SPIN-INDEPENDENT INTERACTION OF DIRAC DARK MATTER FERMIONS WITH NUCLEONS IN COMPOSITE HIGGS MODELS

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based on M.G.Belyakova, R.Nevzorov, arXiv:2406.12483

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OUTLINE

- Introduction
- Composite Higgs models
  - Distinctive features: symmetries and constraints
  - Exotic particles. Dark Matter candidate
  - Derivation of coupling constants
- DM-nucleon spin-independent interaction
- Conclusion

INTRODUCTION

Standard Model (SM) is self-consistent, provides accurate description of known phenomena. SM is based on gauge group

$$SU(3)_C \times SU(2)_L \times U(1)_Y \tag{1}$$

- Hierarchy problem: Planck scale $M_P \approx 10^{18}\ GeV$, Weak scale $M_W \approx 100\ GeV$
- Origin of 125 GeV Higgs boson. Problem of correction to the Higgs boson mass squared.

$$\mathcal{L} = -\lambda_f H\bar{f}f \rightarrow \Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda^2 \tag{2}$$

- Not explained phenomena: neutrino oscillations, dark matter, matter–antimatter asymmetry

RELEVANCE OF DARK MATTER

- Structure formation in universe
- Cluster merging
- Gravitational lensing

Figure 1: Galaxy Cluster Abell 1689

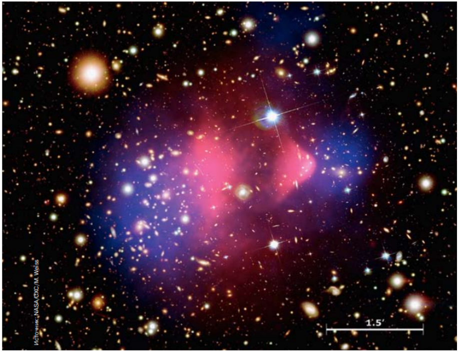

Figure 2: The merging bullet galaxy cluster

COMPOSITE HIGGS MODELS

COMPOSITE HIGGS MODELS: GENERAL FEATURES

- Two sectors: weakly and strongly coupled. All particles from the weakly coupled sector (WCS) have partner from the strongly coupled one (SCS):

$$q_i^0 \in WCS \rightarrow Q_i^0 \in SCS$$
$$At\ low\ energies \quad q_i = q_i^0 cos\theta_q + Q_i^0 sin\theta_q \tag{3}$$

- Higgs doublet emerges as a set of pseudo-Nambu-Goldstone bosons (pNGBs)
- Observed mass hierarchy can be accommodated through partial compositeness

$$\mathcal{L} = Y_d \bar{Q}^0 D^0 H \rightarrow \mathcal{L} = y_d \bar{q} d H, \qquad y_d = Y_d sin\theta_q sin\theta_d \tag{4}$$

MINIMAL COMPOSITE HIGGS MODEL

Symmetry of strongly coupled sector:

$$\begin{aligned} \textit{Global}: \; G = SO(5) \times U(1)_X \xrightarrow{f} SO(4) \times U(1)'_X + 4NGB \\ SO(4) \times U(1)'_X \cong SU(2)_L \times SU(2)_R \times U(1)'_X \end{aligned} \tag{5}$$

$$\textit{Gauge}: \; SU(3)_C \times SU(2)_L \times U(1)_Y \times G'$$

$SO(4) \times U(1)'_X$ contains global $SU(2)_{cust}$ and gauge $SU(2)_L \times U(1)_Y$

K. Agashe, R. Contino and A. Pomarol, Nucl. Phys. B 719 (2005) 165 [hep-ph/0412089].

E_6 INSPIRED COMPOSITE HIGGS MODEL

Symmetry of weakly coupled sector:

$$\text{Gauge} : E_6 \xrightarrow{f \gtrsim 10^{16}\,GeV} SU(3)_C \times SU(2)_L \times U(1)_Y \tag{6}$$

Symmetry of strongly coupled sector:

$$\begin{gathered} \text{Global} : G = SU(6) \times U(1)_B \times U(1)_L \\ SU(6) \times U(1)_B \times U(1)_L \xrightarrow{f \gtrsim 5-10\,TeV} SU(5) \times U(1)_B \times U(1)_L + 11NGB \end{gathered} \tag{7}$$

$$\text{Gauge} : \; SU(3)_C \times SU(2)_L \times U(1)_Y \times G'$$

The $SU(6)$ arises after breakdown of E_6 : $E_6 \to SU(6) \times SU(2)_N$

SU(5) does not contain $SU(2)_{cust}$ subgroup

R. Nevzorov, A. W. Thomas, Phys. Rev. D 92 (2015) 075007 [arXiv:1507.02101 [hep-ph]]. [8] R. Nevzorov, Universe 8 (2022) 33.

PARTICLE CONTENT OF E_6CHM: SCALAR SECTOR

11 NGB: ϕ_0 is a real SM singlet field, $(\phi_1\,\phi_2)$ transform as an $SU(2)_L$, $(\phi_3\,\phi_4\,\phi_5)$, form an $SU(3)_C$ triplet T

11 NGB $\xrightarrow{\text{interaction}}$ pNGB. All pNGB have $B = L = 0$.

$$\Pi = \Pi_a T_{\hat{a}} = \begin{pmatrix} -\frac{\phi_0}{\sqrt{60}} & 0 & 0 & 0 & 0 & \frac{\phi_1}{\sqrt{2}} \\ 0 & -\frac{\phi_0}{\sqrt{60}} & 0 & 0 & 0 & \frac{\phi_2}{\sqrt{2}} \\ 0 & 0 & -\frac{\phi_0}{\sqrt{60}} & 0 & 0 & \frac{\phi_3}{\sqrt{2}} \\ 0 & 0 & 0 & -\frac{\phi_0}{\sqrt{60}} & 0 & \frac{\phi_4}{\sqrt{2}} \\ 0 & 0 & 0 & 0 & -\frac{\phi_0}{\sqrt{60}} & \frac{\phi_5}{\sqrt{2}} \\ \frac{\phi_1^+}{\sqrt{2}} & \frac{\phi_2^+}{\sqrt{2}} & \frac{\phi_3^+}{\sqrt{2}} & \frac{\phi_4^+}{\sqrt{2}} & \frac{\phi_5^+}{\sqrt{2}} & \frac{5\phi_0}{\sqrt{60}} \end{pmatrix} \tag{8}$$

$$\Omega^T = \Omega_0^T e^{i\Pi_a T_{\hat{a}}} = e^{i\frac{\phi_0}{\sqrt{15}f}} \begin{pmatrix} C\phi_1 & C\phi_2 & C\phi_3 & C\phi_4 & C\phi_5 & \cos\frac{\tilde{\phi}}{\sqrt{2}f} + \sqrt{\frac{3}{10}}C\phi_0 \end{pmatrix}$$

$$C = \frac{i}{\tilde{\phi}} \sin\frac{\tilde{\phi}}{\sqrt{2}f}\,, \qquad \tilde{\phi} = \sqrt{\frac{3}{10}\phi_0^2 + |\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2 + |\phi_4|^2 + |\phi_5|^2}\,, \tag{9}$$

PARTICLE CONTENT OF E_6CHM

Fields in weakly coupled sector

$$(q_i,\, d_i^c,\, \ell_i,\, e_i^c) + u_\alpha^c + \boxed{\bar{q} + \bar{d^c} + \bar{\ell} + \bar{e^c}},$$ t^c is not included!

where $\alpha = 1, 2$ and $i = 1, 2, 3$. Extra exotic fermions introduce ensure anomaly cancellation.

Fields in strongly coupled sector

$SU(5)$ group below the compositeness scale f leads to $\mathbf{10} + \overline{\mathbf{5}}$ representations. These $\mathbf{10} + \overline{\mathbf{5}}$ can stem from $\mathbf{15} + \bar{\mathbf{6}}_1 + \bar{\mathbf{6}}_2$ of $SU(6)$.

PARTICLE CONTENT OF E_6CHM

The first and second quantities are the $SU(3)_C$ and $SU(2)_L$ representations, third and fourth quantities are $U(1)_Y$ and $U(1)_B$ charges.

$$\mathbf{15} \quad \to \quad Q = \left(3,\, 2,\, \frac{1}{6},\, -\frac{1}{3}\right), \quad t^c = \left(\bar{3},\, 1,\, -\frac{2}{3},\, -\frac{1}{3}\right), \quad E^c = \left(1,\, 1,\, 1,\, -\frac{1}{3},\, -\frac{1}{3}\right), \quad D = \left(3,\, 1,\, -\frac{1}{3},\, -\frac{1}{3}\right), \quad \overline{L} = \left(1,\, 2,\, \frac{1}{2},\, -\frac{1}{3}\right);$$

$$\overline{\mathbf{6}}_1 \quad \to \quad D_1^c = \left(\bar{3},\, 1,\, \frac{1}{3},\, \frac{1}{3}\right), \quad L_1 = \left(1,\, 2,\, -\frac{1}{2},\, \frac{1}{3}\right), \quad N_1 = \left(1,\, 1,\, 0,\, \frac{1}{3}\right);$$

$$\overline{\mathbf{6}}_2 \quad \to \quad D_2^c = \left(\bar{3},\, 1,\, \frac{1}{3},\, -\frac{1}{3}\right), \quad L_2 = \left(1,\, 2,\, -\frac{1}{2},\, -\frac{1}{3}\right), \quad \overline{N}_2 = \left(1,\, 1,\, 0,\, -\frac{1}{3}\right).$$

PARTICLE CONTENT OF E_6CHM

Mass terms of the exotic states

$$\mathcal{L}_{mass} = \mu_q \bar{q} Q + \mu_e \bar{e^c} E^c + \mu_D D_1^c D + \mu_L \overline{L} L_1 + \mu_d \bar{d}^c D_2^c + \mu_l \bar{\ell} L_2 + \mu_N \overline{N}_2 N_1 + h.c.\,,$$

where $\mu_N \simeq g_N f$, $\mu_D \simeq \mu_L \simeq h_N f$ and $\mu_q \sim \mu_e \sim \mu_d \sim \mu_l \sim f$.

All exotic fermions do not carry any lepton number.

Masses of D and $\overline{L}$

$$\mathcal{L}^d_{SU(6)} = h_N f (\mathbf{15} \times \overline{\mathbf{6}}_\mathbf{1} \times \Omega^\dagger) + h.c.\,. \tag{10}$$

Masses of N_1 and $\overline{N}_2$

$$\mathcal{L}^n_{SU(6)} = g_N f (\overline{\mathbf{6}}_\mathbf{1} \times \Omega)(\overline{\mathbf{6}}_\mathbf{2} \times \Omega) + h.c.\,, \tag{11}$$

APPROXIMATE $U(1)_E$ AND BARYON TRIALITY SYMMETRIES

$E_6 CHM$ has $U(1)_B$ symmetry, hence it possesses baryon triality Z_3 symmetry.

$$\Psi \to e^{2\pi i B_3/3}\Psi, \qquad B_3 = (3B - n_C)_{\text{mod } 3}\,, \tag{12}$$

Standard model bosones and fermions have $B_3 = 0$

Exotic fermions have non-zero $B_3 \to$ lightest exotic particle (LEP) is stable.

Phenomenological viability requires LEP to be SM singlet.

$$\mathcal{L}_{mass} = \mu_q \bar{q} Q + \mu_e \bar{e}^c E^c + \mu_D D_1^c D + \mu_L \overline{L} L_1 + \mu_d \bar{d}^c D_2^c + \mu_l \bar{\ell} L_2 + \mu_N \overline{N}_2 N_1 + h.c.\,,$$

In the limit $\mu_N \to 0$ $\mathcal{L}_{mass}$ invariant under the action of global $U(1)_E$:

$$\overline{\mathbf{6}}_2 \longrightarrow e^{i\beta}\overline{\mathbf{6}}_2, \qquad \bar{d}^c \longrightarrow e^{-i\beta}\bar{d}^c, \qquad \bar{\ell} \longrightarrow e^{-i\beta}\bar{\ell}\,. \tag{13}$$

The approximate $U(1)_E$ symmetry $\to$ the LEP $\chi = N_1 + N_2$.

LIGHTEST EXOTIC FERMION OF E_6CHM

After breakdown of EW symmetry neutral components of the doublet's L_1 and L_2 ν_1 and ν_2 mix with singlet states N_1 and N_2

$$\mathcal{L}_{mix} = h_N(\overline{L}H^c)N_1 + \tilde{h}_N(\bar{\ell}H^c)\overline{N}_2 + h.c.. \tag{14}$$

Exact $U(1)_E$ symmetry limit: two zero mass states, no mixing.

$$\chi_L = N_1 \cos\theta_1 - \nu_1 \sin\theta_1\,, \quad \chi_R = N_2 \cos\theta_2 - \bar{\nu}_2 \sin\theta_2 \tag{15}$$

Mixing angles are defined as:

$$\cos\theta_1 = \frac{\mu_L}{\sqrt{\mu_L^2 + \frac{h_N^2\eta^2}{2}}}, \qquad \cos\theta_2 = \frac{\mu_l}{\sqrt{\mu_l^2 + \frac{\tilde{h}_N^2\eta^2}{2}}}.$$

$U(1)_E$ approximate symmetry: $\mathcal{L}_{N_1N_2} = \mu_N \overline{N}_2 N_1 = m_\chi \bar{\chi}_L \chi_R + ...$

LIGHTEST EXOTIC FERMION E_6CHM: RESULT

- Baryon charge conservation implies lightest exotic fermion to be stable.
- Phenomenologically viability requires lightest exotic fermion to be mostly comprised by SM singlet .

Lightest exotic fermion

$$\chi_L \simeq N_1 \cos\theta_1 - \nu_1 \sin\theta_1 \,, \quad \chi_R \simeq N_2 \cos\theta_2 - \bar{\nu}_2 \sin\theta_2$$

$$m_\chi \simeq \mu_N$$

DM-NUCLEON SPIN-INDEPENDENT INTERACTION

POSSIBLE INTERACTIONS

- Recent experimental constraints on DM magnetic moment: $\mu_\chi \sim 10^{-8} GeV^{-1}$. In the $E_6 CHM$ DM magnetic moment μ_χ is suppresses by $U(1)_E$ hence here the electromagnetic interaction is ignored.
- Weak interaction mediated by Z-boson.
- Interaction mediated by Higgs boson.

Main goal

Estimate SI $\chi-$nucleon cross section as a function of compositeness scale f

DARK MATTER INTERACTION WITH Z-boson

DM possesses admixture of neutral component of weak double, hence DM-Z interaction arises.

$$\chi_L \simeq N_1 \cos\theta_1 - \nu_1 \sin\theta_1\,, \quad \chi_R \simeq N_2 \cos\theta_2 - \bar{\nu}_2 \sin\theta_2$$

General Lagrangian of interection with Z-boson

$$\mathcal{L}_{Z\chi} = \overline{\chi}(a_V^\chi \gamma^\mu + a_{PV}^\chi \gamma^\mu \gamma^5)\chi Z_\mu\,,$$
$$a_V^\chi = \frac{\bar{g}}{4}(\sin^2\theta_1 - \sin^2\theta_2)\,, \qquad a_{PV}^\chi = \frac{\bar{g}}{4}(\sin^2\theta_1 + \sin^2\theta_2)\,. \tag{16}$$

$$a_V^\chi = \frac{\bar{g}\eta^2}{8f^2} c_V\,, \qquad c_V \simeq 1 - \left(\frac{\tilde{h}_N f}{\mu_\ell}\right)^2,$$
$$a_{PV}^\chi = \frac{\bar{g}\eta^2}{8f^2} c_{PV}\,, \qquad c_{PV} \simeq 1 + \left(\frac{\tilde{h}_N f}{\mu_\ell}\right)^2. \tag{17}$$

INTERACTION WITH HIGGS BOSON

Exact $U(1)_E$ symmetry limit: no $\chi - H$ interaction

$U(1)_E$ approximate symmetry: $\mathcal{L}_{H\chi} = \frac{\varepsilon_H}{f} H^\dagger H(\overline{N}_2 N_1) + h.c. \qquad \varepsilon_H \ll 1$

$$\mathcal{L}_{\chi\chi h} = \varepsilon_H \frac{\eta}{f} \bar{\chi}\chi h = g_{\chi\chi h}\bar{\chi}\chi h \qquad \mathcal{L}_{NNh} = g_{NNh}\bar{N}NH \tag{18}$$

$$g_{NNh} = \frac{m_N}{\eta}\left(\sum_{q=u,d,s} f^N_{Tq} + \frac{2}{27}\sum_{c,b,t} f^N_{TQ}\right) \tag{19}$$

$f^p_{Tq} \simeq f^n_{Tq} \simeq f_{Tq}$

$f_{Tu} \simeq 0.0153$, $f_{Td} \simeq 0.0191$ and $f_{Ts} \simeq 0.0447$

$$\langle N|m_q\bar{q}q|N\rangle = m_N f^N_{Tq}\,, \qquad f^N_{TQ} = 1 - \sum_{q=u,d,s} f^N_{Tq}\,.$$

SPIN-INDEPENDENT DM-NUCLEON INTERACTION

In the leading approximation:

$$M^{SI}_{full} = 4m_\chi m_N \left[\frac{g_{\chi\chi h} g_{NNh}}{M_h^2} - \frac{\langle a_v^N \rangle a_v^\chi}{M_Z^2}\right] \rightarrow \sigma = \frac{\mu^2}{\pi}\left[\frac{g_{\chi\chi h} g_{NNh}}{M_h^2} - \frac{\langle a_v^N \rangle a_v^\chi}{M_Z^2}\right]^2 \quad (20)$$

$$\mu = \frac{m_\chi m_N}{m_\chi + m_N}, \qquad \langle a_v^N \rangle = \frac{1}{A}\left(Z a_v^p + (A-Z) a_v^n\right) \qquad a_v^N = T_{3N} - 2s_w^2 Q_N$$

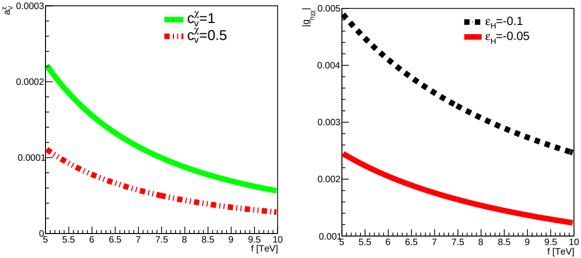

Figure 3: The dependence of the couplings a_V^χ (**Left**) and $|g_{h\chi\chi}|$ (**Right**) on the compositeness scale f.

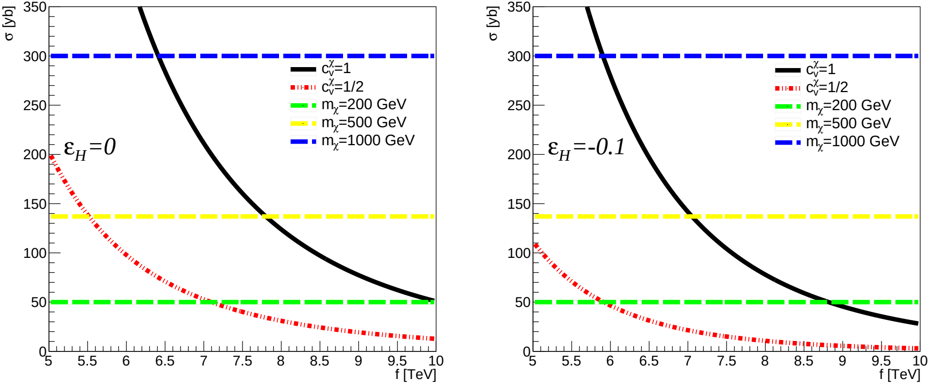

Figure 4: The dependence of the spin–independent $\chi - N$ scattering cross section σ on the compositeness scale f. The solid and dotted lines correspond to $c_V^\chi = 1$ and $c_V^\chi = 0.5$ respectively. The horizontal dashed lines represent the experimental limits on σ for $m_\chi = 1\,\text{TeV}$, $m_\chi = 500\,\text{GeV}$ and $m_\chi = 200\,\text{GeV}$.
Aalbers J. et al. First dark matter search results from the LUX-ZEPLIN (LZ) experiment //Physical review letters. – 2023.

CONCLUSION

In composite Higgs models (Demonstrated on E_6CHM):

- Dark matter candidate may arise as a dirac fermion.
- Recent experimental constraints on DM magnetic moment: $\mu_\chi \sim 10^{-8} GeV^{-1}$.
- Global $U(1)_E$ symmetry suppresses DM-H interaction, DM mass term and its magnetic moment.
- In E_6CHM: there are regions of parameter space which are safe from current constraints and may lead spectacular LHC signatures: color triplet T

$$T \to b\bar{\chi}.$$

THANK YOU FOR YOUR ATTENTION!