Light Fermion Dark Matter

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SM + $B-L$

Add to the SM under gauge $B-L$ the following:
Three $N_R \sim -1$ and one Higgs $\chi \sim 2$.

$\langle\chi\rangle \neq 0$ breaks SM $+$ $B-L$ to SM,
and gives large masses to N_R.

Add now a singlet fermion S and a real singlet scalar σ, both ~ 0 under $B-L$.

S will be freeze-in light dark matter from SM Higgs decay.

Dark Matter Interactions

After integrating out the heavy χ, the scalar potential of σ and the SM Φ is

$$V = -\mu_0^2\Phi^\dagger\Phi + \frac{1}{2}\lambda_0(\Phi^\dagger\Phi)^2 + \frac{1}{2}m_1^2\sigma^2 + \frac{1}{6}\mu_1\sigma^3$$

$$+\frac{1}{24}\lambda_1\sigma^4 + \mu_2\sigma\Phi^\dagger\Phi + \frac{1}{2}\lambda_{01}\sigma^2\Phi^\dagger\Phi,$$

$$\text{with} \quad \mathcal{L}_S = \frac{1}{2}m_2 SS + \frac{1}{2}f\sigma SS + H.c.$$

Universal Softly Broken Symmetry

(arXiv:2311.05859) Consider Z_4 with

$$A_\mu \sim 1, \quad \phi \sim -1, \quad \psi_L \sim i, \quad \psi_R \sim -i,$$

then all dim-2 and dim-4 terms of any Lagrangian are invariant under it. As for the dim-3 terms, i.e.

$$\phi^3, \;\; \bar{\psi}_L \psi_R, \;\; \psi_L \psi_L, \;\; \psi_R \psi_R,$$

they break Z_4 explicitly but softly to Z_2. Hence their couplings (with dimension of mass) may be naturally assumed to be small compared to that of the quadratic scalar mass terms.

Spontaneous breaking of Z_4 also occurs from $\langle \phi \rangle \neq 0$. However, this is usually triggered by only the quadratic and quartic scalar terms which are allowed by Z_4. Hence the dim-3 terms resulting from this breaking are of order the scalar quadratic mass. Nevertheless, it does not affect the claim that the explicit Z_4 breaking terms may be chosen small.

The SM has no dim-3 terms before symmetry breaking, so there are no small mass parameters to be discussed.

Freeze-In Dark Matter from Higgs Decay

Back to S and σ, using Z_4, it is assumed that the parameters μ_1, μ_2, m_2 are small. With $\mu_0^2, m_1^2 > 0$, the spontaneous breakings of ϕ^0 and σ occur:

$$\langle \phi^0 \rangle = v_0 \simeq \sqrt{\frac{\mu_0^2}{\lambda_0}}, \quad \langle \sigma \rangle = v_1 \simeq \frac{-\mu_2 v_0^2}{m_1^2 + \lambda_{01} v_0^2}.$$

Note the important fact that v_1 is now proportional to the Z_4 breaking μ_2 term, unlike v_0 which is of order the allowed μ_0 term.

The mass of S is now $m_S = f v_1 + m_2$ which remains small. Another small parameter appears because of this $Z_4 \to Z_2$ breaking, i.e. the mixing between the SM Higgs boson h and the new σ shifted by v_1.

The square of their masses are $m_h^2 = 2\lambda_0 v_0^2$, $m_\sigma^2 \simeq m_1^2 + \lambda_{01} v_0^2$, with mixing

$$\theta_{h\sigma} \simeq \frac{\sqrt{2}\mu_2 v_0}{m_1^2} \simeq \frac{-\sqrt{2} v_1}{v_0},$$

where $m_\sigma^2 \simeq m_1^2 >> m_h^2$ has been assumed.

If $m_2 << fv_1$ is also assumed, then the coupling of h to SS is determined to be

$$f_h = f\theta_{h\sigma} \simeq \frac{-\sqrt{2}m_S}{v_0}.$$

The decay rate of $h \to SS + \bar{S}\bar{S}$ is

$$\Gamma_h = \frac{f_h^2 m_h}{8\pi}\sqrt{1-4r^2}(1-2r^2),$$

where $r = m_S/m_h$. The correct S relic abundance is obtained for $f_h \sim 10^{-12} r^{-1/2}$, implying $m_S \sim 1.2$ keV.

Martin Hirsch = Shirt Rich Man