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РЕФЕРАТ

A Minimal Dark Matter Model for Muon g-2 with Scalar Lepton Partners up to the TeV Scale

________________ А.А. Каюков

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СОДЕРЖАНИЕ

1. INTRODUCTION

The identification of the nature of the dark matter component of the Universe remains one of most pressing open problems in science today. While cosmological and astrophysical data can provide some insight into the properties of DM, there is no direct evidence that DM corresponds to a new elementary particle (or a new sector of particles). One approach in the last several decades has thus been to look for other hints of new physics which could be related to the DM problem. Besides its numerous successes, the Standard Model (SM) of particle physics is unable to address several questions, including failing to embed candidates for DM and dark energy, and a working mechanism for the generation of the baryon asymmetry in the Universe. While recent searches for the direct production of new particles at the high energy frontier have been unsuccessful, there have been a number of anomalies emerging at the high precision frontier, possibly indirectly pointing to new interaction states.

One of the longest standing potential anomalies within the SM is the discrepancy between the measured values for the anomalous magnetic moment of the muon and its predicted value. Recently the E989 experiment at the Fermi National Laboratory reported its first results [1], confirming, with higher precision, the picture that had already emerged in 2006 with the final report from the E821 experiment at the Brookhaven National Laboratory [2]: the measured magnetic anomaly parameter for the muon $a_\mu = (g_\mu - 2)/2$ differs from its best up-to-date SM prediction [3] at a level which starts to be statistically intriguing, about 4.2σ when combining the result from the two experiments [1]:

$$\Delta a_\mu^{exp} = (25.1 \pm 5.9) \times 10^{-10}$$

While the debate regarding the SM computation of a_μ and its uncertainty is still ongoing, the discrepancy has attracted significant attention in the last two decades since there are several extensions to the SM in which a sizable contribution to $g_\mu - 2$ is predicted. Matching the anomaly with an extra contribution at 1-loop level is possible in rather generic scenarios; the general requirement is to introduce beyond-the-SM (BSM) states that couple to the muon and/or carry muonic lepton number, flip chirality, and are either electrically charged or participate in mediating another coupling to photons. Most minimal setups, featuring a single new BSM field flowing in the loop diagram, such as a second Higgs doublet, a leptoquark, an axion-like particle, or a dark photon/dark Z, have been systematically studied, in general, they are severely constrained by other observables.

A BSM state can play the role of DM if it fulfills several fairly generic requirements: it is stable or very long-lived, its coupling to photons is very strongly suppressed (and it is color neutral), its self-interactions are not too strong, and it starts driving the gravitational collapse of bound structures at the onset of the matter-dominated epoch (DM must be cold or, at most, warm). A key ingredient is also the identification of a viable production mechanism for this state in the early Universe. [4]

2. CONSTRUCTING THE MODEL

The article "A Minimal Dark Matter Model for Muon g-2 with Scalar Lepton Partners up to the TeV Scale"[4] suggests a model adding a new particle - a Bino $\bar{B}^0$, with mass $M_{\bar{B}}$. This is a spin 1/2 Majorana fermion, transforming as a singlet under the SM $SU(2)_L \times U(1)_Y$, $(1, 0)$. It is assumed that the particle is the lightest and most stable in the BSM. It is assumed that the particle is the lightest and most stable in the BSM:

$$L \supset -\lambda_{\bar{\mu}_R} \bar{\mu}_R^* \overset{\simeq}{B}{}^0 P_R \mu - \lambda_{\bar{\mu}_L} \bar{\mu}_L^* \overset{\simeq}{B}{}^0 P_L \mu - \lambda_{\bar{\nu}} \bar{\nu}_\mu^* \overset{\simeq}{B}{}^0 \nu_\mu + h.c.,$$

where P_R and P_L are the right-handed and left-handed projectors, and we have introduced two electrically charged complex scalars, $\bar{\mu}_R^*$ transforming as $(1, 1)$ and the $SU(2)_L$ doublet $\widetilde{l}_L = (\widetilde{\nu}_\mu, \widetilde{\mu}_L)^T$ T , which transforms as $(2, -1/2)$.

While the different λ couplings can in principle be arbitrary without significantly impacting the low-energy phenomenology of the model, in the article they are defined as:

$$\lambda_{\mu_R} = \sqrt{2} g` Y_R \; and \; \lambda_{\mu_L} = \lambda_\nu = \sqrt{2} g` Y_L$$

where $g`$ is the SM hypercharge coupling. On the other hand, they consider a generic mixing for the two charged scalars starting from a fully general mass matrix,

$$L \supset -\begin{pmatrix} \widetilde{\mu}_L^* & \widetilde{\mu}_R^* \end{pmatrix} \begin{pmatrix} m_{LL}^2 & m_{RL}^2 \\ m_{LR}^2 & m_{RR}^2 \end{pmatrix} \begin{pmatrix} \widetilde{\mu}_L \\ \widetilde{\mu}_R \end{pmatrix}$$

and diagonalizing it to find mass eigenstates we have:

$$\begin{pmatrix} \widetilde{\mu}_1 \\ \widetilde{\mu}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\widetilde{\mu}} & -\sin\theta_{\widetilde{\mu}} \\ \sin\theta_{\widetilde{\mu}} & \cos\theta_{\widetilde{\mu}} \end{pmatrix} \begin{pmatrix} \widetilde{\mu}_L \\ \widetilde{\mu}_R \end{pmatrix}$$

The calculation of physical parameters shows:

$$m_{LL}^2 = M_{\mu_1}^2 + (1 - \cos 2\theta_\mu)/2 \cdot \Delta M_{21}^2,$$

$$m_{RR}^2 = M_{\mu_1}^2 + (1 + \cos 2\theta_\mu)/2 \cdot \Delta M_{21}^2,$$

$$m_{LR}^2 = \sin 2\theta_\mu/2 \cdot \Delta M_{21}^2,$$

where $\Delta M_{21} = M_{\mu_2}^2 - M_{\mu_1}^2$.

3. CONSTRAINTS FROM THE MUON ANOMALOUS MAGNETIC DIPOLE MOMENT

The leading extra contribution (the only contribution at 1-loop) to the muon anomalous magnetic dipole moment in model is given by two diagrams. Each of these diagrams involves the Bino and one of the two smuons as virtual states running in the loop, with the external photon attached to the smuon. To lowest order in the muon mass, this contribution can be written as

$$\Delta a_\mu \simeq \frac{g'^2 Y_L Y_R}{16\pi^2} \sin(2\theta_\mu) \frac{m_\mu}{M_B} [L(r_1) - L(r_2)],$$

where the loop function is

$$L(r) = \frac{r}{(1-r)^2}[1 + r + \frac{2rlnr}{(1-r)}] \text{ and } r_i = \frac{M_B^2}{M_{\mu_i}^2},$$

where M_B - Bino mass and M_{μ_i} - Muon mass.

Thus, we can proceed to the evaluation leading extra contribution (the only contribution at 1-loop) to the muon anomalous magnetic dipole momente:

$$\frac{\Delta a_\mu}{25.1 \cdot 10{-}10} = \frac{-\sin(2\theta)}{2.6 \cdot 10{-}2} \cdot \frac{100 \text{ GeV}}{M_B} \cdot \frac{L_{0,2} + L_{1,2} \cdot \Delta_1/0.1}{0.23},$$

where $\Delta_1 = \frac{M_{\mu_1} - M_B}{M_B} = 0.05 - 0.10$, $L_{0,2} = 0.19$ and $L_{1,2} = 0.04$. The loop function, L, in the expression above has been evaluated assuming a fixed ratio between the smuon masses, namely $M_{\mu_2} = 2M_{\mu_1}$.

In Fig. 1 the extra contribution to the muon anomalous magnetic dipole moment, computed considering the full 1-loop result, matches Δa_{exp}.. In the left panel, values of the mixing angle θ_μ are shown plotted against $_B$, having fixed the relative mass splitting Δ_1 between the lightest smuon and the Bino. The mass of the heaviest smuon is fixed by selecting a given value for the parameter:

$$y = \Delta M_{12}^2/(4M_W)^2 \cdot |\sin(2\theta_\mu)|$$

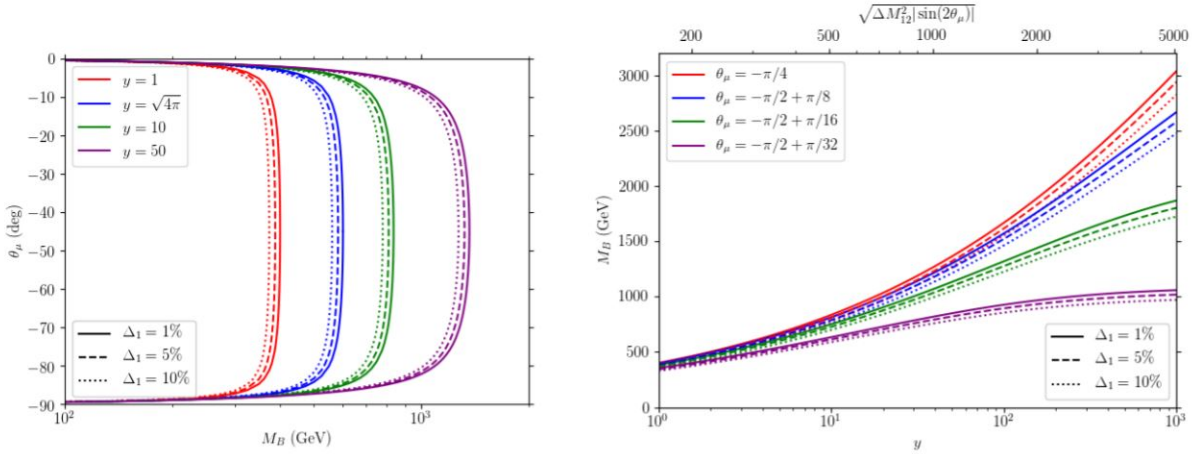

Рисунок 1 — Left panel: Plot of the mixing angle θ_μ, in degrees, corresponding to an extra contribution to $g_\mu - 2$ matching the central value, for a given value of the Bino mass M_B , a few sample choices of the relative mass splitting between the Bino and the lightest smuon Δ_1, and fixed values of the parameter y, which contains information on the mass of the heaviest smuon. Right panel: Plot of the Bino mass for which a $g_\mu - 2$ match is possible versus the parameter y and sample choices of θ_μ and Δ_1; labels at the top of the plot indicate the one-to-one correspondence between y and the smuon mass squared differences ΔM_{21}^2 for fixed θ_μ.

4. CONCLUSIONS

Rather generic extensions to the SM of particle physics can provide extra 1-loop contributions to the muon g - 2, possibly accounting for the 4.2σ anomaly reported by the E989 experiment. Considered in the work [4] a minimal BSM framework in which the extra states responsible for the muon g - 2 discrepancy also provide for a dark matter candidate and determine its relic abundance in the early Universe.

The analysis has been carried out within a specific model in which the essential BSM states are: a Majorana fermion with no electric charge or muonic lepton number, playing the role of dark matter; a scalar with mixed chirality carrying electric and muon leptonic charges. The particle spectrum of this model, with the appropriate choices of $SU(2)_L \times U(1)_Y$ quantum number assignments, maps onto a small subset of the particle content of the MSSM, from which we have borrowed the terminology—the extra states just mentioned are referred to as, respectively, the Bino and a smuon—and that exploit as an embedding framework when specifying the origin of the chiral mixing for the leptonic scalar.

The model has a reduced parameter space, essentially only 3 masses and one mixing angle. Requiring that the model satisfies the $g_\mu - 2$ anomaly foliates this parameter space along left-handed or right-handed branches for the lightest smuon. Along these branches the level of left-right mixing, dictated by the chirality flip necessary for the BSM contribution to $g_\mu - 2$, is much larger than what is usually considered in the MSSM under the assumption of minimal flavor violation.

The requirement that the Bino relic density matches the dark matter density of the Universe leads to consider scenarios in which the sleptons are just slightly heavier than the Bino (relative mass splittings of order 10% or lower). Since the sleptons interact with the heat bath more efficiently than the Bino, the charged scalars can drive thermal freeze out via coannihilation effects. For coannihilating particles with relatively light masses 400 GeV, the parameter space for which our model satisfies both $g_\mu - 2$ and the relic density is similar to that of Bino-slepton coannihilation scenarios previously investigated in the so-called bulk region of the MSSM. However, once the assumption of minimal flavor violation is relaxed, the viable parameter space of model opens up into regions in which the coannihilating particles are sensibly heavier. Upon a detailed examination of the relic density calculation in this parameter space characterized by heavy Binos, large y and sizable mixing, we see that some of the relevant cross sections tend to become large, although not large enough to violate face-value perturbative unitarity bounds. Taking one step further and borrowing the structure of the full scalar potential from the MSSM, a comprehensive analysis of the full S-matrix shows that unitarity rules out large to moderate values of y, depending on whether the mixing is mild or maximal. The parameter space is constrained even further when considering the stability of the electroweak vacuum. For models with sizable smuon mixing and large trilinear couplings, the scalar potential can develop minima deeper than the EW vacuum. Requiring that the tunneling time from the EW vacuum to the true vacuum is longer than the age of the Universe sets the tightest constraints on the parameter space of the model: y cannot exceed moderate values regardless of the smuon mixing angle and the Bino mass scale cannot be larger than about 1 TeV.

The prospects of testing with the next generation of direct detection experiments are unfortunately limited to a marginal portion of the viable parameter space. There is no tree-level coupling between the Bino and SM quarks in model, and the anapole operator relevant for direct detection searches is only sufficiently enhanced for cases with very small mass splittings between the Bino and lightest smuon. On the other hand, a future lepton collider with a relatively large center of mass energy could directly probe the extended parameter space of model. Since the most stringent constraints arise from perturbative unitarity and vacuum stability in our simplified model, it would also be interesting to consider the phenomenological implications of embedding our simplified model into a framework which provides for a more theoretically consistent extension of the SM.

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