Dark Matter Aspects of Composite Higgs Models

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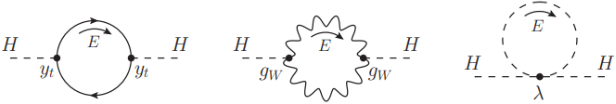
Motivation

Three open questions in particle physics:

- the Hierarchy problem



$$\delta m_H^2 \approx \frac{3y_t^2}{8\pi^2}\Lambda_{\text{SM}}^2$$

Λ_{SM}: scale at which New Physics emerges

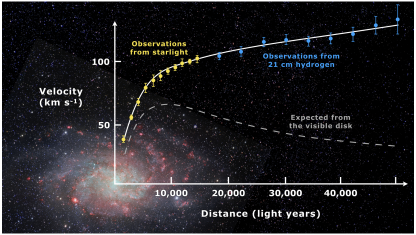
$\Rightarrow$ $\Lambda_{\text{SM}} \sim TeV$

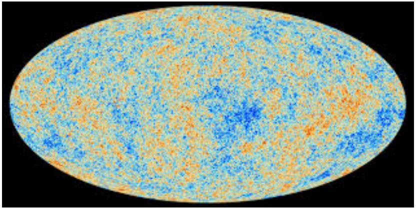
$\Rightarrow$ Composite Higgs (CH) models

Motivation

Three open questions in particle physics:

- Dark Matter (DM)





What we know about DM:

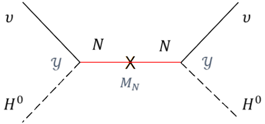
- ✓ $\sim 85\%$ of total matter content
- ✓ interacting gravitationally
- ✓ cold: non-relatvistic in eraly universe

Motivation

Three open questions in particle physics:

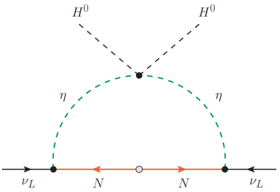
- Small neutrino masses ($m_\nu < 0.2$eV)

Canonical Seesaw:



- Introducing Majorana neutrino N
- Typical seesaw scale $M_N \sim \mathcal{O}(10^9)$GeV

Loop-level mass generation:



- A discrete $\mathbb{Z}_2$ symmetry
- Loop-level neutrino mass generation
- Loop suppression $\rightarrow$ reduced seesaw scale $M_N \sim$ TeV
- DM candidate protected by the $\mathbb{Z}_2$ symmetry

$\Rightarrow$ Scotogenic Models

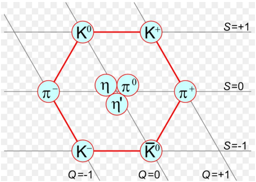
What is a Composite Higgs?

Goldstone's Theorem: A massless particle from each SB **global** symmetry

$$n_{\mathrm{NGB}} = \dim[\mathcal{G}] - \dim[\mathcal{H}]$$

	Chiral Symmetry	**CH**
$\mathcal{G}$	$\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R$	Eg. SU(4)
$\downarrow$ SSB	$\Lambda_{\mathrm{QCD}} \downarrow \langle \bar{q}_{Li} q_{Rj} \rangle \neq 0$	$m_* \downarrow \langle \bar{\psi}\psi \rangle \neq 0$
$\mathcal{H}$	$\mathrm{SU}(3)_V$	Sp(4)
Explicit SB:	m_q, Electromagnetism	m_ψ, gauge couplings, ...

pNGBs:



pNGBs		
$\mathrm{SU}(2)^2$	$\mathrm{SU}(2)_D$	name
(2,2)	3	φ
	1	H
(1,1)	1	η

Electroweak Symmetry Breaking in CH

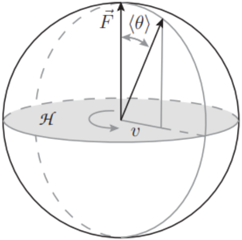


Figure: EWSB by vacuum misalignment

EWSB in CH

$$\mathcal{G} \xrightarrow{\text{SSB}} \mathcal{H} \quad \Rightarrow \text{Higgs}$$

$$SU(2)_L \times SU(2)_R \in \mathcal{H}$$

$$SU(2)_L \times SU(2)_R \xrightarrow{\text{Higgs vev}} SU(2)_V$$

θ: misalignment angle

$|\vec{F}|$: scale of CH symmetry breaking

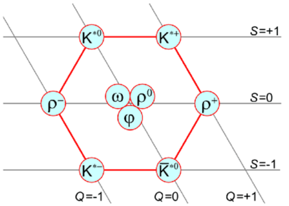
SM Higgs vev: $v_{EW} = |\vec{F}| \cdot \sin(\theta)$

Heavy Spin-1 Resonances in CH

$$\text{fermion + fermion} \quad \to \quad \text{scalar + vector}$$
$$\mathbf{2} \otimes \mathbf{2} \quad \to \quad \mathbf{1} \oplus \mathbf{3}$$

Chiral Symmetry

$SU(3)_L \times SU(3)_R \to SU(3)_V$



CH

Eg. SU(4)→Sp(4)

	$\mathcal{A}_\mu$			$\mathcal{V}_\mu$	
$SU(2)^2$	$SU(2)_D$	name	$SU(2)^2$	$SU(2)_D$	name
(2,2)	3	a_μ	(2,2)	3	$\hat{r}_\mu$
	1	$\hat{y}_{1\mu}$		1	$\hat{x}_{1\mu}$
(1,1)	1	$\hat{y}_{2\mu}$	(3,1)+(1,3)	3	$v_{1\mu}$
				3	$v_{2\mu}$

$$n_{\text{Ax}} = \dim[\mathcal{G}] - \dim[\mathcal{H}]$$
$$n_{\text{Vec}} = \dim[\mathcal{G}] - n_{\text{Ax}}$$

Recap

- the Hierarchy problem
  - $\Rightarrow$ Composite Higgs models
- Dark Matter (DM)
- Small neutrino masses
  - $\Rightarrow$ Scotogenic model

Composite Higgs Models: Higgs emerges as a pNGB of SSB of an approximate symmetry
Scotogenic Models: DM and neutrino masses simutaneously
My goal: realising Scotogenic Models within Composite Higgs scenario

Embedding EW Symmetry in SU(6)

hyper-fermions	$SU(2)_L \times SU(2)_R$	$SU(2)_L$	$SU(2)_R$	$\mathbb{Z}_2$
$\Psi_1 \equiv (\psi_1\ \psi_2)^T$	(2,1)	$SU(2)_1 + SU(2)_3$	$SU(2)_2$	+
$\Psi_2 \equiv (\psi_3\ \psi_4)^T$	(1,2)			+
$\Psi_3 \equiv (\psi_5\ \psi_6)^T$	(2,1)			-

$$SU(2)_L \text{ generatgors: } T_L^i = 1/2 \begin{pmatrix} \sigma^i & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \sigma^i \end{pmatrix}$$

$$SU(2)_R \text{ generatgors: } T_R^i = 1/2 \begin{pmatrix} 0 & 0 & 0 \\ 0 & -\sigma_i^T & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Vacuum Misalignment

EW Vacuum:

$$\langle\psi\psi\rangle \sim \Sigma_0 = \begin{pmatrix} i\sigma_2 & 0 & 0 \\ 0 & -i\sigma_2 & 0 \\ 0 & 0 & i\sigma_2 \end{pmatrix}$$

preserves the EW symmetry:

$U_L \cdot \Sigma_0 \cdot U_L^T = \Sigma_0$

$U_R \cdot \Sigma_0 \cdot U_R^T = \Sigma_0$

$$\xrightarrow[\text{pNGB vev}]{\text{explicit breaking}}$$

CH Vacuum:

$$\Sigma_\theta = \Omega(\theta) \cdot \Sigma_0 \cdot \Omega^T(\theta) = \begin{pmatrix} i\sigma_2 \cos\theta & \mathbb{I}_2 \sin\theta & 0 \\ -\mathbb{I}_2 \sin\theta & -i\sigma_2 \cos\theta & 0 \\ 0 & 0 & i\sigma_2 \end{pmatrix}$$

$\Omega(\theta) = \exp\left(\sqrt{2} i\theta X^H\right)$: rotation induced by Higgs

pNGBs

14 pNGBS in the SU(6)/Sp(6) coset:

	EW vacuum ($\theta = 0$)	CH vacuum ($\theta \neq 0$)
$\mathbb{G}_0/\mathbb{H}_0$	$H = (2,2)_+$ $\eta_1 = (1,1)_+$	$h = 1_+$ $\eta_1 = 1_+$
$\mathbb{Z}_2$–odd	$\Delta = (3,1)_-$ $\eta_3 = (1,1)_-$ $\Phi = (2,2)_-$	$\Delta^\pm, \Delta^0 = 3_-$ $\eta_3 = 1_-$ $\phi^\pm, \phi^0 = 3_-$ $\eta_4 = 1_-$
$\mathbb{Z}_2$–even	$\eta_2 = (1,1)_+$	$\eta_2 = 1_+$

Heavy Spin-1 Resonances

$$\mathcal{F}_\mu = \mathcal{A}_\mu + \mathcal{V}_\mu$$
$$\mathbf{35}_{\mathrm{SU(6)}} = \mathbf{14}_{\mathrm{Sp(6)}} + \mathbf{21}_{\mathrm{Sp(6)}}$$

	$\mathcal{V}_\mu$ name	$\mathrm{SU}(2)^2$	$\mathrm{SU}(2)_V$	$\mathcal{A}_\mu$ name	$\mathrm{SU}(2)^2$	$\mathrm{SU}(2)_V$
$\mathbb{G}_0/\mathbb{H}_0$	$v_{1\mu}$	$(3,1)\oplus(1,3)$	3	$a_{1\mu}$	(2,2)	3
	$v_{2\mu}$	$(3,1)\oplus(1,3)$	3	$y_{1\mu}$	(2,2)	1
	$r_{1\mu}$	(2,2)	3	$y_{2\mu}$	(1,1)	1
	$x_{1\mu}$	(2,2)	1			
$\mathbb{Z}_2$–odd	$r_{2\mu}$	(3,1)	3	$a_{2\mu}$	(3,1)	3
	$x_{2\mu}$	(1,1)	1	$y_{4\mu}$	(1,1)	1
	$r_{3\mu}$	(2,2)	3	$a_{3\mu}$	(2,2)	3
	$x_{3\mu}$	(2,2)	1	$y_{5\mu}$	(2,2)	1
$\mathbb{Z}_2$–even	$v_{3\mu}$	(3,1)	3	$y_{3\mu}$	(1,1)	1

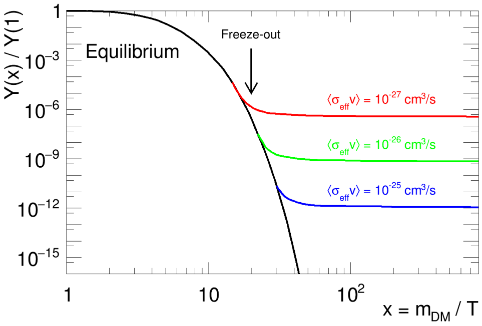
Relic Density: Freeze-Out

DM creation and annihilation:

$$\mathrm{SM} + \mathrm{SM} \leftrightarrow \mathrm{DM} + \mathrm{DM}$$

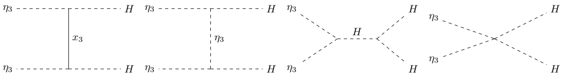
Boltzmann Eq.:

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{\mathrm{eq}}^2)$$

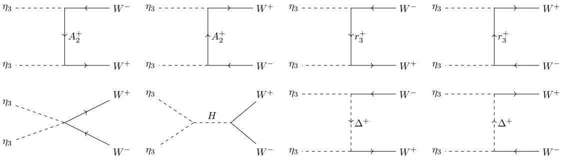


Dominant η_3 Annihilation Channels

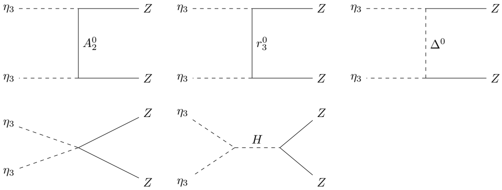
$\eta_3 + \eta_3 \to H + H$:



$\eta_3 + \eta_3 \to W^+ + W^-$:

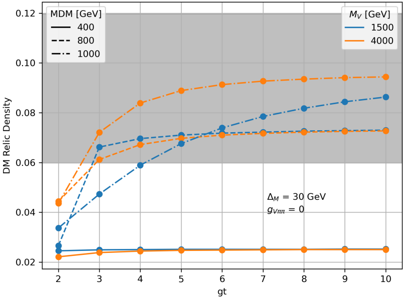


$\eta_3 + \eta_3 \to Z + Z$:

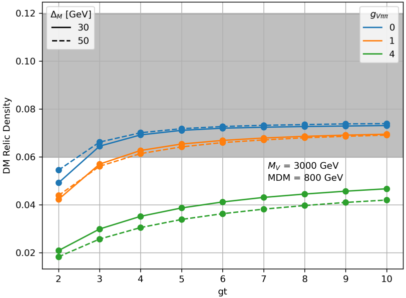


η_3 Freeze-Out Abundance

Parameters of the model: $m_{\rm DM}$, Δ_M, M_V, $\tilde{g}$, $g_{V\pi\pi}$, θ



(a) Ω vs. $\tilde{g}$ for difference $m_{\rm DM}$ and M_V



(b) Ω vs. $\tilde{g}$ for difference Δ_M and $g_{V\pi\pi}$

Conclusion

Observations:

- In CH models, Higgs appears as a pNGB of SSB of an approximate symmetry
- Dynamic EWSB due to the Higgs vev
- DM candidates among pNGBs in the SU(6)/Sp(6) coset
- Relic Density calculation favors large pNGB masses and decoupling limit

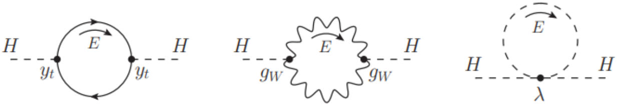
Next steps:

- Other bounds from DM aspects?
- Identifying Majorana neutrinos among the spin-1/2 bound states
- Constraints from neutrino masses and EW precision tests

Thank you for your attention!

The Hierarchy Problem

An open question in particle physics:



$$\delta m_H^2 = \int_0^{\lesssim \Lambda_{\mathrm{SM}}} dE\, \frac{dm_H^2}{dE}(E; p_{\mathrm{true}}) + \int_{\lesssim \Lambda_{\mathrm{SM}}}^{\infty} dE\, \frac{dm_H^2}{dE}(E; p_{\mathrm{true}})$$

$$= \delta_{\mathrm{SM}} m_H^2 + \delta_{\mathrm{BSM}} m_H^2$$

$$\approx \frac{3y_t^2}{8\pi^2}\Lambda_{\mathrm{SM}}^2 + ?$$

Electroweak Symmetry Breaking

Higgs Mechanism: SSB of a **gauge** symmetry $\rightarrow$ no Goldstone boson but mass of the gauge field.

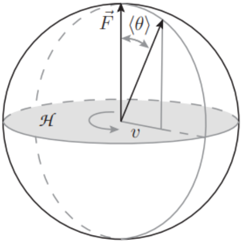


Figure: EWSB by vacuum misalignment[**Panico˙2016**]

Before Misalignment: $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \in \mathcal{H}$

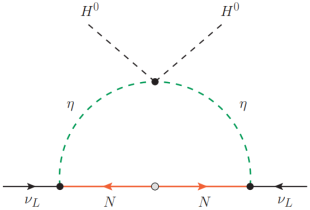
$\downarrow$ θ: misalignment angle

$v_{\mathrm{EW}} = |\vec{F}| \cdot \sin(\theta)$

After Misalignment: $\mathrm{SU}(2)_V \in \mathcal{H}'$

Scotogenic Models

Field	Generations	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
ℓ_L	3	**1**	**2**	$-1/2$	$+$
e_R	3	**1**	**1**	-1	$+$
H	1	**1**	**2**	$1/2$	$+$
η	n_η	**1**	**2**	$1/2$	$-$
N	n_N	**1**	**1**	0	$-$



$$\mathcal{L} \supset y_{na\alpha} \overline{N}_n \eta_a l_L^\alpha + \frac{1}{2} M_{N_n} \overline{N^c}_n N_n + \lambda \eta^2 H^2 + \text{h.c.}$$

Heavy Spin-1 Resonances

Hidden Symmetry Formulism

Introducing low energy spin-1 resonances:

$$
\begin{array}{ccccc}
\mathcal{G}_0 & & \mathcal{G}_1 & & \\
\downarrow \pi_0 & & \downarrow \pi_1 & & \pi_\mathrm{p}, \cancel{\pi_\mathrm{u}} \to \mathcal{A}_\mu \\
\mathcal{H}_0 & & \mathcal{H}_1 & & \pi_\mathrm{p}, \mathcal{A}_\mu \\
 & \searrow \quad \swarrow & & & \cancel{K} \to \mathcal{V}_\mu \\
 & \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \in \mathcal{H}_\mathrm{v} & & & \pi_\mathrm{p}, \mathcal{A}_\mu, \mathcal{V}_\mu \\
 & \downarrow \text{EWSB} & & & \\
 & \mathrm{SU}(2)_V & & & \pi_\mathrm{p} - 3, W_\mu^\pm, Z_\mu, \mathcal{A}_\mu, \mathcal{V}_\mu
\end{array}
$$

Mixing with the EW Bosons

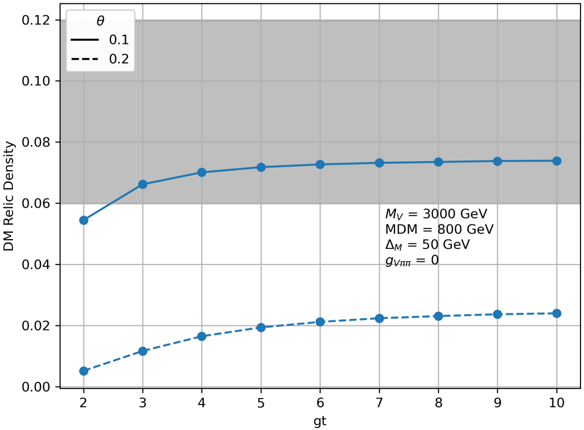
$$\begin{pmatrix} \widetilde{W}_\mu^+ \\ a_{1\mu}^+ \\ v_{1\mu}^+ \\ v_{2\mu}^+ \\ v_{3\mu}^+ \end{pmatrix} = \mathcal{C} \begin{pmatrix} W_\mu^+ \\ A_{1\mu}^+ \\ V_{1\mu}^+ \\ V_{2\mu}^+ \\ V_{3\mu}^+ \end{pmatrix}, \qquad \begin{pmatrix} B_\mu \\ \widetilde{W}_\mu^3 \\ a_{1\mu}^0 \\ v_{1\mu}^0 \\ v_{2\mu}^0 \\ v_{3\mu}^0 \end{pmatrix} = \mathcal{N} \begin{pmatrix} A_\mu \\ Z_\mu \\ A_{1\mu}^0 \\ V_{1\mu}^0 \\ V_{2\mu}^0 \\ V_{3\mu}^0 \end{pmatrix}$$

Interactions

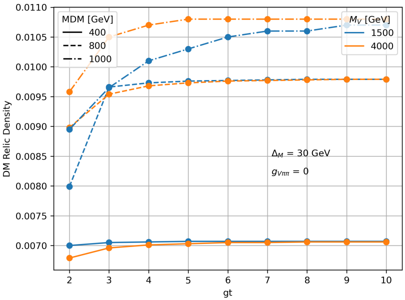
$$
\begin{aligned}
\mathrm{i}U_i^\dagger D_\mu U_i \approx & i(\mathbb{I}_6 - \frac{i\sqrt{2}}{f_i}\Pi - \frac{1}{f_i^2}\Pi^2)(\partial_\mu - i\mathcal{F}_\mu)(\mathbb{I}_6 + \frac{i\sqrt{2}}{f_i}\Pi - \frac{1}{f_i^2}\Pi^2) \\
= & - i\mathcal{F}_\mu \\
& + \frac{1}{f_i}(i\sqrt{2}\partial_\mu\Pi + \sqrt{2}\mathcal{F}_\mu\Pi - \sqrt{2}\Pi\mathcal{F}_\mu) \\
& + \frac{1}{f_i^2}(i\mathcal{F}_\mu\Pi^2 + i\Pi^2\mathcal{F}_\mu - 2i\Pi\mathcal{F}_\mu\Pi) \\
& + \mathcal{O}(\frac{1}{f_i^3})
\end{aligned}
$$

$$\Rightarrow V_\mu V^\mu + \pi V_\mu V^\mu + \pi\pi + \pi\partial_\mu\pi V^\mu + \pi\pi V_\mu V^\mu$$

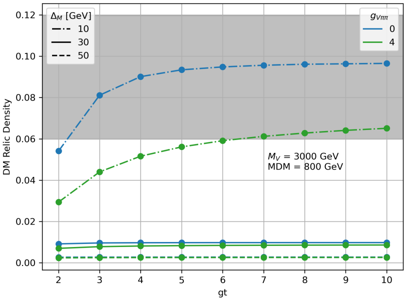
η_3 Freeze-Out Abundance



η_4 Freeze-Out Abundance



(a) Ω vs. $\tilde{g}$ for difference m_{DM} and M_V



(b) Ω vs. $\tilde{g}$ for difference Δ_M and $g_{V\pi\pi}$