Dirac dark matter scattering on xenon and argon targets in Composite Higgs models

Maria Belyakova
LPI RAS

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LAYOUT

- Composite Higgs Models
  - Higgs sector: $SO(5)$ and $SU(6)$ global symmetries
  - Fields: elementary and strongly coupled sectors; lightest exotic state
- Interactions of dark matter in E_6 inspired Composite Higgs Models
- Results

COMPOSITE HIGGS MODELS: motivation

- Grand Unified theories with a fundamental scalar: The problem of the stabilization of the electroweak scale.

  In such theories, no symmetry to protect mass of the fundamental scalar $\rightarrow$ large sensitivity to radiative corrections.

- In Composite Higgs Models (CHMs):

  The Higgs doublet arises as a set of composite pseudo-Nambu–Goldstone bosons (pNGBs), analogous to pions in QCD.

COMPOSITE HIGGS MODELS: sectors

- Strongly coupled sector with approximate G symmetry $\to$ at scale f result in a set of resonances. These resonances are embedded in complete representations of G.
- Elementary sector presented by fields with SM quantum numbers.
- Higgs doublet is assumed to interact only with fields from strongly coupled sector.
- There is mixing between sectors $\to$ SM fields are superpositions of elementary particles and resonances.

$$\mathcal{L}^u_{mix} = \lambda_u Q H^c \bar{U}_R + \mu_q \bar{Q}_2 q + m_Q \bar{Q}_2 Q + h.c., \quad \mu_q \ll m_Q \tag{1}$$

$$q_L \simeq q - \frac{\mu_q}{m_Q} Q, \qquad Q_L = Q + \frac{\mu_q}{m_Q} q \tag{2}$$

$$\mathcal{L}_Y = Y_{ij} \left(\bar{q}_{Li} H^c u_{Rj} \right), \; Y_{ij} = \lambda_{ij} s_{qi} s_{uj}. \tag{3}$$

MINIMAL COMPOSITE HIGGS MODELS

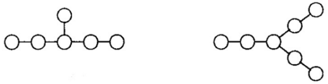
In the SM, the Higgs sector exhibits an approximate $SO(4)_H \cong SU(2)_W \times SU(2)_{\text{cust}}$ symmetry.

In the Minimal Composite Higgs Model, the strongly coupled sector possesses an approximate $SO(5)$ symmetry.
At the scale $f \gtrsim 1$ TeV, $SO(5)$ breaks to $SO(4) \cong SU(2)_W \times SU(2)_{\text{cust}}$, giving rise to four pNGBs: (H, H^c).

- H. Terazawa, K. Akama, Y. Chikashige, Phys. Rev. D 15 (1977) 480; H. Terazawa, Phys. Rev. D 22 (1980) 184.
- D. B. Kaplan, H. Georgi, Phys. Lett. B 136 (1984) 183
- K. Agashe, R. Contino and A. Pomarol, Nucl. Phys. B 719 (2005) 165.

E_6 INSPIRED COMPOSITE HIGGS MODEL: symmetry

- Composite Higgs Models may arise within E_6 GUT.



- E_6 includes the maximal subgroups: $SU(6) \times SU(2)_N$, $SU(3) \times SU(3) \times SU(3)$, and $SO(10) \times U(1)$.

At high energies, $E_6 \to SU(3)_C \times SU(2)_W \times U(1)_Y$.

$SU(6) \subset E_6$ can remain an approximate symmetry up to the scale $f \sim 5 - 10$ TeV.

$$SU(6) \times U(1)_B \xrightarrow{f \sim 5-10\,TeV} SU(5) \times U(1)_B + 11pNGB :$$

$SU(3)_C$ triplet T, $SU(2)_W$ doublet H, $SU(5)$ singlet ϕ_0

- Global baryon $U(1)_B$ symmetry $\to Z_3$ symmetry: $B_3 = (3B - n_C)_{mod\,3}$, where $n_C = 1$ for colored triplets and $n_C = -1$ for antitriplets, and $n_C = 0$ otherwise. $B_3 = 0$ for all SM fields. Fields with $B_3 \neq 0$ will be called exotic.

R. Nevzorov, A. W. Thomas, Phys. Rev. D **92** (2015).

E_6 INSPIRED COMPOSITE HIGGS MODEL: fields

We assume that right–handed t quark t^c is composite. Strong dynamics may result in following multiplets:

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

$$\overline{\mathbf{6}}_1 \quad \to \quad D^c_1 = \left(\bar{3},\, 1,\, \frac{1}{3},\, \frac{1}{3}\right)\,, \quad L_1 = \left(1,\, 2,\, -\tfrac{1}{2},\, \frac{1}{3}\right)\,, \quad N_1 = \left(1,\, 1,\, 0,\, \frac{1}{3}\right);$$

$$\overline{\mathbf{6}}_2 \quad \to \quad D^c_2 = \left(\bar{3},\, 1,\, \frac{1}{3},\, -\frac{1}{3}\right)\,, \quad L_2 = \left(1,\, 2,\, -\tfrac{1}{2},\, -\frac{1}{3}\right)\,, \quad \overline{N}_2 = \left(1,\, 1,\, 0,\, -\frac{1}{3}\right),$$

where in brackets $SU(3)_C \times SU(2)_W$ representations and $U(1)_Y \times U(1)_B$ charges.

E_6 INSPIRED COMPOSITE HIGGS MODEL: fields

To ensure anomaly cancellation, we introduce exotic elementary states

$$\bar{q} = \left(\bar{3}, \bar{2}, -\frac{1}{6}, -\frac{1}{3}\right), \bar{d}^c = \left(3, 1, -\frac{1}{3}, \frac{1}{3}\right), \bar{e}^c = \left(1, 1, -1, \frac{1}{3}\right), \bar{l} = \left(1, \bar{2}, \frac{1}{2}, \frac{1}{3}\right)$$

$$\bar{q} \in \mathbf{1\bar{5}}, \qquad \bar{d}^c \in \mathbf{6}, \qquad \bar{e}^c \in \mathbf{1\bar{5}}, \qquad \bar{l} \in \mathbf{6}. \tag{4}$$

where in brackets $SU(3)_C \times SU(2)_W$ representations and $U(1)_Y \times U(1)_B$ charges.

- All composite fields are embedded in complete $SU(6)$ representations.
- All elementary fields are embedded in incomplete $SU(6)$ representations
- Mixing between sectors and SM gauge couplings break $SU(6)$ explicitly.
- Exotic elementary and composite states acquire masses of order f and form vector-like fermions.

LIGHTEST EXOTIC STATE

The lightest exotic state is stable due to Z_3 symmetry.

- Scenarios with stable pNGB T colored triplet are phenomenologically excluded.
- Mass terms of exotic fermions

$$\mathcal{L}_{mass} = \mu_q \bar{q} Q + \mu_e \bar{e^c} E^c + \mu_D D_1^c D + \mu_L \bar{L} L_1 + \mu_d \bar{d}^c D_2^c + \mu_l \bar{\ell} L_2 + \mu_N \bar{N}_2 N_1 + h.c. \,, \quad (5)$$

In the presence of an approximate $U(1)_E$: $\overline{\mathbf{6}}_{\mathbf{2}} \to e^{i\beta} \overline{\mathbf{6}}_{\mathbf{2}}$, $\bar{d}^c \to e^{-i\beta} \bar{d}^c$, $\bar{\ell} \to e^{-i\beta} \bar{\ell}$ mass parameter μ_N is suppressed $\to$ Z_3 symmetry ensures the stability of $SU(5)$ singlet $\chi \simeq N_1 + N_2$.

Lightest Dirac composite particle (LDCP) χ may contribute to the Universe's dark matter density.

INTERACTIONS OF LDCP

- Interaction with H is suppressed by $U(1)_E$ symmetry and large enough f:

$$\frac{\varepsilon_H}{f} H^\dagger H(\overline{N}_2 N_1) + \text{h.c.} \to \mathcal{L}_{\chi\chi h} = \varepsilon_H \frac{\eta}{f} \bar{\chi}\chi h, \qquad \varepsilon_H \ll 1.$$

- Electromagnetic interaction of χ in E_6CHM is also suppressed by $U(1)_E$:

$$\frac{\mu_\chi}{2} \bar{\chi}_R \sigma^{\mu\nu} \chi_L F_{\mu\nu} + \text{h.c.}, \quad \mu_{\text{DM}}^{exp} \lesssim 10^{-8} \text{ GeV}^{-1}$$

- Interaction with Z is suppressed by large enough f:

$$\mathcal{L}_{Z\chi\chi} = \frac{c_1}{f^2}\left(H^\dagger i D_\mu H\right) \bar{N}_1 \gamma^\mu N_1 + \frac{c_2}{f^2}\left(H^\dagger i D_\mu H\right) \bar{N}_2 \gamma^\mu N_2.$$

$$\mathcal{L}_{Z\chi\chi} = \overline{\chi}(a_V^\chi \gamma^\mu + a_{PV}^\chi \gamma^\mu \gamma^5)\chi Z_\mu, \qquad a_V^\chi = \frac{\bar{g}\eta^2}{8f^2} c_V^\chi, \qquad a_{PV}^\chi = \frac{\bar{g}\eta^2}{8f^2} c_{PV}^\chi, \qquad (6)$$

where $c_V^\chi = \lambda_1 + \lambda_2$, $c_{PV}^\chi = \lambda_1 - \lambda_2$ and $\eta \simeq 246\,\text{GeV}$.

B. Ali *et al.* [PICO], Phys. Rev. D **106** (2022).

SI INTERACTION OF LDCP WITH NUCLEONS

In the non–relativistic limit for $\mu_\chi = 0$ one gets the cross–section of SI LDCP–N scattering

$$\sigma^N_{SI} \simeq \frac{m_r^2}{\pi}\left|\frac{\varepsilon_H a^N_H m_N}{f m_H^2} - \frac{\bar{g}^2\langle a_V\rangle}{2m_Z^2}\frac{\eta^2}{8f^2}c^\chi_V\right|^2, \quad \langle a_V\rangle = \frac{1}{A}\left(Za^p_V + (A-Z)a^n_V\right), \quad m_r = \frac{m_N m_\chi}{m_N + m_\chi}, \tag{7}$$

where a^N_V, a^N_{PV} and a^N_H are nucleon effective coupling constants:

$$\langle N'|J^\mu_{NC}|N\rangle = \bar{\psi}'_N\gamma^\mu\left(a^N_V + a^N_{PV}\gamma_5\right)\psi_N, \quad \frac{1}{\eta}\langle N'|\sum_q m_q\bar{q}q|N\rangle = a^N_H\frac{m_N}{\eta}\bar{\psi}'_N\psi_N,$$

- Main contribution to σ^N_{SI} is from Z-boson exchange
- Main free model parameters: m_χ, f, c^χ_V, ε_H
- LZ limits on SI cross-section of DM–nucleon scattering set strict constraints on the E_6CHM parameter space.

J. Aalbers *et al.* [LZ], Phys. Rev. Lett. **135** (2025) no.1, 011802.

CONSTRAINTS ON THE $f - c_V^\chi$ PLANE

- Constraints can be weakened if LDCP forms just a fraction of DM

$$\sigma_{\chi N}^{exp} = \frac{\rho_{DM}}{\rho_\chi}\sigma_{DM}^{exp} = \xi^{-1}\sigma_{DM}^{exp} \tag{8}$$

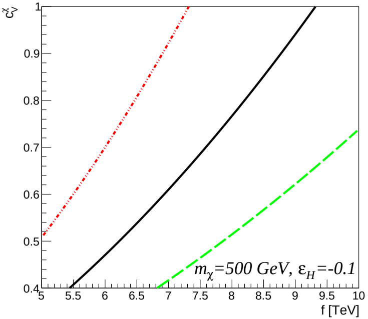


Figure 1: Regions of the CHM parameter space in the $f - c_V^\chi$. Below dashed–dotted, solid and dashed lines ρ_χ is allowed to be bigger than $0.1 \cdot \rho_{DM}$, $0.3 \cdot \rho_{DM}$ and may constitute full dark matter density ρ_{DM}, respectively.

SD INTERACTION OF LDCP WITH NUCLEONS

$$\sigma_{SD}^{N} \simeq \frac{m_r^2}{2\pi}\left[\frac{3}{2}\left(\frac{\bar{g}^2 a_{PV}^N}{m_Z^2}\frac{\eta^2}{8f^2}c_{PV}^{\chi}\right)^2 + 2\left(\frac{\bar{g}^2 a_{PV}^N}{m_Z^2}\frac{\eta^2}{8f^2}c_{PV}^{\chi}\right)\left(\frac{e\mu_\chi}{m_N}F_m^N\right) + \left(\frac{e\mu_\chi}{m_N}F_m^N\right)^2\right], \quad (9)$$

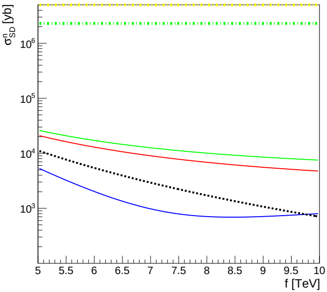


Figure 2: Spin-dependent LDCP-neutron scattering cross sections as a function of the compositeness scale f. Black dashed lines correspond to $\mu_\chi = 0$. Green, red and blue lines represent $\mu_\chi = 1.4 \cdot 10^{-8}$ GeV^{-1}, $\mu_\chi = 10^{-8}$ GeV^{-1}, and $\mu_\chi = -10^{-8}$ GeV^{-1}, respectively. The horizontal yellow and green lines show the experimental limits on σ_{SD}^n for $m_\chi = 1000$ GeV and 500 GeV, respectively.

LDCP INTERACTION WITH NUCLEI

$$\frac{d\sigma_{SI}}{dy} \simeq \frac{{M_r}^2 F_{SI}^2(|\mathbf{q}|^2)}{\pi}\left[\left(\frac{Ze\mu_\chi}{2m_\chi} - \frac{A\bar{g}\langle a_V\rangle a_V^\chi}{2m_Z^2} + \frac{A\varepsilon_H a_H^N}{fm_H^2}\right)^2 + \frac{(e\mu_\chi Z)^2}{4M_r^2}\left(\frac{1}{y} - 1\right)\right], \quad (10)$$

$$y = \frac{\varepsilon_{rec}}{\varepsilon_{max}}, \quad M_r = \frac{m_T m_\chi}{m_T + m_\chi}, \quad (11)$$

$$\frac{d\sigma_{SD}}{dy} \simeq \frac{M_r^2 F_{SD}^2(\mathbf{q}^2)}{\pi}\frac{(J+1)}{12J}\left[\left(c_4 - \frac{e\mu_\chi\mu_T}{m_N}\right)^2 + 2c_4^2\right], \quad (12)$$

$$c_4 = \mathcal{S}_p\left[\frac{2\bar{g}a_{PV}^p a_{PV}^\chi}{m_Z^2}\right] + \mathcal{S}_n\left[\frac{2\bar{g}a_{PV}^n a_{PV}^\chi}{m_Z^2}\right] + \frac{e\mu_\chi\mu_T}{m_N}, \quad \langle T'|\sum \hat{\mathbf{s}}_{p,\,n}|T\rangle = \frac{\mathcal{S}_{p,\,n}}{J}\langle T'|\hat{\mathbf{J}}|T\rangle \quad (13)$$

- The SI cross-section is about two orders of magnitude larger than the SD one.
- Enhancement at low-recoil energy of nuclei become apparent for $f \simeq 10$ TeV.
- We consider elastic scattering of LDCP on xenon and argon targets.

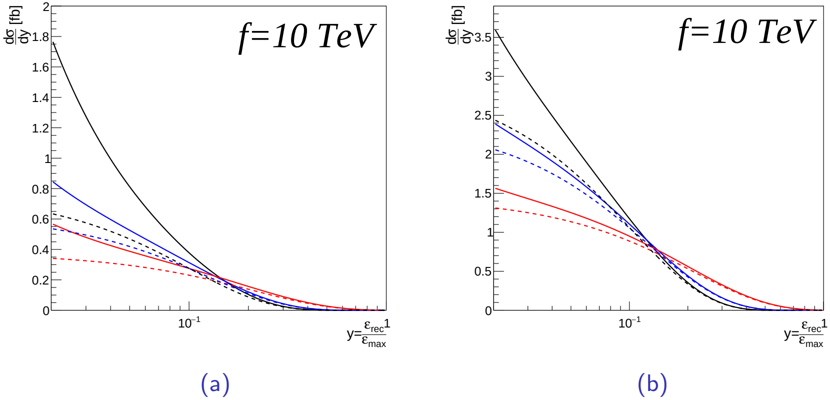
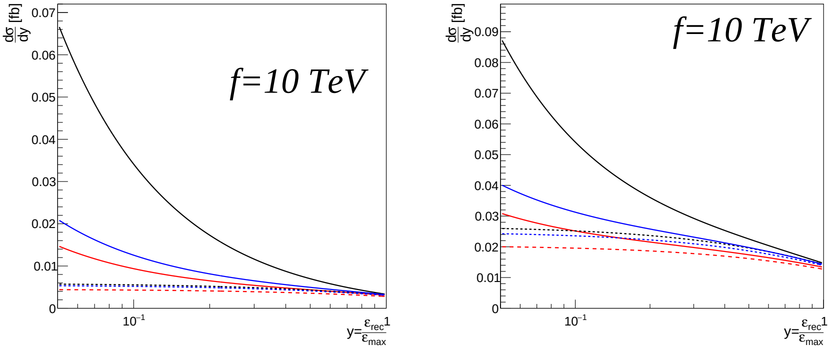


Figure 3: Differential cross-section of LDCP-Xe scattering, averaged over Xe isotopes. Red, blue and black lines correspond to $m_\chi = 200$ GeV, $m_\chi = 500$ GeV and $m_\chi = 1000$ GeV, respectively. Solid lines represent the LDCP magnetic moment $\mu_\chi = \xi^{-1/2}\mu_\chi^{\exp}(m_\chi)$ for $\xi = 0.1$. Dashed lines are for $\mu_\chi = 0$. Panels: (a) $c_V^\chi = 0.5$, $\varepsilon_H = -0.1$, $f = 10$ TeV; (b) $c_V^\chi = 0.5$, $\varepsilon_H = 0$, $f = 10$ TeV.



(a) (b)

Figure 4: Differential cross-section of LDCP-Ar scattering, averaged over Ar isotopes. Red, blue and black lines correspond to $m_\chi = 200$ GeV, $m_\chi = 500$ GeV and $m_\chi = 1000$ GeV, respectively. Solid lines represent the LDCP magnetic moment $\mu_\chi = \xi^{-1/2}\mu_\chi^{\text{exp}}(m_\chi)$ for $\xi = 0.1$. Dashed lines are for $\mu_\chi = 0$. Panels: (a) $c_V^\chi = 0.5$, $\varepsilon_H = -0.1$, $f = 10$ TeV; (b) $c_V^\chi = 0.5$, $\varepsilon_H = 0$, $f = 10$ TeV.

CONCLUSION

- Composite Higgs models may include neutral stable Dirac fermions that can contribute to the dark matter density.
- The dark matter's interaction with the Higgs is suppressed by an approximate $U(1)_E$ symmetry and by the scale f. The interaction with the Z boson is suppressed by the scale f.
- Experimental constraints on spin-independent DM–nucleon scattering cross sections set strict limits on the model parameter space.
- In some phenomenologically viable regions of E_6CHM the LDCP–nuclei interaction manifests a visible enhancement in the differential cross-section, associated with its electromagnetic interaction. This growth is especially distinctive in the case of an Ar target.
- The model predicts a distinctive signature – a colored triplet T with mass $2 - 3$ TeV, which can be produced at the LHC.