Possible strong interaction in dark matter sector of IDM

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BASICS

The Inert Doublet Model (IDM) – variant of 2HDM, in which the SM with standard Higgs field ϕ_S is supplemented by Higgs field ϕ_D, having no interaction with matter fields and v.e.v. $\langle\phi_D\rangle = 0$. The Lagrangian contains $SU(2)\times U(1)$ SM interaction of gauge bosons and fermions, Yukawa interaction of fermions f with Higgs field ϕ_S only and Z_2-symmetric potential V. In this model

$$\phi_S = \begin{pmatrix} G^+ \\ (v+h+iG^0)/\sqrt{2} \end{pmatrix}, \quad \phi_D = \begin{pmatrix} D^+ \\ (D+iD_A)/\sqrt{2} \end{pmatrix}, \quad v = 246\, GeV.$$

Here $G^\pm$, G^0 are Goldstone modes, h is SM-like Higgs boson with mass $M_h \approx 125$ GeV, D, D_A and $D^\pm$ are physical particles with masses $M_D \leq M_A < M_\pm \equiv M_+$ respectively. The particle D is candidate for DM particle.

$$V = V_0 + M_\pm^2 \phi_D^\dagger \phi_D + \frac{\lambda_1}{2}\left(\phi_S^\dagger \phi_S - \frac{v^2}{2}\right)^2 + \frac{\lambda_2}{2}(\phi_D^\dagger \phi_D)^2$$
$$+\lambda_3(\phi_S^\dagger \phi_S - \frac{v^2}{2})(\phi_D^\dagger \phi_D)$$
$$+\lambda_4(\phi_S^\dagger \phi_D)(\phi_D^\dagger \phi_S) + \lambda_5 Re\left((\phi_S^\dagger \phi_D)^2\right).$$

The parameters of this potential simply expressed through observable quantities: $\lambda_1 = M_h^2/v^2 \approx 0.25$, $\lambda_4 = (M_D^2 + M_A^2 - 2M_\pm^2)/v^2 < 0$, $\lambda_5 = (M_D^2 - M_A^2)/v^2$ with $\lambda_4 + \lambda_5 < 0$, $\lambda_3 = g(H^+H^-h)/v$ and $\lambda_2 = g(H^+H^-H^+H^-)$. Possible masses M_D, M_A, $M_\pm$ are constrained by the accelerator and astrophysical data. They can be measured in the experiments at high energy e^+e^- colliders (ILC, CLIC, ...) in processes $e^+e^- \to D^+D^- \to DDW^+W^-$, $e^+e^- \to DD_A \to DDZ$,...

To realize discussed ground state, the parameters of potential should obey conditions

$$\lambda_3 < 2M_\pm^2/v^2 \quad \text{or} \quad \lambda_3 > 2M_\pm^2/v^2 > \lambda_3 - \sqrt{\lambda_1\lambda_2}\,.$$

The positivity constraints mean that $V > 0$ at large quasi-classical values of fields:

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 + \lambda_4 + \lambda_5 + \sqrt{\lambda_1\lambda_2} > 0\,, \quad \lambda_3 + \sqrt{\lambda_1\lambda_2} > 0\,.$$

Interactions

• Interactions of scalar h to fermions and gauge bosons, just as their self-interaction, are the same as for Higgs boson in the SM.
• Scalars D, D_A, $D^{\pm}$ don't interact with fermions and couple to gauge bosons W, Z, γ via covariant derivative in kinetic term $\left(D_\mu \phi_D^\dagger D_\mu \phi_D\right)$. The interactions of D and D_A are identical. They have opposite P-parities, but their proper P-parities cannot be fixed. Choice of notations is fixed by condition $M_D < M_A$.
• Complete list of Dh interactions is

$$\frac{2v \cdot h + hh}{4}\left[4\lambda_3 D^+D^- + (\lambda_3+\lambda_4)(DD + D_A D_A) + \lambda_5 (DD - D_A D_A)\right].$$

• Complete list of DD interactions is

$$\lambda_2 \cdot \left[\frac{1}{8}(DD + D_A D_A)(DD + D_A D_A + 4D^+D^-) + D^+D^-D^+D^-\right].$$

Possible strong interaction of D-particles

Let $M_A^2 - M_D^2,\ \ M_\pm^2 - M_D^2 < 0.5$ TeV^2 (for $M_D < 100$ GeV it means that $M_A,\ M_\pm < 0.7$ TeV. If additionally $|\lambda_3| < 8\pi/3$, parameters $|\lambda_3|,\ |\lambda_4|,\ |\lambda_5|,\ |\lambda_4 + \lambda_5| < 8\pi/3$ are within perturbativity region – radiative corrections due to these terms of Lagrangian changes only weakly corresponding tree values.

The value of parameter λ_2 cannot be constrained by measurements of these masses and two photon width of SM-like Higgs boson h.

Moreover, parameter λ_2 can be large, providing

strong interaction in dark sector.

This strong interaction can shift masses M_D, M_A, $m_\pm$ but mass differences changes at large λ_2 only weakly. Indeed in the first nontrivial approximation of perturbation theory these shifts are determined by standard two-loop diagrams of similar forms for D, D_A, $D_\pm$. The contributions of these diagrams into the mass operator are $\sim \left(\lambda_2/2/(4\pi)^2\right)^2 v$ with logarithmic enhancement like $\ln(M_\pm/M_D)$. At $\lambda_2 < 16\pi^2$ this contribution is small.

In this very approximation the dimensionless amplitudes of $DD \to DD$, $DD \to D_+D_-$, $DD_A \to D_+D_-$, etc. processes are $\propto (\lambda_2/8\pi)^2$.

Therefore at $16\pi^2 > \lambda_2 > 8\pi$ we deals with strong interaction of D-particles with differences of masses, determined perturbatively.

Main features of this strong interaction.

At the tree level this interaction is repulsion ($\lambda_2 > 0$). Therefore "light"DD, D^+D^-, DD^+, etc. "molecules"don't appear.

However, the scattering amplitudes for D-particles are large and increase with energy. These amplitudes can have resonances, similar those discussed in many papers devoted to the strong interaction in Higgs sector (similar to ρ, f_2, σ for pions) – usual strong interaction in Higgs sector. Their masses are determined by values of M_D, M_A, $M_\pm$. We expect that these resonances are heavier than 1 TeV.

The final picture should be different from that discussed in respect of strong interaction in Higgs sector (usual case) and pion physics:

1. Constituents have definite masses, like π, σ for pion physics, but instead of Higgs field with indefinite mass in the usual case.

2. Masses of D-particles generally differ strong from each other (in contrast with both usual Higgs model and pion physics).

3. D-particles don't interact with fermions in contrast with both usual Higgs model and pion physics.

The discussed resonances can be seen in principle in decays to the states to WW, ZZ, $\gamma\gamma$, WZ,... with small partial widths and in decays to $D^+D^- \to DDW^+W^-$, $D_AD_A \to DDZZ$, $D^+D \to DDW^+$, $DD_A \to DDZ$,... with large missed E_T (in the latter cases corresponding signature should be studied).

Cosmological consequences of this strong interaction (if they exist) should be studied elsewhere.

THE END