

Pseudo-Nambu-Goldstone Dark Matter and Two-Higgs-doublet Models

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Based on Xue-Min Jiang, Chengfeng Cai, Zhao-Huan Yu, Yu-Pan Zeng, and Hong-Hao Zhang, 1907.09684, PRD



Composite 2019
Sun Yat-Sen University, Guangzhou
November 22, 2019



Thermal Dark Matter

✨ Con conventionally, **dark matter (DM)** is assumed to be a **thermal relic** remaining from the early Universe

🌙 DM relic abundance observation

👉 Particle mass $m_\chi \sim \mathcal{O}(\text{GeV}) - \mathcal{O}(\text{TeV})$

Interaction strength $\sim$ **weak strength**

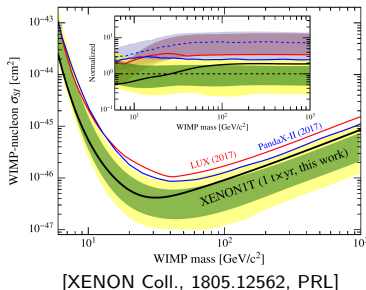
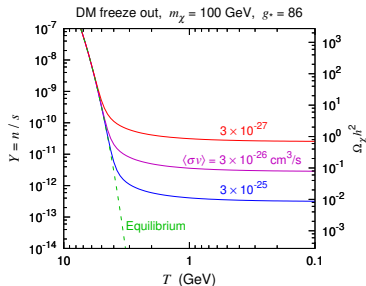
“Weakly interacting massive particles”

“WIMPs”

🔍 **Direct detection** for WIMPs

👉 **No robust signal found so far**

☁ **Great challenge** to the thermal dark matter paradigm



Save the Thermal DM Paradigm



Enhance DM annihilation at the **freeze-out epoch**



Coannihilation, resonance effect, Sommerfeld enhancement, etc.



Suppress DM-nucleon scattering at **zero momentum transfer**



Isospin-violating interactions with protons and neutrons

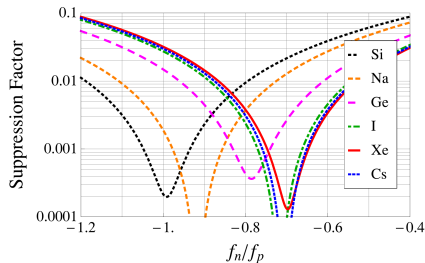
Feng *et al.*, 1102.4331 PLB; Frandsen *et al.*, 1107.2118, JHEP; ...



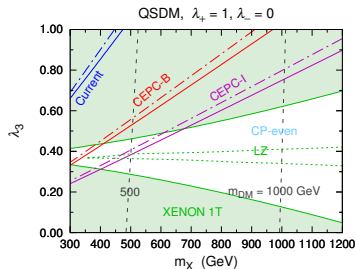
“Blind spots”: particular parameter values lead to suppression

Cheung *et al.*, 1211.4873, JHEP; Cai, ZHY, Zhang, 1705.07921, NPB;

Han *et al.*, 1810.04679, JHEP; Altmannshofer, *et al.*, 1907.01726, PRD; ...



[Frandsen *et al.*, 1107.2118, JHEP]



[Cai, ZHY, Zhang, 1705.07921, NPB]

Save the Thermal DM Paradigm

☀️ **Suppress DM-nucleon scattering** at **zero momentum transfer**

● **Mediated by **pseudoscalars**: velocity-dependent SD scattering**

Ipek *et al.*, 1404.3716, PRD; Berlin *et al.*, 1502.06000, PRD;
Goncalves, *et al.*, 1611.04593, PRD; Bauer, *et al.*, 1701.07427, JHEP; ...

● **Relevant DM couplings vanish due to **special symmetries****

Dedes & Karamitros, 1403.7744, PRD; Tait & **ZHY**, 1601.01354, JHEP;
Cai, **ZHY**, Zhang, 1611.02186, NPB; ...

Triplet-quadruplet fermionic DM model

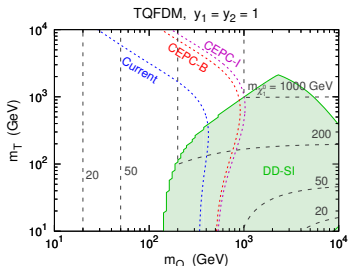
Custodial symmetry limit $y_1 = y_2$



DM couplings to h and Z vanish for $m_Q < m_T$



DM-nucleon scattering vanishes at tree level



[Cai, **ZHY**, Zhang, 1611.02186, NPB]

● DM particle is a **pseudo-Nambu-Goldstone boson (pNGB)** protected by an **approximate global symmetry** [Gross, Lebedev, Toma, 1708.02253, PRL]

pNGB Dark Matter [Gross, Lebedev, Toma, 1708.02253, PRL]

-  Standard model (SM) Higgs doublet H , **complex scalar** S (SM singlet)
-  Scalar potential respects a **softly broken global U(1) symmetry** $S \rightarrow e^{i\alpha} S$
-  U(1) **symmetric** $V_0 = -\frac{\mu_H^2}{2}|H|^2 - \frac{\mu_S^2}{2}|S|^2 + \frac{\lambda_H}{2}|H|^4 + \frac{\lambda_S}{2}|S|^4 + \lambda_{HS}|H|^2|S|^2$
-  **Soft breaking** $V_{\text{soft}} = -\frac{\mu'_S}{4}S^2 + \text{H.c.}$
-  Soft breaking parameter μ'_S can be made **real** and **positive** by redefining S
-  V_{soft} can be justified by treating μ'_S as a **spurion** from an underlying theory
-  H and S develop vacuum expectation values (VEVs) v and v_s

$$H \rightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}, \quad S = \frac{1}{\sqrt{2}}(v_s + s + i\chi)$$

-  The soft breaking term V_{soft} give a mass to χ : $m_\chi = \mu'_S$
-  χ is a **stable pNGB**, acting as a **DM candidate**

Scalar Mixing and Interactions [Gross, Lebedev, Toma, 1708.02253, PRL]

☾ **Mixing** of the **CP-even Higgs bosons** h and s

$$\mathcal{M}_{h,s}^2 = \begin{pmatrix} \lambda_H v^2 & \lambda_{HS} v v_s \\ \lambda_{HS} v v_s & \lambda_S v_s^2 \end{pmatrix}, \quad O^T \mathcal{M}^2 O = \begin{pmatrix} m_{h_1}^2 & \\ & m_{h_2}^2 \end{pmatrix}$$

$$O = \begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix}, \quad c_\theta \equiv \cos \theta, \quad s_\theta \equiv \sin \theta, \quad \tan 2\theta = \frac{2\lambda_{HS} v v_s}{\lambda_S v_s^2 - \lambda_H v^2}$$

$$\begin{pmatrix} h \\ s \end{pmatrix} = O \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}, \quad m_{h_1, h_2}^2 = \frac{1}{2} \left(\lambda_H v^2 + \lambda_S v_s^2 \mp \frac{\lambda_S v_s^2 - \lambda_H v^2}{\cos 2\theta} \right)$$

★ **Higgs portal** interactions

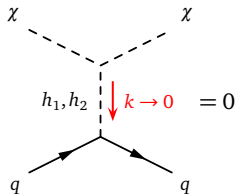
$$\begin{aligned} \mathcal{L} \supset & -\frac{\lambda_{HS} v}{2} h \chi^2 - \frac{\lambda_S v_s}{2} s \chi^2 - \sum_f \frac{m_f}{v} h \bar{f} f \\ & = \frac{m_{h_1}^2 s_\theta}{2v_s} h_1 \chi^2 - \frac{m_{h_2}^2 c_\theta}{2v_s} h_2 \chi^2 - \sum_f \frac{m_f}{v} (h_1 c_\theta + h_2 s_\theta) \bar{f} f \end{aligned}$$

DM-nucleon Scattering [Gross, Lebedev, Toma, 1708.02253, PRL]

✨ **DM-quark** interactions induce **DM-nucleon** scattering in direct detection

✎ **DM-quark scattering amplitude** from Higgs portal interactions

$$\begin{aligned}\mathcal{M}(\chi q \rightarrow \chi q) &\propto \frac{m_q s_\theta c_\theta}{v v_s} \left(\frac{m_{h_1}^2}{t - m_{h_1}^2} - \frac{m_{h_2}^2}{t - m_{h_2}^2} \right) \\ &= \frac{m_q s_\theta c_\theta}{v v_s} \frac{t(m_{h_1}^2 - m_{h_2}^2)}{(t - m_{h_1}^2)(t - m_{h_2}^2)}\end{aligned}$$



🔥 **Zero momentum transfer limit** $t = k^2 \rightarrow 0$, $\mathcal{M}(\chi q \rightarrow \chi q) \rightarrow 0$

👉 DM-nucleon scattering cross section **vanishes** at tree level

💡 Tree-level interactions of a **pNGB** are generally **momentum suppressed**

☁️ **One-loop corrections** typically lead to $\sigma_{\chi N}^{\text{SI}} \lesssim \mathcal{O}(10^{-50}) \text{ cm}^2$

[Azevedo *et al.*, 1810.06105, JHEP; Ishiwata & Toma, 1810.08139, JHEP]

👉 **Beyond capability** of current and near future direct detection experiments

Generalizations

● Generalize the softly broken global $U(1)$ to $O(N)$, $SU(N)$ or $U(1) \times S_N$

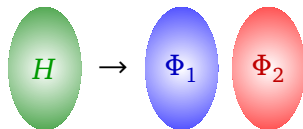
[Alanne *et al.*, 1812.05996, PRD; Karamitros, 1901.09751, PRD]

👉 Multiple pNGBs constituting **multi-component** dark matter

● We extend the study to **two-Higgs-doublet models (2HDMs)**

? Does **DM-nucleon scattering** still **vanish** at zero momentum transfer?

? How do current **Higgs measurements** in the LHC experiments constrain such a model?



? Can the observed **relic abundance** be obtained via the thermal mechanism?

? How are the constraints from **indirect detection**?

pNGB DM and Two Higgs Doublets



Two Higgs doublets Φ_1 and Φ_2 with $Y = 1/2$, complex scalar singlet S



Scalar potential respects a softly broken global U(1) symmetry $S \rightarrow e^{i\alpha} S$



Two **common assumptions** for 2HDMs

- CP is conserved in the scalar sector
- There is a Z_2 symmetry $\Phi_1 \rightarrow -\Phi_1$ or $\Phi_2 \rightarrow -\Phi_2$ forbidding quartic terms that are odd in Φ_1 or Φ_2 , but it can be softly broken by quadratic terms



Scalar potential constructed with Φ_1 and Φ_2

$$V_1 = m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1) + \frac{\lambda_1}{2} |\Phi_1|^4 + \frac{\lambda_2}{2} |\Phi_2|^4 \\ + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 + \frac{\lambda_5}{2} [(\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2]$$



U(1) symmetric potential terms involving S

$$V_2 = -m_S^2 |S|^2 + \frac{\lambda_S}{2} |S|^4 + \kappa_1 |\Phi_1|^2 |S|^2 + \kappa_2 |\Phi_2|^2 |S|^2$$



Quadratic term **softly breaking** the global U(1): $V_{\text{soft}} = -\frac{m_S'^2}{4} S^2 + \text{H.c.}$

Scalars

 Φ_1 , Φ_2 , and S develop VEVs v_1 , v_2 and v_s

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ (v_1 + \rho_1 + i\eta_1)/\sqrt{2} \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ (v_2 + \rho_2 + i\eta_2)/\sqrt{2} \end{pmatrix}, \quad S = \frac{v_s + s + i\chi}{\sqrt{2}}$$

★ χ is a **stable pNGB** with $m_\chi = m'_S$, acting as a **DM candidate**

☾ Mass terms for **charged scalars** and **CP-odd scalars**

$$-\mathcal{L}_{\text{mass}} \supset \left[m_{12}^2 - \frac{1}{2}(\lambda_4 + \lambda_5)v_1v_2 \right] (\phi_1^-, \phi_2^-) \begin{pmatrix} v_2/v_1 & -1 \\ -1 & v_1/v_2 \end{pmatrix} \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix} \\ + \frac{1}{2}(m_{12}^2 - \lambda_5v_1v_2) (\eta_1, \eta_2) \begin{pmatrix} v_2/v_1 & -1 \\ -1 & v_1/v_2 \end{pmatrix} \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix}$$

$$\begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix} = R(\beta) \begin{pmatrix} G^+ \\ H^+ \end{pmatrix}, \quad \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix} = R(\beta) \begin{pmatrix} G^0 \\ a \end{pmatrix}, \quad R(\beta) = \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix}, \quad \tan \beta = \frac{v_2}{v_1}$$

● $G^\pm$ and G^0 are **massless Nambu-Goldstone bosons** eaten by $W^\pm$ and Z

● $H^\pm$ and a are **physical states**

$$m_{H^\pm}^2 = \frac{v_1^2 + v_2^2}{v_1v_2} \left[m_{12}^2 - \frac{1}{2}(\lambda_4 + \lambda_5)v_1v_2 \right], \quad m_a^2 = \frac{v_1^2 + v_2^2}{v_1v_2} (m_{12}^2 - \lambda_5v_1v_2)$$

CP-even Scalars and Weak Gauge Bosons

☀ Mass terms for **CP-even scalars** $-\mathcal{L}_{\text{mass}} \supset \frac{1}{2}(\rho_1, \rho_2, s) \mathcal{M}_{\rho s}^2 \begin{pmatrix} \rho_1 \\ \rho_2 \\ s \end{pmatrix}$

$$\mathcal{M}_{\rho s}^2 = \begin{pmatrix} \lambda_1 v_1^2 + m_{12}^2 \tan \beta & \lambda_{345} v_1 v_2 - m_{12}^2 & \kappa_1 v_1 v_s \\ \lambda_{345} v_1 v_2 - m_{12}^2 & \lambda_2 v_2^2 + m_{12}^2 \cot \beta & \kappa_2 v_2 v_s \\ \kappa_1 v_1 v_s & \kappa_2 v_2 v_s & \lambda_s v_s^2 \end{pmatrix}, \quad \lambda_{345} \equiv \lambda_3 + \lambda_4 + \lambda_5$$

$$\begin{pmatrix} \rho_1 \\ \rho_2 \\ s \end{pmatrix} = O \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}, \quad O^T \mathcal{M}_{\rho s}^2 O = \text{diag}(m_{h_1}^2, m_{h_2}^2, m_{h_3}^2), \quad m_{h_1} \leq m_{h_2} \leq m_{h_3}$$

💡 One of h_i should behave like the **125 GeV SM Higgs boson**

🌍 Mass terms for **weak gauge bosons**

$$-\mathcal{L}_{\text{mass}} \supset \frac{g^2}{4}(v_1^2 + v_2^2) W^{-,\mu} W_{\mu}^{+} + \frac{1}{2} \frac{g^2}{4c_W^2}(v_1^2 + v_2^2) Z^{\mu} Z_{\mu}, \quad c_W \equiv \cos \theta_W$$

$$m_W = \frac{gv}{2}, \quad m_Z = \frac{gv}{2c_W}, \quad v \equiv \sqrt{v_1^2 + v_2^2} = (\sqrt{2}G_F)^{-1/2} = 246.22 \text{ GeV}$$

Yukawa Couplings

😬 In 2HDMs, diagonalizing the **fermion mass matrix** **cannot** make sure that the **Yukawa interactions** are simultaneously diagonalized

👉 Tree-level **flavor-changing neutral currents (FCNCs)** 👉 flavor problems

😊 If all fermions with the same quantum numbers just couple to the one **same** Higgs doublet, the FCNCs will be **absent** at tree level

[Glashow & Weinberg, PRD 15, 1958 (1977); Paschos, PRD 15, 1966 (1977)]

💡 This can be achieved by assuming particular Z_2 **symmetries** for the Higgs doublets and fermions

✎ **Four independent types** of Yukawa couplings without tree-level FCNCs

Type I: $\mathcal{L}_{Y,I} = -y_{\ell_i} \bar{L}_{iL} \ell_{iR} \Phi_2 - \tilde{y}_d^{ij} \bar{Q}_{iL} d'_{jR} \Phi_2 - \tilde{y}_u^{ij} \bar{Q}_{iL} u'_{jR} \tilde{\Phi}_2 + \text{H.c.}$

Type II: $\mathcal{L}_{Y,II} = -y_{\ell_i} \bar{L}_{iL} \ell_{iR} \Phi_1 - \tilde{y}_d^{ij} \bar{Q}_{iL} d'_{jR} \Phi_1 - \tilde{y}_u^{ij} \bar{Q}_{iL} u'_{jR} \tilde{\Phi}_2 + \text{H.c.}$

Lepton specific: $\mathcal{L}_{Y,L} = -y_{\ell_i} \bar{L}_{iL} \ell_{iR} \Phi_1 - \tilde{y}_d^{ij} \bar{Q}_{iL} d'_{jR} \Phi_2 - \tilde{y}_u^{ij} \bar{Q}_{iL} u'_{jR} \tilde{\Phi}_2 + \text{H.c.}$

Flipped: $\mathcal{L}_{Y,F} = -y_{\ell_i} \bar{L}_{iL} \ell_{iR} \Phi_2 - \tilde{y}_d^{ij} \bar{Q}_{iL} d'_{jR} \Phi_1 - \tilde{y}_u^{ij} \bar{Q}_{iL} u'_{jR} \tilde{\Phi}_2 + \text{H.c.}$

[Branco *et al.*, 1106.0034, Phys. Rept.]

Four Types of Yukawa Couplings

 Yukawa interactions for the **fermion mass eigenstates**

$$\mathcal{L}_Y = \sum_{f=\ell_j, d_j, u_j} \left[-m_f \bar{f} f - \frac{m_f}{v} \left(\sum_{i=1}^3 \xi_{h_i}^f h_i \bar{f} f + \xi_a^f a \bar{f} i \gamma_5 f \right) \right] \\ - \frac{\sqrt{2}}{v} [H^+ (\xi_a^{\ell_i} m_{\ell_i} \bar{\nu}_i P_R \ell_i + \xi_a^{d_j} m_{d_j} V_{ij} \bar{u}_i P_R d_j + \xi_a^{u_i} m_{u_i} V_{ij} \bar{u}_i P_L d_j) + \text{H.c.}]$$

	Type I	Type II	Lepton specific	Flipped
$\xi_{h_i}^{\ell_j}$	$O_{2i}/\sin\beta$	$O_{1i}/\cos\beta$	$O_{1i}/\cos\beta$	$O_{2i}/\sin\beta$
$\xi_{h_i}^{d_j}$	$O_{2i}/\sin\beta$	$O_{1i}/\cos\beta$	$O_{2i}/\sin\beta$	$O_{1i}/\cos\beta$
$\xi_{h_i}^{u_j}$	$O_{2i}/\sin\beta$	$O_{2i}/\sin\beta$	$O_{2i}/\sin\beta$	$O_{2i}/\sin\beta$
$\xi_a^{\ell_j}$	$\cot\beta$	$-\tan\beta$	$-\tan\beta$	$\cot\beta$
$\xi_a^{d_j}$	$\cot\beta$	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
$\xi_a^{u_j}$	$-\cot\beta$	$-\cot\beta$	$-\cot\beta$	$-\cot\beta$

Vanishing of DM-nucleon Scattering

💡 Take the **type-I** Yukawa couplings as an example

★ **Higgs portal** interactions $\mathcal{L}_{h_i\chi^2} = \frac{1}{2} \sum_{i=1}^3 g_{h_i\chi^2} h_i \chi^2$

$$g_{h_i\chi^2} = -\kappa_1 v_1 O_{1i} - \kappa_2 v_2 O_{2i} - \lambda_S v_s O_{3i}$$

✨ **DM-quark scattering** amplitude

$$\mathcal{M}(\chi q \rightarrow \chi q) \propto \frac{m_q}{v s_\beta} \left(\frac{g_{h_1\chi^2} O_{21}}{t - m_{h_1}^2} + \frac{g_{h_2\chi^2} O_{22}}{t - m_{h_2}^2} + \frac{g_{h_3\chi^2} O_{23}}{t - m_{h_3}^2} \right)$$

$$\xrightarrow{t \rightarrow 0} \frac{m_q}{v s_\beta} (\kappa_1 v_1, \kappa_2 v_2, \lambda_S v_s) O (\mathcal{M}_h^2)^{-1} O^T \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} = \frac{m_q}{v s_\beta} (\kappa_1 v_1, \kappa_2 v_2, \lambda_S v_s) (\mathcal{M}_{\rho_s}^2)^{-1} \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$$

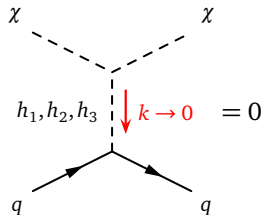
Interaction basis expression

$$= \frac{m_q}{v s_\beta \det(\mathcal{M}_{\rho_s}^2)} (\kappa_1 v_1 \mathcal{A}_{12} + \kappa_2 v_2 \mathcal{A}_{22} + \lambda_S v_s \mathcal{A}_{32}) = 0$$

$$\mathcal{M}_h^2 \equiv \text{diag}(m_{h_1}^2, m_{h_2}^2, m_{h_3}^2)$$

$$O(\mathcal{M}_h^2)^{-1} O^T = (\mathcal{M}_{\rho_s}^2)^{-1} = \frac{\mathcal{A}}{\det(\mathcal{M}_{\rho_s}^2)}, \quad \mathcal{A}_{12} = -(\lambda_{345} v_1 v_2 - m_{12}^2) \lambda_S v_s^2 + \kappa_1 \kappa_2 v_1 v_2 v_s^2$$

$$\mathcal{A}_{22} = (\lambda_1 v_1^2 + m_{12}^2 \tan \beta) \lambda_S v_s^2 - \kappa_1^2 v_1^2 v_s^2, \quad \mathcal{A}_{32} = -(\lambda_1 v_1^2 + m_{12}^2 \tan \beta) \kappa_2 v_2 v_s + (\lambda_{345} v_1 v_2 - m_{12}^2) \kappa_1 v_1 v_s$$



Alignment Limit

💡 **Higgs basis** 📌 Φ_h (h) acts as the **SM Higgs doublet (boson)**

$$\begin{pmatrix} \Phi_h \\ \Phi_H \end{pmatrix} \equiv R^{-1}(\beta) \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix}, \quad \Phi_h = \begin{pmatrix} G^+ \\ (v + h + iG^0)/\sqrt{2} \end{pmatrix}, \quad \Phi_H = \begin{pmatrix} H^+ \\ (H + ia)/\sqrt{2} \end{pmatrix}$$

$$V_1 = m_{hh}^2 |\Phi_h|^2 + m_{HH}^2 |\Phi_H|^2 - m_{hH}^2 (\Phi_h^\dagger \Phi_H + \Phi_H^\dagger \Phi_h) + \frac{\lambda_h}{2} |\Phi_h|^4 + \frac{\lambda_H}{2} |\Phi_H|^4 + \tilde{\lambda}_3 |\Phi_h|^2 |\Phi_H|^2 \\ + \tilde{\lambda}_4 |\Phi_h^\dagger \Phi_H|^2 + \frac{1}{2} [\tilde{\lambda}_5 (\Phi_h^\dagger \Phi_H)^2 + \tilde{\lambda}_6 |\Phi_h|^2 \Phi_H^\dagger \Phi_h + \tilde{\lambda}_7 |\Phi_H|^2 \Phi_h^\dagger \Phi_H + \text{H.c.}]$$

$$V_2 = -m_s^2 |S|^2 + \frac{\lambda_s}{2} |S|^4 + \tilde{\kappa}_1 |\Phi_h|^2 |S|^2 + \tilde{\kappa}_2 |\Phi_H|^2 |S|^2 + \tilde{\kappa}_3 (\Phi_h^\dagger \Phi_H + \Phi_H^\dagger \Phi_h) |S|^2$$

🖋️ Mass-squared matrix for CP -even scalars (h, H, s)

$$\mathcal{M}_{hHs}^2 = \begin{pmatrix} \lambda_h v^2 & \tilde{\lambda}_6 v^2/2 & \tilde{\kappa}_1 v v_s \\ \tilde{\lambda}_6 v^2/2 & m_{HH}^2 + (\tilde{\lambda}_{345} v^2 + \tilde{\kappa}_2 v_s^2)/2 & \tilde{\kappa}_3 v v_s \\ \tilde{\kappa}_1 v v_s & \tilde{\kappa}_3 v v_s & \lambda_s v_s^2 \end{pmatrix}$$

🐟 **Alignment Limit** $\begin{cases} \tilde{\lambda}_6 = -s_{2\beta}(c_\beta^2 \lambda_1 - s_\beta^2 \lambda_2) + s_{2\beta} c_{2\beta} \lambda_{345} = 0 \\ \tilde{\kappa}_1 = c_\beta^2 \kappa_1 + s_\beta^2 \kappa_2 = 0 \end{cases}$

📌 Couplings of $h_{125} = h$ to SM particles are **identical** to **SM** Higgs couplings

Parameter Scan

 **12 free parameters** in the model

$$\nu_s, m_\chi, m_{12}^2, \tan\beta, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_S, \kappa_1, \kappa_2$$

 **Random scan** within the following ranges

$$\begin{aligned} 10 \text{ GeV} < \nu_s < 10^3 \text{ GeV}, \quad 10 \text{ GeV} < m_\chi < 10^4 \text{ GeV}, \\ (10 \text{ GeV})^2 < |m_{12}^2| < (10^3 \text{ GeV})^2, \quad 10^{-2} < \tan\beta < 10^2, \\ 10^{-3} < \lambda_1, \lambda_2, \lambda_S < 1, \quad 10^{-3} < |\lambda_3|, |\lambda_4|, |\lambda_5|, |\kappa_1|, |\kappa_2| < 1 \end{aligned}$$

 Select the parameter points satisfying **two conditions**

 Positive $m_{h_{1,2,3}}^2$, $m_{H^+}^2$, and m_a^2  ensuring **physical** scalar masses

 One of the *CP*-even Higgs bosons h_i has a mass within the 3σ range of the measured SM-like Higgs boson mass $m_h = 125.18 \pm 0.16 \text{ GeV}$ [PDG 2018]

 Recognize this scalar as the **SM-like** Higgs boson and denote it as h_{SM}

κ -framework

 Couplings of the **SM-like Higgs boson** h_{SM} to SM particles

$$\begin{aligned}\mathcal{L}_{h_{\text{SM}}} = & \kappa_W g m_W h_{\text{SM}} W_\mu^+ W^{-,\mu} + \kappa_Z \frac{g m_Z}{2c_W} h_{\text{SM}} Z_\mu Z^\mu - \sum_f \kappa_f \frac{m_f}{v} h_{\text{SM}} \bar{f} f \\ & + \kappa_g g_{hgg}^{\text{SM}} h_{\text{SM}} G_{\mu\nu}^a G^{a\mu\nu} + \kappa_\gamma g_{h\gamma\gamma}^{\text{SM}} h_{\text{SM}} A_{\mu\nu} A^{\mu\nu} + \kappa_{Z\gamma} g_{hZ\gamma}^{\text{SM}} h_{\text{SM}} A_{\mu\nu} Z^{\mu\nu}\end{aligned}$$

 g_{hgg}^{SM} , $g_{h\gamma\gamma}^{\text{SM}}$, and $g_{hZ\gamma}^{\text{SM}}$ are **loop-induced** effective couplings

 Modifier for the h_{SM} decay width $\kappa_H^2 \equiv \frac{\Gamma_{h_{\text{SM}}} - \Gamma_{h_{\text{SM}}}^{\text{BSM}}}{\Gamma_h^{\text{SM}}}$, $\Gamma_{h_{\text{SM}}}^{\text{BSM}} = \Gamma_{h_{\text{SM}}}^{\text{inv}} + \Gamma_{h_{\text{SM}}}^{\text{und}}$

 $\Gamma_{h_{\text{SM}}}^{\text{inv}}$ is the decay width into **invisible** final states, e.g., $\chi\chi$

 $\Gamma_{h_{\text{SM}}}^{\text{und}}$ is the decay width into **undetected** beyond-the-SM (BSM) final states, e.g., aa , H^+H^- , $h_i h_j$, aZ , and $H^\pm W^\mp$

 In the SM, $\kappa_W = \kappa_Z = \kappa_f = \kappa_g = \kappa_\gamma = \kappa_{Z\gamma} = \kappa_H = 1$

 In our model, assuming $h_{\text{SM}} = h_i$ and **type-I** Yukawa couplings,

$$\kappa_Z = \kappa_W \equiv \kappa_V = c_\beta O_{1i} + s_\beta O_{2i}, \quad \kappa_f = O_{2i}/s_\beta$$

Global Fit with Higgs Measurement Data



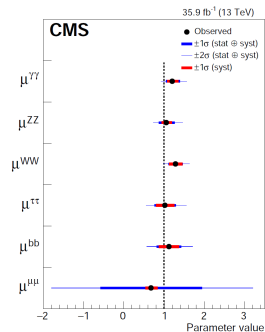
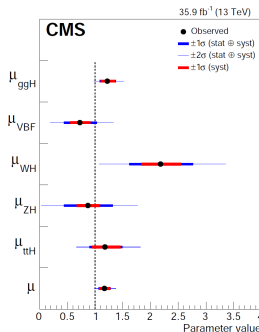
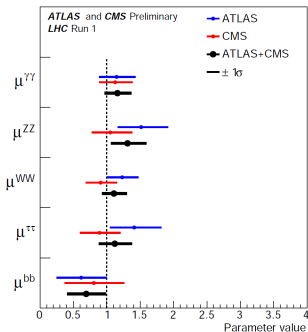
We utilize a numerical tool **Lilith** to construct an approximate likelihood based on experimental results of **Higgs signal strength measurements**



Calculate the **likelihood** $-2\ln L$ for each parameter points based on Tevatron data as well as LHC Run 1 and Run 2 data from ATLAS and CMS

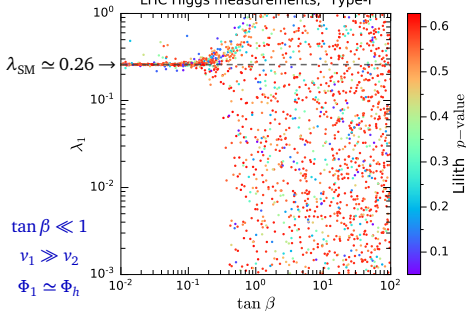


Transform $-2\ln L$ to ***p-value***, and select parameter points with $p > 0.05$, *i.e.*, discard parameter points that are excluded by data at **95% C.L.**

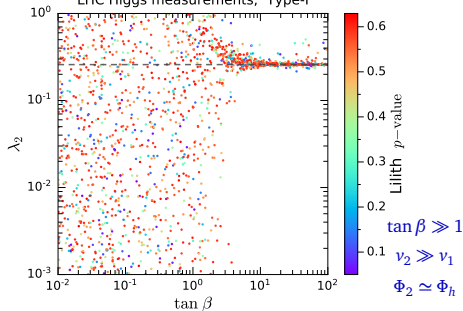


[ATLAS-CONF-2015-044/CMS-PAS-HIG-15-002; CMS coll., 1809.10733, EPJC]

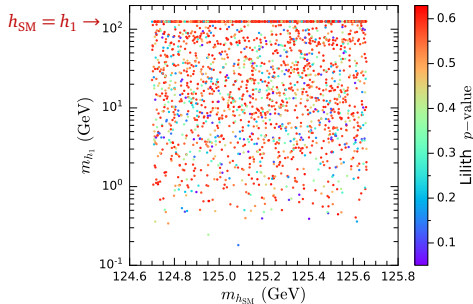
LHC Higgs measurements, Type-I



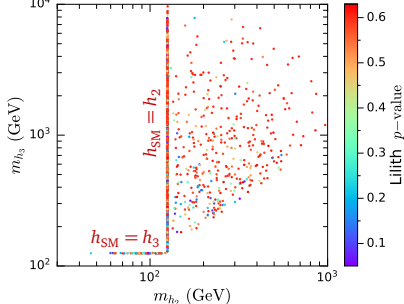
LHC Higgs measurements, Type-I

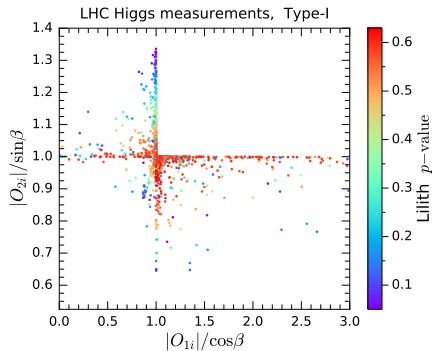
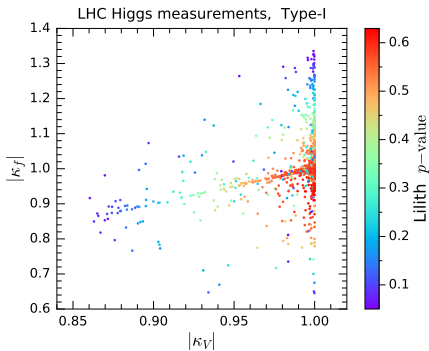


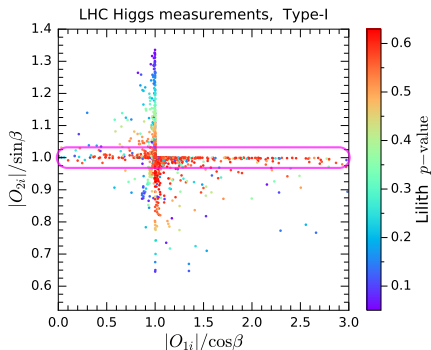
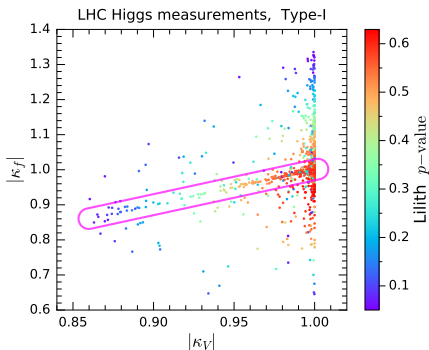
LHC Higgs measurements, Type-I



LHC Higgs measurements, Type-I





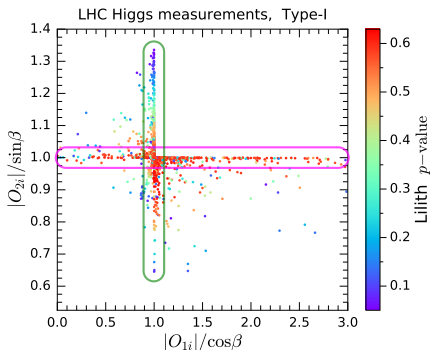
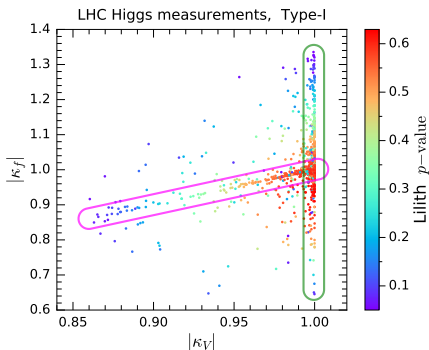


Category 1: $\kappa_V \simeq \kappa_f$ (nearly total positive correlation)

$\tan\beta \gg 1$ $\beta \simeq \pi/2$ $c_\beta O_{1i} + s_\beta O_{2i} = \kappa_V \simeq O_{2i} \simeq \kappa_f = O_{2i}/s_\beta$

$|O_{2i}| \leq 1$ $|\kappa_V|, |\kappa_f| \leq 1$

Most of parameter points in Category 1 correspond to $|O_{2i}|/s_\beta \simeq 1$



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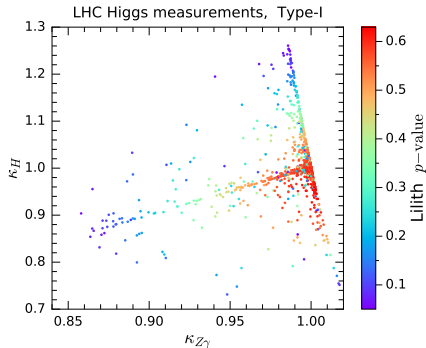
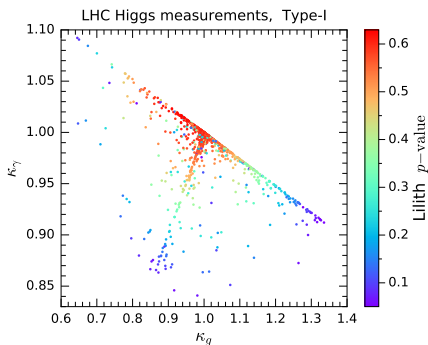
$$|O_{2i}| \leq 1 \quad \text{point} \quad |\kappa_V|, |\kappa_f| \leq 1$$

Most of parameter points in Category 1 correspond to $|O_{2i}|/s_\beta \simeq 1$

Category 2: $|\kappa_V| \simeq 1$ with varying $|\kappa_f|$, corresponding to $|O_{1i}|/c_\beta \simeq 1$

$$|O_{1i}| \simeq c_\beta, \quad |O_{2i}| \simeq s_\beta \quad \text{point} \quad |\kappa_V| = |c_\beta O_{1i} + s_\beta O_{2i}| \simeq c_\beta^2 + s_\beta^2 = 1$$

For small β , the 2nd relation $|O_{2i}| \simeq s_\beta$ is not important for $|\kappa_V| \simeq 1$

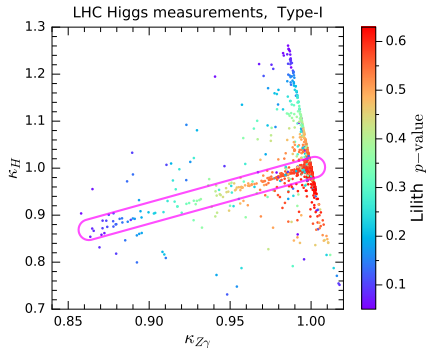
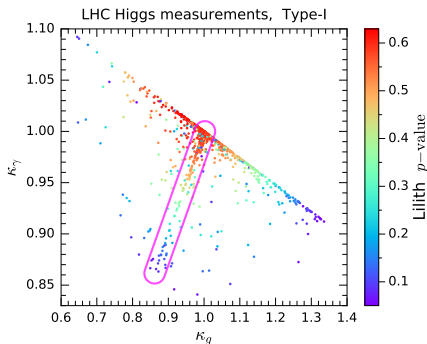


💡 Parametrizations for κ_g , κ_γ , $\kappa_{Z\gamma}$, and κ_H [PDG 2018]

$$\kappa_g^2 = 1.06\kappa_t^2 + 0.01\kappa_b^2 - 0.07\kappa_t\kappa_b$$

$$\kappa_\gamma^2 = 1.59\kappa_W^2 + 0.07\kappa_t^2 - 0.66\kappa_W\kappa_t, \quad \kappa_{Z\gamma}^2 = 1.12\kappa_W^2 + 0.03\kappa_t^2 - 0.15\kappa_W\kappa_t$$

$$\kappa_H^2 = 0.57\kappa_b^2 + 0.06\kappa_\tau^2 + 0.03\kappa_c^2 + 0.22\kappa_W^2 + 0.03\kappa_Z^2 + 0.09\kappa_g^2 + 0.0023\kappa_\gamma^2$$



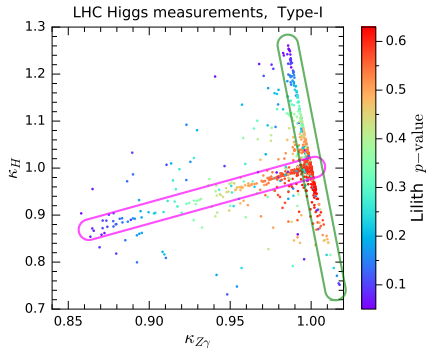
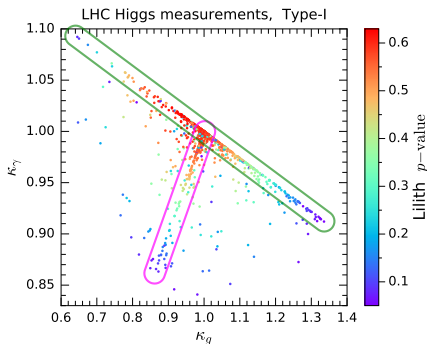
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🟡 **Category 1:** $\kappa_V \simeq \kappa_f$ 👉 κ_g ($\kappa_{Z\gamma}$) is **positively** correlated to κ_γ (κ_H)



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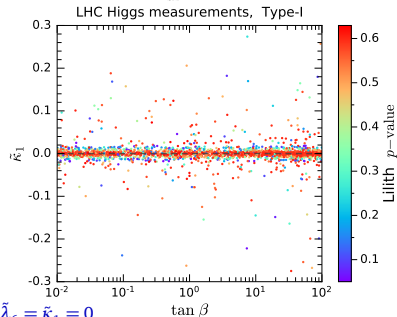
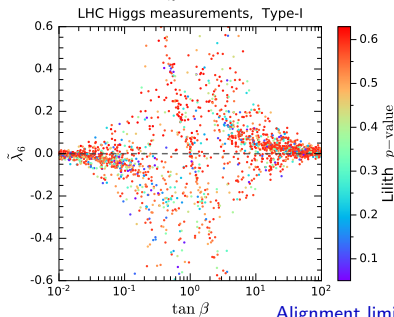
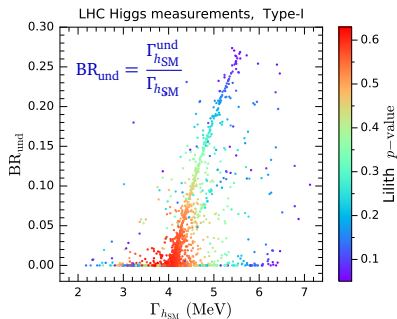
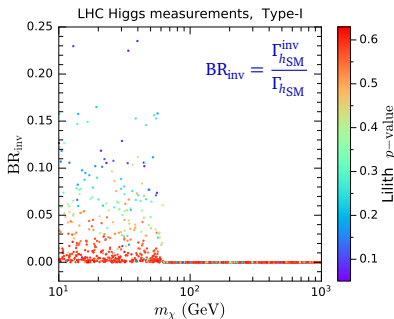
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$\kappa_V\kappa_f > 0$ satisfied, κ_g (κ_γ) is **positively** (**negatively**) correlated to $|\kappa_f|$

κ_H ($\kappa_{Z\gamma}$) is **positively** (**negatively**) correlated to $|\kappa_f|$



Alignment limit $\tilde{\lambda}_6 = \tilde{\kappa}_1 = 0$

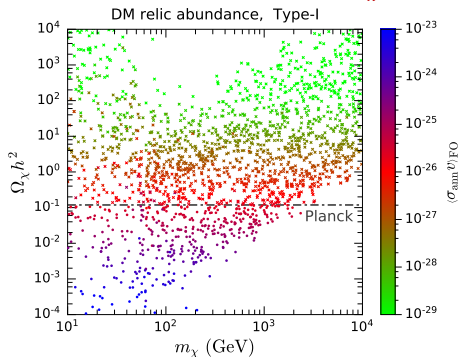
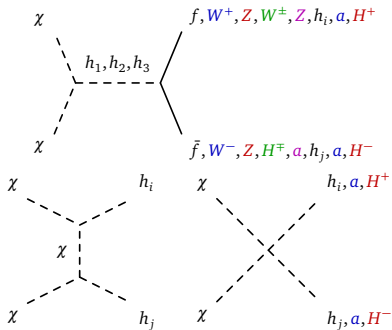
DM Relic Abundance

🎯 **Planck** observed DM relic abundance $\Omega_{\text{DM}} h^2 = 0.1186 \pm 0.0020$

[Planck coll., 1502.01589, Astron. Astrophys.]



Numerical tools: **FeynRules** ➡ **MadGraph** ➡ **MadDM** ➡ $\Omega_\chi h^2$



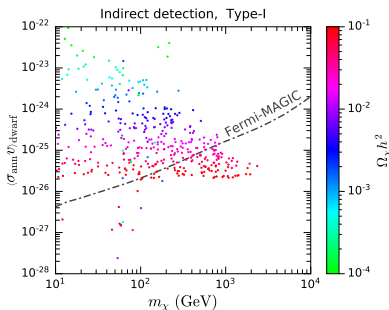
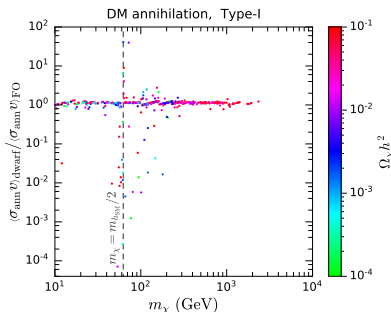
- **Colored dots:** $\Omega_\chi h^2$ is **equal or lower** than observation
- **Colored crosses:** χ is **overproduced**, contradicting standard cosmology
- For $m_\chi \gtrsim 3$ TeV, the observed relic abundance **could not** be achieved

Indirect Detection

✨ **Dwarf galaxies** are the **largest substructures** of the **Galactic dark halo**

👉 Perfect targets for **γ -ray indirect detection** experiments

🔧 We utilize **MadDM** to calculate $\langle\sigma_{\text{ann}}v\rangle_{\text{dwarf}}$ with a typical average velocity of DM particles in dwarf galaxies $\bar{v} = 2 \times 10^{-5}$



● $\langle\sigma_{\text{ann}}v\rangle_{\text{dwarf}}$ differs from the freeze-out value $\langle\sigma_{\text{ann}}v\rangle_{\text{FO}}$ due to **resonance effect**

● The parameter points with $m_\chi \gtrsim 100$ GeV and $\Omega_\chi h^2 \sim 0.1$ are **not excluded** by Fermi-LAT and MAGIC γ -ray observations [MAGIC & Fermi-LAT, 1601.06590, JCAP]

Conclusions

- We study the **pNGB DM framework** with two Higgs doublets
- Because of the pNGB nature of the DM candidate χ , the tree-level **DM-nucleon scattering amplitude vanishes** in direct detection
- We perform a random scan to find the parameter points consistent with **current Higgs measurements**
- Some parameter points with $100 \text{ GeV} \lesssim m_\chi \lesssim 3 \text{ TeV}$ can give an **observed relic abundance** and evade the constraints from **indirect detection**

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Thanks for your attention!