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CP violating portal to Dark Sectors

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The prospect of a Dark Sector neutral under Standard Model interactions represents a compelling explanation for the existence of Dark Matter. A popular class of models considers kinetic mixing as a portal between the visible and the Dark Sector. The introduction of a non-abelian $SU(N)_D$ group can cause kinetic mixing via higher-dimensional operators, justifying the experimental constraints on kinetic mixing parameters. Assuming the presence of a non-abelian CP-odd portal, we investigate the parameter space allowing for a sizeable electron Electric Dipole Moment (eEDM), taking into consideration present and future experimental sensitivities. We show that potentially observable eEDM can be produced in vast regions of the parameter space compatible with current experimental constraints and observed dark matter abundance.

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1. Introduction

The prospect of a sector neutral under the SM gauge group (i.e. Dark Sector (DS)) represents a compelling scenario for addressing many unsolved puzzles in particle physics and cosmology. In fact, hidden sectors can offer viable scenarios for DM candidates and might also introduce the necessary ingredients for baryogenesis, such as new sources of CP violation.

Typically, DM production requires an interaction with SM particles (other than gravity), making the presence of portals connecting dark and visible sectors necessary. Assuming that the DS interactions are governed by local gauge symmetries, a portal can be generated by the interaction of two different gauge field strength tensors. A vector portal is possible at the renormalizable level only for abelian group $U(1)_D$, through the lagrangian term

$$\epsilon X^{\mu\nu} B_{\mu\nu}. \tag{1}$$

Although dark photon searches put severe limits on the kinetic mixing parameter ϵ, Eq. (1) gives no indication about the origin of this suppressed value.

Interestingly, for a non-abelian $SU(N)_D$ dark sector, gauge invariance forbids kinetic mixing at the renormalizable level, facilitating a more natural explanation of the experimental bounds. Indeed, in this case, a kinetic mixing can arise only from effective operators of at least dimension 5:

$$\frac{1}{\Lambda}\mathrm{Tr}[\Sigma G_{\mu\nu}]B^{\mu\nu}, \tag{2}$$

where Σ^a is a scalar field in the adjoint representation of the dark gauge group, Λ is the UV scale, and $G^a_{\mu\nu}$, $B_{\mu\nu}$ are the strength tensors of the dark and hypercharge gauge fields, respectively. If Σ^a acquires a nontrivial vacuum expectation value (VEV), spontaneous symmetry breaking (SSB) of the dark group can occur, leading to kinetic mixing between the SM and hidden sector gauge bosons, as in Eq. (1). As a result, a natural suppression proportional to the ratio between the VEV and the UV scale is obtained.

Provided that the hidden sector contains sources of CP violation, which may be necessary for baryogenesis, the CP-odd analogue of the operator in Eq. (2) is also possible:

$$\frac{1}{\Lambda}\mathrm{Tr}[\Sigma G_{\mu\nu}]\tilde{B}^{\mu\nu}, \tag{3}$$

where $\tilde{B}^{\mu\nu} = \epsilon_{\mu\nu\alpha\beta}B^{\alpha\beta}/2$. The CP-even and CP-odd operators in Eq. (2,3) share the same UV origin from integrating out heavy fermions charged both the hypercharge and the dark gauge group. As a result, we can set $\tilde{C} = \tan\chi C$, where $\tan\chi$ is related to the ratio between the imaginary and the real part of couplings (more details can be found in [1]).

The most sensitive observables to CP-violating interactions are Electric Dipole Moments (EDMs). Since the SM prediction is much smaller than the current and future experimental sensitivities, they are considered an appealing target for indirect searches of new physics. Among them, electron's EDM (eEDM) is usually the most constraining when considering beyond the standard model scenarios.

The current and future sensitivities on eEDM are summarized in Tab. (1)

Experiment	Current bound/Upcoming sensitivity
JILA eEDM	$< 4.1 \times 10^{-30}$ e cm [2]
ACME III	$\sim 1 \times 10^{-30}$ e cm [3]
YBF	$\sim 1 \times 10^{-31}$ e cm [4]
BaF	$\sim 1 \times 10^{-33}$ e cm [5]

Table 1: Current (JILA eEDM) bound on the electron EDM and expected future sensitivities of the upcoming searches.

In [1], we analyze the phenomenology of the non-abelian CP-odd portal and discuss its complementarity with the more studied CP-even mixing, also showing how a model of inelastic Dark Matter (iDM) can be implemented in a non-abelian dark sector framework.

2. Model and eEDM prediction

We consider a hidden sector that is invariant under a non-Abelian gauge group $SU(N)_D$, with SM particles that transform as singlets. We assume that $SU(N)_D$ is spontaneously broken by the dark scalar sector, which contains scalars in the adjoint representation of $SU(N)_D$. The Lagrangian takes the following general form:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DS} + {\rm Tr}[(D_\mu\Sigma)^\dagger(D^\mu\Sigma)] - V(\Sigma) + \mathcal{L}_{\rm SM-DS}, \tag{4}$$

where

$$\mathcal{L}_{\rm SM-DS} \supset -\frac{C}{\Lambda}{\rm Tr}[\Sigma X^{\mu\nu}]B_{\mu\nu} - \frac{\tilde{C}}{\Lambda}{\rm Tr}[\Sigma X^{\mu\nu}]\tilde{B}_{\mu\nu} - \lambda(H^\dagger H){\rm Tr}(\Sigma^\dagger\Sigma). \tag{5}$$

The kinetic and scalar mixings are derived from the SSB of $SU(N)_D$. Indeed, if $\langle\Sigma\rangle = v_a T^a$, the first part of Eq. (5) reads:

$$\mathcal{L}_{\rm SM-DS} \supset -\frac{\epsilon_a}{2}X_a^{\mu\nu}B_{\mu\nu} - \frac{\epsilon_a}{2v_a}\phi^a X_a^{\mu\nu}B_{\mu\nu} - \frac{\tilde{\epsilon}_a}{2}X_a^{\mu\nu}\tilde{B}_{\mu\nu} - \frac{\tilde{\epsilon}_a}{2v_a}\phi^a X_a^{\mu\nu}\tilde{B}_{\mu\nu}, \tag{6}$$

where we have defined $\epsilon_a = Cv_a/\Lambda$ and $\tilde{\epsilon}_a = \tilde{C}v_a/\Lambda$. Once $SU(2)_L$ is broken, the quartic coupling in Eq. (5) induces off-diagonal two-point functions, leading to mixing in the scalar sector. A detailed description of the mixing would require the specifics of the model, which are irrelevant for the scope of this analysis. Indeed, the phenomenology of the CP-odd portal can be studied under some simplification. Assuming just one scalar and one gauge boson mixing with the SM particles, mass eigenstates are obtained from the following rotation matrices:

$$\begin{pmatrix} A \\ Z \\ X \end{pmatrix} = \begin{pmatrix} 1 & 0 & -c_\theta\epsilon \\ 0 & 1 & -\frac{s_\theta\epsilon M_X^2}{M_Z^2-M_X^2} \\ 0 & \frac{s_\theta\epsilon M_Z^2}{M_Z^2-M_X^2} & 1 \end{pmatrix}\begin{pmatrix} A' \\ Z' \\ X' \end{pmatrix}; \qquad \begin{pmatrix} h \\ \phi \end{pmatrix} \simeq \begin{pmatrix} 1 & -\beta \\ \beta & 1 \end{pmatrix}\begin{pmatrix} h' \\ \phi' \end{pmatrix}, \tag{7}$$

where primed fields are the mass eigenstates.

After the rotations in Eq. (7), the new gauge and scalar bosons can interact with SM fermions, so that dipole interactions can stem from the diagram in Fig. (1).

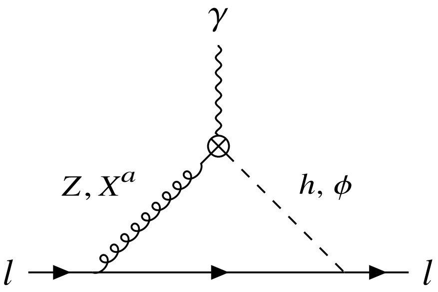

Figure 1: One-loop contribution to fermion dipole moments.

Under these assumptions, the predicted EDM reads:

$$d_l \simeq \frac{Y_l}{8\pi^2 v_D}\epsilon^2 \tan\chi\, \beta c_\theta^2\, e\left(\frac{\log(x_{X\phi})}{x_{X\phi}-1} - \frac{\log(x_{Xh})}{x_{Xh}-1}\right), \tag{8}$$

where Y_l is the SM Yukawa coupling and $x_{ij} = m_i^2/m_j^2$. In Eq. (8), the Z boson contribution has been neglected due to the accidentally suppressed vector coupling of the Z boson to the fermionic current.

Based on the present and future experimental sensitivities on eEDM, Eq. (8) can be translated into sensitivities on ϵ and compared to other experimental bounds, as shown in Fig. (2). We assumed that tan$\chi \sim 1$, which is expected if the UV contains large CP-odd phases.

3. A model of Inelastic Dark Matter

Given the introduction of a new portal connecting the visible and dark sectors, it is tempting to devise a mechanism for DM production. Since both DM production and the predicted eEDM will depend on ϵ, our goal is to test if the parameter space that results in the correct relic abundance can be probed by future eEDM searches. Among a plethora of DM production paradigms, the freeze-out mechanism requires a sizeable interaction between dark bosons and SM particles, which in our model is proportional to ϵ.

However, freeze-out production via DM annihilation into SM particles is extremely constrained by indirect and direct experimental searches. On the one hand, DM annihilation at the CMB epoch would release energy in the intergalactic medium, altering the CMB anisotropy spectrum. Planck collaboration places a model independent lower limit of $m_{DM} \gtrsim 30$ GeV for an s-wave annihilation [6]. On the other hand, direct detection searches for elastic scattering of DM on nuclei severely constrain ϵ for $m_{DM} \gtrsim 10$ GeV. As can be easily shown, both indirect and direct detection bounds can be evaded in a model of iDM [7]. Assuming a dark sector composed of states χ_i with different masses and with suppressed or absent diagonal interactions, the correct relic abundance can be set by off-diagonal scattering processes $\chi_i\chi_j \to$ SM, followed by the decay of the heavier dark particles into SM + χ_1 (DM candidate). Since the heavier states decayed long before the CMB epoch and DM self-interaction is forbidden, indirect and direct detection bounds are relaxed.

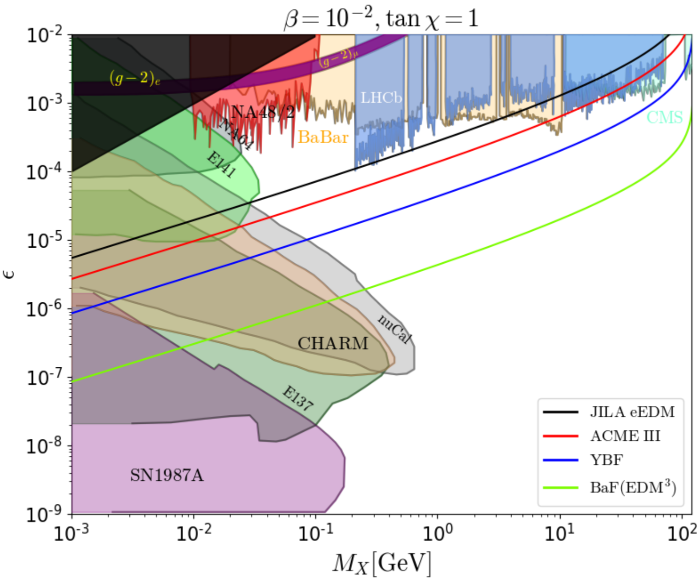

Figure 2: Plot of kinetic mixing parameter ϵ vs dark boson mass. Colored bands represent the region of parameter space saturated by the current and future experimental sensitivity of the eEDM. Reprinted from [1].

We consider a $SU(2)_D$ dark gauge group augmented with two scalars Σ_1^a, Σ_2^a and two chiral $SU(2)_D$ doublets χ_L, ψ_R. In addition to the portal and scalar interactions in Eq. (4), the Lagrangian includes:

$$\begin{aligned}\mathcal{L} \;\supset\; & -m_D \overline{\chi_L}\psi_R - \sum_{i=1,2} Y_{D,i}\overline{\chi_L}\Sigma_i\psi_R - \sum_{i=1,2} Y_{L,i}\overline{\chi_L^c}i\sigma_2\Sigma_i\chi_L - \sum_{i=1,2} Y_{R,i}\overline{\psi_R^c}i\sigma_2\Sigma_i\psi_R + \text{h.c.}\\ & - \frac{g_D}{2}\overline{\chi_L}\gamma_\mu\sigma^a X_a^\mu\chi_L - \frac{g_D}{2}\overline{\psi_R}\gamma_\mu\sigma^a X_a^\mu\psi_R .\end{aligned} \tag{9}$$

Upon SSB of $SU(2)_D$, induced by the scalar potential, we obtain a gauge boson and scalar mixing similar to Eq. (1). Linear combinations of the chiral doublets are merged into two Dirac fermions Ψ_H, Ψ_S with small mass splitting.

In addition to this, an off-diagonal interaction $g_D X_i^\mu \bar{\Psi}_H \gamma_\mu \Psi_S$ is obtained, while diagonal interactions are forbidden or strongly suppressed.

We perform a scan over the parameter space of the model, varying the parameters accordingly to existing experimental bounds. In Fig. (3), we show the predicted eEDM and DM mass for each of the parameter space points. The DM mass is obtained by fixing the effective coannihilation cross-section for the process $\Psi_S\Psi_H \to SM$ to $\sim 1.7 \times 10^{-9}\text{GeV}^{-2}$, the value needed to obtain the correct relic abundance. We show in Fig. (3) that, in a large region of the parameter space, the predicted eEDM lies between the current experimental bounds and the future experimental sensitivity, making the model testable in future eEDM searches.

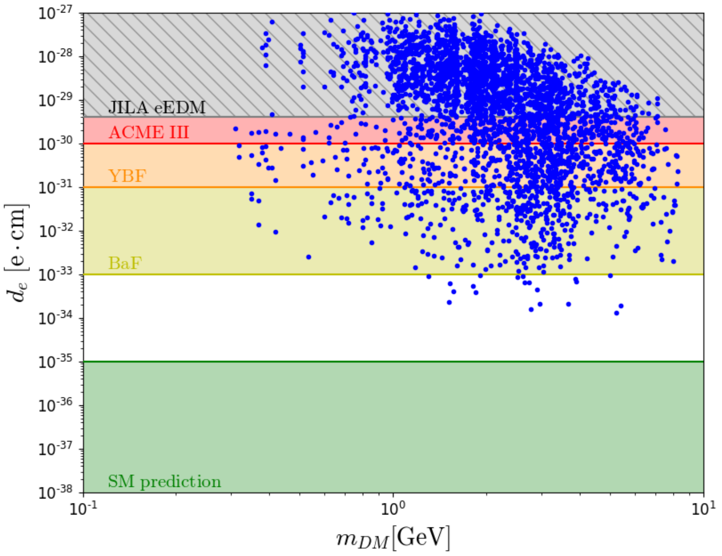

Figure 3: Scatter plot representing on the y-axis the predicted eEDM and on the x-axis the DM mass satisfying the correct relic abundance. Blue points represent the predicted eEDM and DM mass for parameters randomly chosen accordingly to the present bounds.

4. Conclusion

We used an effective field theory approach to show how the presence of a non-abelian dark sector enables a kinetic mixing portal with a naturally suppressed kinetic mixing parameter. Furthermore, if physical phases are present in the UV completion of the model, a sizeable CP-odd portal can arise. Due to the impressive sensitivities of eEDM experiments, kinetic mixing and CP-violation can be traced by future searches across a wide range of the parameter space not yet probed by current collider and beam dump experiments. Finally, we show how a non-abelian gauge dark sector can be used to implement a model of iDM, which could be indirectly probed through future searches for a permanent eEDM.

5. Acknowledgement

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