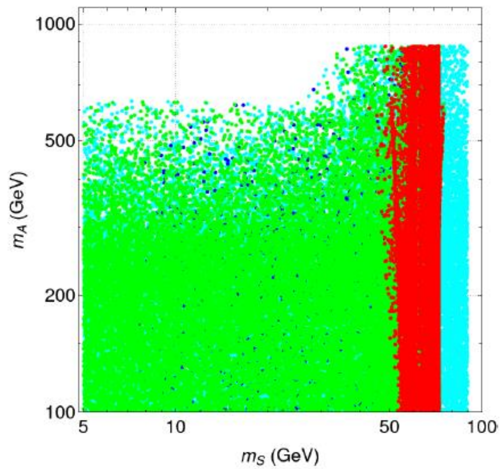
$$T \propto (m_{\phi_l} - m_A)(m_{\phi_l} - m_S)$$

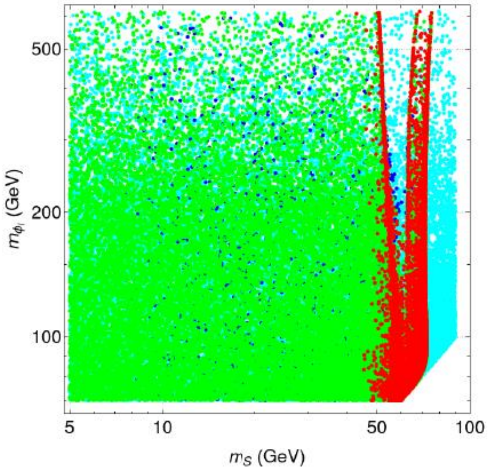
EW constraints

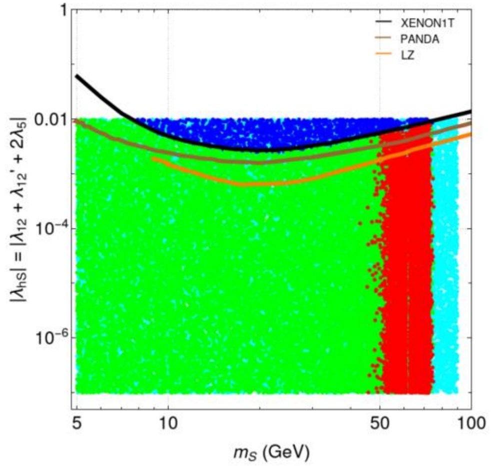


Results

- For the **DM mass**, we have **42 GeV $< m_S < 76$ GeV** (in **Model 5, 30 GeV $< m_S < 350$ GeV**), thus, the DM mass is limited in a very narrow range in Model 3, while for Model 5 its range is much broader. For the remaining parameters we observe **$|\lambda_{hs}| \leq 0.008$**, and **$m_{\phi I} < 621$ GeV**. The constraint on $m_{\phi I}$ keeps $\lambda_{12} < 4\pi$.







Conclusions

- A **model with a new dark sector** which provides a **DM candidate** and is able to solve some discrepancies in **B meson decays** and the **muon (g-2)** was explored (Model 3) and compared to a previously studied model (Model 5).

- **Both models have regions satisfying all the constraints**. The **contributions to the flavor observables and the muon (g-2) do not change** since the vertices contributing to the loop processes are the same.

- However, there are **differences** in the allowed parameter space **related to DM physics**. The main one is due to the **DM relic density constraint**, which sets an **upper limit of 80 GeV for the DM mass** in **Model 3**. In Model 5, the DM mass range is much broader. This occurs because of the **different SU(2) representations** of the models.

THE END
THANK YOU!

Direct Detection vs Collider Searches