The Minimal Simple Composite Higgs Model

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Based on arXiv:1904.02560 [hep-ph], w/ L. Da Rold
The main idea behind CHM

SM

NP
The main idea behind CHM

SM

NP

\[ G \xrightarrow{\text{SSB}} H \]
The main idea behind CHM

SM \[\xrightarrow{\text{INT}}\] NP

\[G \xrightarrow{\text{SSB}} H\]
The main idea behind CHM

Why a non-minimal CHM?
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Why a non-minimal CHM?

- LHC results constrain severely the MCHM.
The main idea behind CHM

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- LHC results constrain severely the MCHM.
- Non-minimal CHMs satisfy the bounds better.
Why a non-minimal CHM?

- LHC results constrain severely the MCHM
- Non-minimal CHMs satisfy the bounds better
- Different and rich phenomenology, less explored.
Minimal CHM

$\text{SO}(5) \times U(1)_X / \text{SO}(4) \times U(1)_X$

Agashe et al (hep-ph/0412089)
Minimal CHM

\[ \text{SO}(5) \times U(1)_X / \text{SO}(4) \times U(1)_X \]

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Next to MCHM

\[ \text{SO}(6) \times U(1)_X / \text{SO}(5) \times U(1)_X \]

Gripaios et al (0902.1483)
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SO(7) CHM

$\text{SO}(7) \times \text{U}(1)_X / \text{SO}(6) \times \text{U}(1)_X$

Chala et al (1605.08663), Balkin et al (1707.07685, 1809.09106)
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SO(7) CHM

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Nevertheless...
SO(7) ⊂ SO(6) ⊂ SO(4) × U(1)
$\text{SO}(7) \supset \text{SO}(6) \supset \text{SO}(4) \times \text{U}(1)$

$\text{SO}(7) \times \text{U}(1)_X \big/ \text{SO}(6) \times \text{U}(1)_X$
$\text{SO}(7) \supset \text{SO}(6) \supset \text{SO}(4) \times \text{U}(1)$

$\text{SO}(7) \times \text{U}(1)_X \not\sim \text{SO}(6) \times \text{U}(1)_X$
\[
\text{SO}(7) \supset \text{SO}(6) \supset \text{SO}(4) \times \text{U}(1)
\]

\[
\text{SO}(7) \times \text{U}(1)_X \not\twoheadrightarrow \text{SO}(6) \times \text{U}(1)_X
\]

\[
\text{SO}(7) / \text{SO}(6)
\]

The Minimal Simple CHM
\[ \text{SO}(7) \supset \text{SO}(6) \supset \text{SO}(4) \times \text{U}(1) \]

\[ \text{SO}(7) \times \text{U}(1) \times \text{SO}(6) \times \text{U}(1) \]

\[ \text{SO}(7) / \text{SO}(6) \]

**The Minimal Simple CHM**

✓ Simple Lie groups
The Minimal Simple CHM

- Simple Lie groups
- Higgs doublet
The Minimal Simple CHM

\[ \text{SO}(7) \supset \text{SO}(6) \supset \text{SO}(4) \times \text{U}(1) \]

\[ \text{SO}(7) \times \text{U}(1)_X \bigg/ \text{SO}(6) \times \text{U}(1)_X \]

The Minimal Simple CHM

- Simple Lie groups
- Higgs doublet
- Custodial Symmetry
The Minimal Simple CHM

\[ \text{Simple Lie groups} \]
\[ \text{Higgs doublet} \]
\[ \text{Custodial Symmetry} \]
\[ \text{Unifies EW group} \]
What are the pNGBs there like?
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\[ \text{SO}(6) \times (\text{SU}(2)_L, \text{SU}(2)_R)_X \]

\[ 6 \sim (2, 2)_0 + (1, 1)_{\pm 1/\sqrt{2}} \]
What are the pNGBs there like?

$$\text{SO}(6) \times (\text{SU}(2)_L, \text{SU}(2)_R)_X$$

$$6 \sim (2, 2)_0 + (1, 1)_{\pm 1/\sqrt{2}}$$

↓

Higgs boson

↓

$\chi$ boson
What are the pNGBs there like?

\[
SO(6) \quad (SU(2)_L, SU(2)_R)_X \\
6 \sim (2, 2)_0 + (1, 1)_{\pm 1/\sqrt{2}}
\]

\[
\downarrow \quad \downarrow
\]

Higgs boson \quad \chi \text{ boson}

EW embedding
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\[ \downarrow \quad \text{Higgs boson} \]

\[ \downarrow \quad \chi \text{ boson} \]

**EW embedding**

\[ Y = T_R^3 + \frac{2\sqrt{2}}{3} X \]

\[ Q = T_L^3 + Y \]
What are the pNGBs there like?

\[ \text{SO}(6) \rightarrow (\text{SU}(2)_L, \text{SU}(2)_R)_X \]

\[ 6 \sim (2, 2)_0 + (1, 1)_{\pm 1/\sqrt{2}} \]

\[ \downarrow \quad \text{Higgs boson} \quad \downarrow \quad \chi \text{ boson} \]

**EW embedding**

\[ Y = T^3_R + \frac{2\sqrt{2}}{3} X \]

\[ Q = T^3_L + Y \]

\[ \text{H: } 2 \frac{1}{2} \]

\[ \chi: 1 \frac{2}{3} \]

\[ SU(2)_L \times U(1)_Y \]
Parameter space scan

\[ m_h \text{ [TeV]} \]

\[ m_\chi \text{ [TeV]} \]

\[ \langle \chi \rangle = 0 \quad \langle h \rangle > 0 \]
Resonances

Vector bosons

$|Q| = 0, 1/3, 2/3, 1, 5/3$

Dirac fermions

$|Q| = 0, 1/3, 2/3, 1, 5/3$
Resonances

Vector bosons

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Dirac fermions

$|Q| = 0, 1/3, 2/3, 1, 5/3$

$$\xi = \left( \frac{v}{f} \right)^2 = \sin^2 \left( \frac{\langle h \rangle}{f} \right)$$
Decay width and BRs

\[ \xi = \left( \frac{v}{f} \right)^2 = \sin^2 \left( \frac{\langle h \rangle}{f} \right) \]
Higgs self-couplings
Exotic stable particle
Exotic stable particle

$\chi$

$|Q| = 2/3$
Exotic stable particle

$\chi$  
$|Q| = 2/3$

$\psi$  
$|Q| = 0$

Quorn

De Luca et al (1801.01135)  
Gross et al (1811.08418)
Conclusions
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Conclusions

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4. Suppression in Higgs couplings, decay and production amplitudes of order 5-10%.
5. Stronger suppression in Higgs self couplings.
Conclusions

1. We built a new CHM based on the minimal coset of simple Lie groups that gives the Higgs with the right charges.
2. This model is phenomenologically viable.
3. New particles with exotic charges appear.
4. Suppression in Higgs couplings, decay and production amplitudes of order 5-10%.
5. Stronger suppression in Higgs self couplings.
6. There is an exotic stable particle, which might be a DM candidate.
Thank you!

Any question?
SO(7) irreps decomposed... 
  ...into SO(6)

\[ 7 \sim 6 + 1 \quad 21 \sim 15 + 6 \quad 35 \sim 15 + 10 + \overline{10} \]

...into SU(2) \times SU(2) \times U(1)

\[ 10 \sim (2, 2)_0 + (3, 1)_{1/\sqrt{2}} + (1, 3)_{-1/\sqrt{2}} \]

\[ 15 \sim (2, 2)_{\pm 1/\sqrt{2}} + (3, 1)_0 + (1, 3)_0 + (1, 1)_0 \]

\[ 21_{SO(7)} = (3, 1)_0 \oplus (1, 3)_0 \oplus (1, 1)_0 \oplus (2, 2)_{\frac{1}{\sqrt{2}}} \]

\[ \oplus (2, 2)_{-\frac{1}{\sqrt{2}}} \oplus (2, 2)_0 \oplus (1, 1)_{\frac{1}{\sqrt{2}}} \oplus (1, 1)_{-\frac{1}{\sqrt{2}}} \]
SM fermions embedding and Partial compositeness

| Field | $T^3_R$ | $\text{SO}(4) \times \text{U}(1)_X$ | $\text{SO}(6)$ | $\text{SO}(7)$ |
|-------|---------|-----------------------------------|----------------|----------------|
| $q$   | -1/2    | $(2, 2)_{1/\sqrt{2}}$             | 15             | 21             |
| $u$   | 0       | $(1, 3)_{1/\sqrt{2}}$             | $\overline{10}$| 35             |
| $d$   | -1      | $(1, 3)_{1/\sqrt{2}}$             | $\overline{10}$| 35             |
| $\ell$| -1/2    | $(2, 2)_0$                        | 6              | 7              |
| $e$   | -1      | $(1, 3)_0$                        | 15             | 21             |

\[
M \mathcal{E}_\psi = \cos(\theta_\psi) \psi + \sin(\theta_\psi) \mathcal{C}_\psi
\]

\[
y_\psi \sim y_\psi \, \sin(\theta_\psi) \sin(\hat{\theta}_\psi) \quad m_\psi \sim y_\psi \, u
\]

\[
\tan(\theta_\psi) = \frac{f_0 \lambda_\psi}{m_\psi}
\]
2-site model

Elementary sector. Copy of the SM without the Higgs.

\[ \mathcal{L}_{\text{Mixing}} \supset \lambda \bar{\psi}_{SM} \hat{O}_{NP} \]

It generates the potential for the NGB. Partial compositeness for all the fermions.

\[ \xi = \left( \frac{v}{f} \right)^2 = \sin^2 \left( \frac{\langle h \rangle}{f} \right) \]
Site 1, mixing and pNGBs

\[
\mathcal{L}_1 = -\frac{1}{4g_1^2} F^a_{\mu\nu} F^{a,\mu\nu} + \frac{f_1^2}{4} d^a_{\mu} d^{\dot{a}}_{\mu} + \bar{Q}(\not{D} - m_Q)Q + \bar{U}(\not{D} - m_U)U + \bar{D}(\not{D} - m_D)D \\
+ \bar{L}(\not{D} - m_L)L + \bar{E}(\not{D} - m_E)E + f_1 y_U [(\bar{Q}_L U_1)_{15}(U_1^\dagger U_R)_{15}]_1 \\
+ f_1 y_D [(\bar{Q}_L U_1)_{15}(U_1^\dagger D_R)_{15}]_1 + f_1 y_E [(\bar{L}_L U_1)_{6}(U_1^\dagger E_R)_{6}]_1 + \text{h.c.}
\]

\[
\mathcal{L}_{\text{mix}} = \frac{f_0^2}{4} |D_\mu \Omega|^2 + f_0 \sum_i \lambda_i \bar{\psi}_i \Omega \Psi_i + \text{h.c.}
\]

\[
\psi_i = q, u, d, \ell, e \ , \quad \Psi_i = Q, U, D, L, E \ ,
\]

\[
\Gamma_1^2 = \sum (\Pi_1^\hat{\dagger})^2 \quad U_1^\dagger D_\mu U_1 = i e^a_{\mu} T^a + i d^\hat{a}_{\mu} T^{\hat{a}} \\
\Omega = e^{i\sqrt{2}\Pi_0/f_0} \bigg| U_1 = e^{i\sqrt{2}\Pi_1/f_1} \bigg| \quad \Pi_1 = \Pi_1^\hat{\dagger} T^{\hat{a}}
\]

\[
U_1 = I + i \frac{\sin(\Gamma_1/f_1)}{\Gamma_1} \Pi_1 + 2 \frac{\cos(\Gamma_1/f_1) - 1}{\Gamma_1^2} \Pi_1^2
\]
Physical pNGBs and EW bosons identification

\[ U = e^{i\sqrt{2}\Pi/f} , \quad \Pi = \Pi^a T^a , \quad \frac{1}{f^2} = \frac{1}{f_0^2} + \frac{1}{f_1^2} \]

\[ \frac{1}{g^2} = \frac{1}{g_0^2} + \frac{1}{g_1^2} \quad \frac{1}{g'^2} = \frac{17}{9} \left( \frac{1}{g_0'^2} + \frac{1}{g_1'^2} \right) \]

\[ W^i_\mu = \cos (\varphi) \, w^i_\mu + \sin (\varphi) \, A^{L,i}_\mu \]

\[ B_\mu = \cos (\omega) \, b_\mu + \sin (\omega) \, \left[ \cos (\theta_Y) \, A^{R,3}_\mu + \sin (\theta_Y) \, A^X_\mu \right] \]

\[ \tan (\varphi) = \frac{g_0}{g_1} \quad \tan (\omega) = \frac{g_0'}{g_1} \quad \tan (\theta_Y) = \alpha = \frac{2\sqrt{2}}{3} \]

\[ D_\mu \Omega = \partial_\mu \Omega - i A^0 A T^A \Omega + i A^1 A \Omega T^A \]
| Name   | Mass                                      | $|Q_{em}|$                      | Multiplicity |
|--------|-------------------------------------------|------------------------------|--------------|
| $m^1_A$ | $\frac{f_0 g_1}{\sqrt{2}}$               | $\{0, 1/3, 2/3, 1, 5/3\}$  | $\{1, 2, 4, 2, 2\}$ |
| $m^2_A$ | $f_0 \sqrt{\frac{g_0^2 + g_1^2}{2}} + \epsilon$ | 0                            | 1            |
| $m^3_A$ | $f_0 \sqrt{\frac{g_0^2 + g_1^2}{2}} + \eta$ | 1                            | 2            |
| $m^4_A$ | $f_0 \sqrt{\frac{g_0^2 + g_1^2}{2}} + \Delta$ | 0                            | 1            |
| $m^5_A$ | $g_1 \sqrt{\frac{f_0^2 + f_1^2}{2}}$     | $\{2/3, 0\}$                | $\{2, 1\}$  |
| $m^6_A$ | $g_1 \sqrt{\frac{f_0^2 + f_1^2}{2}} + \delta$ | 1                            | 2            |
| $m^7_A$ | $g_1 \sqrt{\frac{f_0^2 + f_1^2}{2}} + \alpha$ | 0                            | 1            |
# Fermion resonances spectrum

| Name   | $Q_{em}$                                      | Number of Dirac fermions |
|--------|-----------------------------------------------|--------------------------|
| $m^1_F$ | $\{0, \pm 1, -2/3\}$                        | $\{2, 2, 1\}$           |
| $m^2_F$ | $\{0, \pm 1/3, 2/3, -2/3, \pm 1, \pm 5/3\}$ | $\{4, 4, 1, 2, 4, 4\}$  |
| $m^3_F$ | $2/3$                                         | $1$                      |
| $m^4_F$ | $2/3$                                         | $1$                      |
| $m^5_F$ | $2/3$                                         | $1$                      |
| $m^6_F$ | $2/3$                                         | $1$                      |
| $m^7_F$ | $2/3$                                         | $1$                      |
| $m^8_F$ | $2/3$                                         | $1$                      |
| $m^9_F$ | $\{0, 1/3, -2/3, \pm 1, \pm 5/3\}$          | $\{3, 1, 2, 4, 2\}$     |
| $m^{10}_F$ | $\{0, 1/3, -2/3, \pm 1, \pm 5/3\}$         | $\{3, 1, 2, 4, 2\}$     |
| $m^{11}_F$ | $-\frac{1}{3}$                            | $1$                      |
| $m^{12}_F$ | $-\frac{1}{3}$                            | $1$                      |
Effective theory

\[ \mathcal{L}_{\text{eff}} \supset \frac{f^2}{4} d_{\mu}^{\dagger} d_{\mu}^{\dagger} + \sum_{r=6,15} \Pi_r(p^2)(U^{\dagger} a_{\mu})_r(U^{\dagger} a^{\mu})_r + \sum_{i=q,u,d,\ell,e} \sum_{r} \Pi_r^{i}(p^2)(U^{\dagger} \psi_i)_r \not \psi_i (U^{\dagger} \psi_i)_r \]

\[ + \sum_{i=u,d} \sum_{r} M_r^{i}(p^2)(U^{\dagger} \psi_q)_r(U^{\dagger} \psi_i)_r + \sum_{r} M_r^{u}(p^2)(U^{\dagger} \psi_{\ell})_r(U^{\dagger} \psi_e)_r . \]

\[ \mathcal{L}_{\text{eff}} \supset \frac{1}{2}[Z_w + \Pi_w(p^2)] w^i_\mu w^{\mu i} + \frac{1}{2}[Z_b + \Pi_b(p^2)] b_\mu b^{\mu} + \Pi_{ib}(p^2) w^i_\mu b^{\mu} \]

\[ + \bar{q}_L \not \psi (Z_q + \Pi_q) q_L + \sum \bar{\psi}_R \not \psi (Z_\psi + \Pi_\psi) \psi_R + \bar{q}_L M_{q\psi} \psi_R + \text{h.c.} \]

CW potential

\[ V = \int \frac{d^4 p}{(2\pi)^4} \left( -2N_c \ln \left[ \frac{\det [A_F]}{\det [A_F|_0]} \right] + \frac{3}{2} \ln \left[ \frac{\det [A_B]}{\det [A_B|_0]} \right] \right) \]

\[ V = m_H^2 H^2 + m_\chi^2 \chi^2 + \lambda_H H^4 + \lambda_{H\chi} H^2 \chi^2 + \lambda_\chi \chi^4 + \mathcal{O}(\phi^6) \]
Parameter space scan

\[ f_{0,1} \sim 1 \text{ TeV} \quad m_{U,Q} \in (0.5, 10) \text{ TeV} \]
\[ \theta_{q,u} \in (0.4, \pi/2) \quad y_U \in (0.1, 3) \quad g_1 \in (1, 6) \]
\[ g = 0.65 \quad g' = 0.35 \quad \langle \chi \rangle = 0 \quad 0 < \xi < 1 \]

Benchmark points criteria

\[ \nu = 246 \text{ GeV} \quad f_0 g_1 > 2 \text{ TeV} \quad 100 \text{ GeV} < m_H < 145 \text{ GeV} \]
\[ 140 \text{ GeV} < m_t < 175 \text{ GeV} \quad \xi < 0.25 \]

Point for systematic scan

\[ f_0 = 1.47 \text{ TeV} \quad f_1 = 2.34 \text{ TeV} \quad m_U = 2.44 \text{ TeV} \]
\[ m_Q = 1.26 \text{ TeV} \quad \theta_u = 0.79 \quad \theta_q = 1.37 \]
\[ g_1 = 1.95 \quad y_U = 2.52 \]
Yukawa couplings

\[ \frac{y}{y^{SM}} \]

\[ \sqrt{1 - \xi} \]

- Top
- Bottom

\[ \sqrt{\xi} \]
Higgs- EW vector bosons couplings

\[
\frac{g}{g_{\text{SM}}} \quad \sqrt{1 - \xi} \quad 1 - 2\xi
\]
Corrections w.r.t. the SM couplings

\[ \frac{y^{(0)}_{\psi}}{m^{(0)}_{\psi}} \sim \frac{F_{\psi}(\xi)}{\sqrt{\xi f}} \left[ 1 + \mathcal{O} \left( \frac{\lambda_{\psi L}^2 f^2}{m_{\psi}^2}, \frac{\lambda_{\psi R}^2 f^2}{m_{\psi}^2} \right) \right] \]

\[ F_u = F_d = F_e = \sqrt{1 - \xi} \]

\[ \frac{y_d}{m_d} \sim \frac{F_d}{\sqrt{\xi f}} \left[ 1 - \xi \frac{f_1^2 y_d^2}{4} \frac{\sin^2(\theta_d)}{m_Q^2} + \mathcal{O} \left( \sin^4(\theta_{q,d}) \right) \right] \]

\[ \frac{y_u}{m_u} \sim \frac{F_u}{\sqrt{\xi f}} \left[ 1 + \xi \frac{f_1^2 y_U^2}{4} \left( \frac{\sin^2(\theta_q)}{m_U^2} - \frac{\sin^2(\theta_u)}{m_Q^2} \right) + \mathcal{O} \left( \sin^4(\theta_{q,u}) \right) \right] \]

\[ \frac{g_{\text{SM}}^{WWh}}{g_{\text{SM}}^{WWhh}} \sim \sqrt{1 - \xi} \left\{ 1 + \xi \frac{3}{4} \frac{g_0^2}{(g_0^2 + g_1^2)^2} \frac{f_4^4}{f_0^4 f_1^4} \left[ f_1^2 g_1^2 + f_0^2 (g_0^2 + 2g_1^2) \right] \right\} \]

\[ \frac{g_{\text{SM}}^{WWhh}}{g_{\text{SM}}^{WWhh}} \sim 1 - 2\xi + \xi (3 - 4\xi) \frac{g_0^2}{g_0^2 + g_1^2} \frac{g_1^2 f_1^2}{f_0^2 + f_1^2} + f_0^2 \]
Vector boson fusion

$q \rightarrow z/w \rightarrow H$

$ttH$ and gluon fusion
Decay to photons
\[ c_{gg\chi^2} = \sum_{\psi,n} \frac{y_{\psi\chi^2}^{(n)}}{m_{\psi}^{(n)}} A_{1/2} \left( \frac{Q^2}{(2m_{\psi}^{(n)})^2} \right) \]
Dipole operator

$$\Gamma_{rst}(p^2) \left[ (U^\dagger \psi_L)_r (U^\dagger a_{\mu\nu})_s \sigma^{\mu\nu} (U^\dagger \psi_R)_t \right]_1$$

SO(7) generators

$$(T_{ij})_{k\ell} = \frac{i}{\sqrt{2}} (\delta_{ik} \delta_{j\ell} - \delta_{i\ell} \delta_{jk}), \quad i < j, \quad i = 1, \ldots 6, \quad j = 2, \ldots 7$$

$$T_1^L = -\frac{1}{\sqrt{2}} (T_{23} + T_{14}) \quad T_2^L = \frac{1}{\sqrt{2}} (T_{13} - T_{24}) \quad T_3^L = -\frac{1}{\sqrt{2}} (T_{12} + T_{34})$$

$$T_1^R = -\frac{1}{\sqrt{2}} (T_{23} - T_{14}) \quad T_2^R = \frac{1}{\sqrt{2}} (T_{13} + T_{24}) \quad T_3^R = -\frac{1}{\sqrt{2}} (T_{12} - T_{34})$$

$$X = T_{67}.$$ 

$$7 \otimes 21 \sim 7 \oplus 35 \oplus 105$$