Near-conformal dynamics in a chirally broken system

[arXiv:2007.01810]

Oliver Witzel
Lattice Strong Dynamcis collaboration

University of Colorado
Boulder

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introduction

Composite Higgs models: general idea

- Extend the Standard Model by a new, strongly coupled gauge-fermion system
- The Higgs boson arises as bound state of this new sector
  → Mass and quantum numbers match experimental values
    when accounting for SM interactions/corrections
- System exhibits a large separation of scales
  → Explaining why a 125 GeV Higgs boson but no other states have been found
  → Indications that such a system cannot be QCD-like (e.g. quark mass generation)
    ⇝ near-conformal gauge theories
- Exhibits mechanism to generate masses for SM fermions and gauge bosons
- In agreement with electro-weak precision constraints (e.g. S-parameter)?
- Mass-split models can accomodate the Higgs both as dilaton-like (0^{++}) or pNGB particle

Mass-split models

- Promising candidates are chirally broken in the IR but conformal in the UV
  [Luty, Okui JHEP09(2006)070], [Dietrich, Sannino PRD75(2007)085018], [Vecchi 1506.00623], [Ferretti, Karateev JHEP03(2014)077]

UV → IR

	conformal		chirally broken
Λ_{UV}	fermion masses	Λ_{IR}	Higgs dynamics

- Mass-split models e.g. SU(3) gauge theory with "heavy" and "light" (massless) fundamental flavors
  - Add $N_h = 6$ heavy flavors to push the system near an IRFP of a conformal theory
    ↓
    heavy flavors could be invisible to SM
  - $N_\ell = 4$ light flavors are chirally broken in the IR
    ↓
    fundamental composite 2HDM with 4 flavors in SU(3) gauge [Ma, Cacciapaglia JHEP03(2016)211]

The mass-split paradigm

- In QCD: $g^2 \to 0$ (continuum limit); fermion mass $m_f \to 0$ (chiral limit)

- Theory with degenerate $N_f = N_h + N_\ell$ is (mass-deformed) conformal and exhibits an IRFP
  - All ratios of hadron masses scale with the anomalous dimension (hyperscaling)
  - → Continuum limit is taken by sending fermion mass $m_f \to 0$

- Mass-split models live in the basin of attraction of the IRFP of N_f degenerate flavors
  - → Inherit hyperscaling of ratios of hadron masses but are chirally broken
  - → Continuum limit: $m_h \to 0$ keeping m_ℓ/m_h fixed
  - → Chiral limit: $m_\ell \to 0$ i.e. $m_\ell/m_h \to 0$
  - → Gauge coupling is irrelevant
  - → No free parameters after taking the chiral and continuum limit,
    but light-light, heavy-light, and heavy-heavy bound states

[Hasenfratz, Rebbi, OW PLB773(2017)86]

hyperscaling

Deriving hyperscaling from Wilsonian Renormalization Group

- In the UV: $\widehat{m}_\ell,\ \widehat{m}_h \ll \Lambda_{cut} = 1/a$ and $\widehat{m}_\ell \ll 1,\ \widehat{m}_h \ll 1$
- Lowering the energy scale μ from Λ_{cut}, RG flowed lattice action moves in the infinite parameter action space as dictated by the fixed point structure of the N_f conformal theory
- Masses scale according to their scaling dimension: $\widehat{m}_{\ell,h} \to \widehat{m}_{\ell,h}\,(a\mu)^{-y_m}$
  $\to$ Assuming masses are still small so the system remains close to the conformal critical surface
- Gauge couplings take their IRFP value i.e. only masses change under RG flow
- Physical quantities of mass dimension one follow at leading order the scaling form

$$aM_H = \widehat{m}_h^{1/y_m}\ \Phi_H(\widehat{m}_\ell/\widehat{m}_h)$$

Hyperscaling of hadronic masses

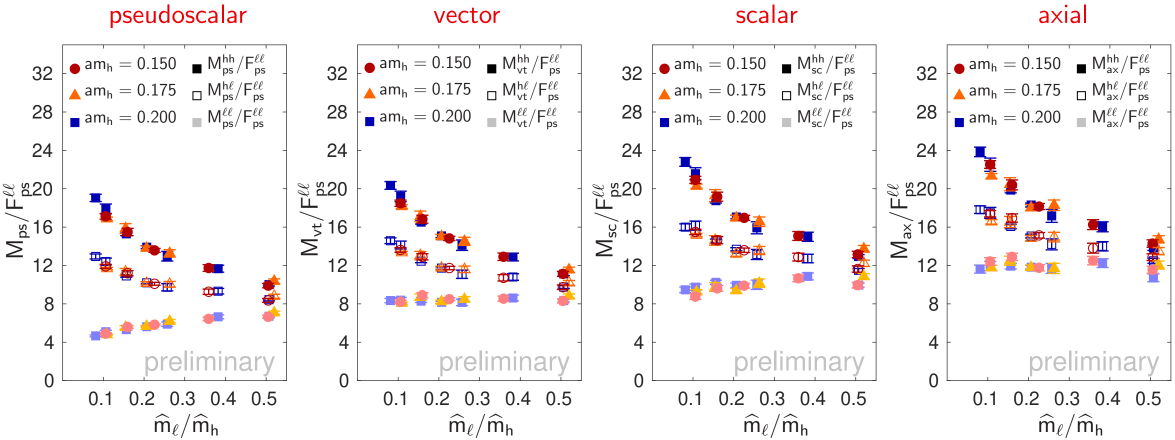
- Hyperscaling relation

$$aM_H = \widehat{m}_h^{1/y_m}\,\Phi_H(\widehat{m}_\ell/\widehat{m}_h) \quad\Rightarrow\quad \frac{M_{H1}}{M_{H2}} = \frac{\Phi_{H1}(\widehat{m}_\ell/\widehat{m}_h)}{\Phi_{H2}(\widehat{m}_\ell/\widehat{m}_h)}$$

→ aM_H lattice hadron masses
(physical quantity of mass dimension)
→ $\widehat{m}_h$ lattice fermion mass
$\widehat{m}_x \equiv a\widetilde{m}_x = a(m_x + m_{\text{res}}),\ x = \ell,\ h$
→ $y_m = 1 + \gamma_m^*$ scaling dimension
→ Φ_H some function of $\widehat{m}_l/\widehat{m}_h$

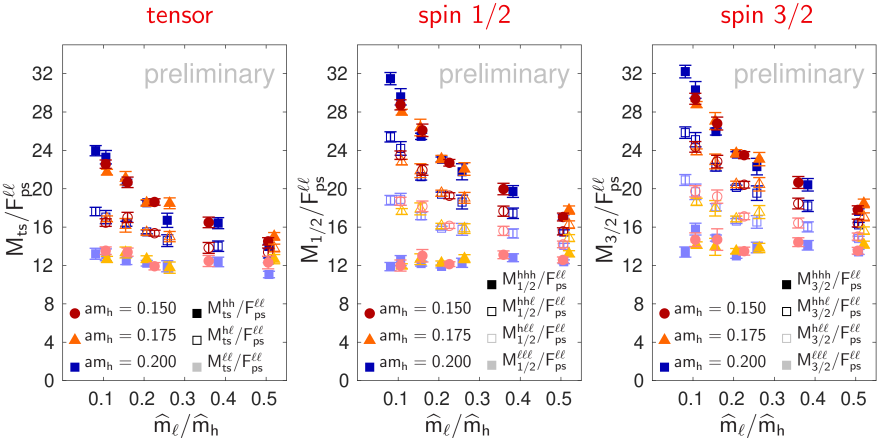
→ Ratios depend only on $\widehat{m}_l/\widehat{m}_h$

Ratios over $F_{ps}^{\ell\ell}$ (I)



- light-light ($\ell\ell$), heavy-light ($h\ell$), heavy-heavy (hh) states

Ratios over $F_{ps}^{\ell\ell}$ (II)

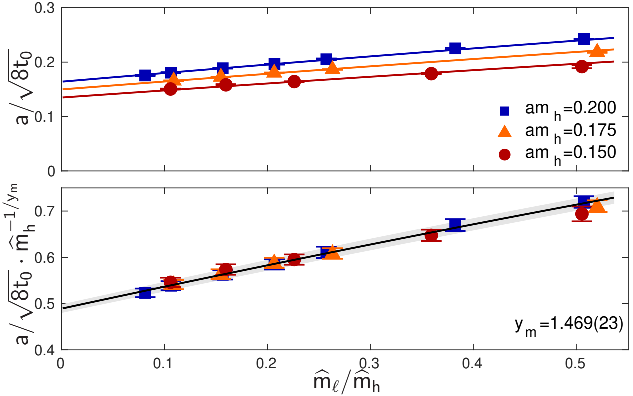


- light-light-light ($\ell\ell\ell$), heavy-light-light ($h\ell\ell$), heavy-heavy-light ($hh\ell$), heavy-heavy-heavy (hhh) states

Determine y_m from hyperscaling relation: $a/\sqrt{8t_0}$

$$aM_H = \widehat{m}_h^{1/y_m}\, \Phi_H(\widehat{m}_\ell/\widehat{m}_h)$$

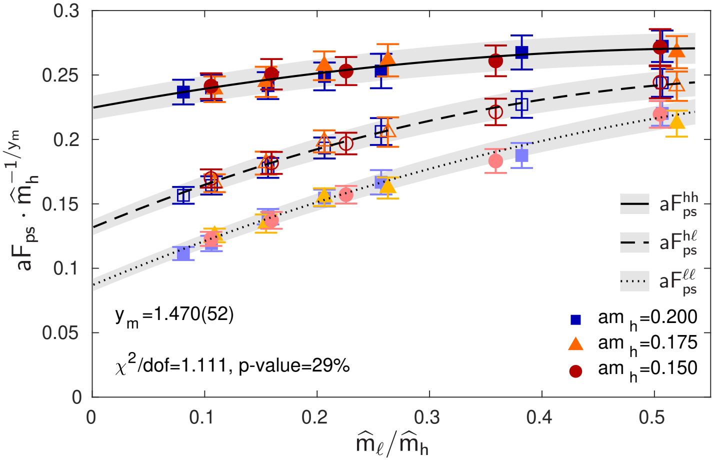
- Choose e.g. the gradient flow lattice scale $a/\sqrt{8t_0}$ as quantity of mass dimension aM_H
- Polynomial ansatz for $\Phi_H(\widehat{m}_\ell/\widehat{m}_h)$
- Fit $\widehat{m}_h^{1/y_m} \cdot \left(c_2(\frac{\widehat{m}_l}{\widehat{m}_h})^2 + c_1(\frac{\widehat{m}_l}{\widehat{m}_h}) + c_0\right)$ to all 17 data points at three $\widehat{m}_h$ values and determine $y_m = 1.469(23)$
- Note: $\Phi_{\sqrt{8t_0}}(0) \approx 0.48$



Determine y_m from hyperscaling relation: aF_{ps}

$$aM_H = \widehat{m}_h^{1/y_m}\ \Phi_H(\widehat{m}_\ell/\widehat{m}_h)$$

- Polynomial ansatz for $\Phi(\widehat{m}_\ell/\widehat{m}_h)$
- Pseudoscalar decay constants $aF_{ps}^{\ell\ell}$, $aF_{ps}^{h\ell}$, aF_{ps}^{hh}
- Combined, correlated fit to all 51 data points at three $\widehat{m}_h$ values to determine $y_m = 1.470(52)$
- Chiral limit of $aF_{ps}^{\ell\ell} \sim 0.08/\widehat{m}_h^{-1/y_m}$
  $\rightsquigarrow$ light sector is chirally broken



effective field theory

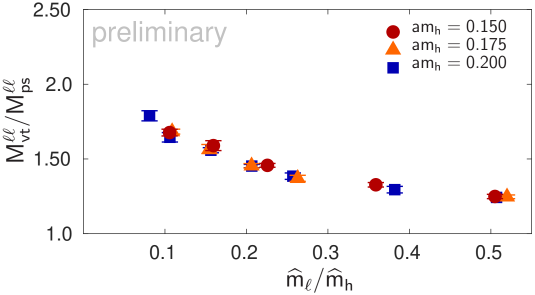
Hadronic scale Λ_H

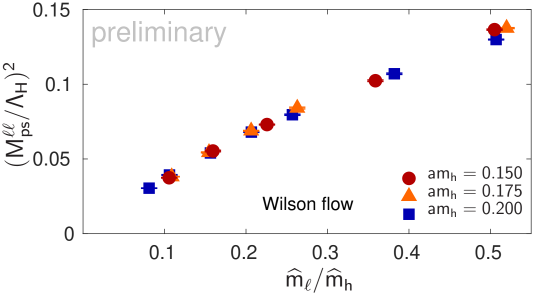
- Heavy flavors decouple, light flavors condense and spontaneously break chiral symmetry when $\widehat{m}_h(a\mu)^{-y_m} \approx 1$
- Introduce hadronic or chiral symmetry breaking scale $\Lambda_H = \widehat{m}_h^{1/y_m} a^{-1}$
- If energy scale μ is lowered below Λ_H, gauge coupling starts running again
- Using the scaling relation for $\sqrt{8t_0}$, we can define Λ_H

$\rightarrow$ In the chiral limit: $a = (\widehat{m}_h)^{1/y_m} \cdot \Phi_{\sqrt{8t_0}}(0) \cdot \sqrt{8t_0}|_{m_\ell=0}$

$$\Rightarrow \Lambda_H^{-1} = \Phi_{\sqrt{8t_0}}(0) \cdot \sqrt{8t_0}|_{m_\ell=0}$$

Chiral $\widehat{m}_\ell/\widehat{m}_h \to 0$ limit





- $M^{\ell\ell}_{vt}/M^{\ell\ell}_{ps}$ increases for $\widehat{m}_\ell/\widehat{m}_h \to 0$ (diverges for chirally broken theories)
- $(M^{\ell\ell}_{ps})^2$ is close to linear in $\widehat{m}_\ell/\widehat{m}_h$ (small curvature visible for $\widehat{m}_\ell/\widehat{m}_h \gtrsim 0.25$)

Low energy effective description

- In the low energy IR limit our system exhibits spontaneous chiral symmetry breaking
- Seek chiral effective Lagrangian smoothly connecting to hyperscaling relation valid at $\mu = \Lambda_H$
- Express lattice scale a in terms of Λ_H: $M_H/\Lambda_H = (aM_H) \cdot \widehat{m}_h^{-1/y_m} = \Phi_H(\widehat{m}_\ell/\widehat{m}_h)$
- Below Λ_H, the 4+6 system reduces to chirally broken $N_f = 4$ with running fermion mass m_f
- Scaling of the light flavor mass implies: $m_f \propto \widehat{m}_\ell (a\Lambda_H)^{-y_m} \cdot \Lambda_H = (\widehat{m}_\ell/\widehat{m}_h) \cdot \Lambda_H$
- Continuum limit taken by tuning $m_h \to 0$ while keeping $\widehat{m}_\ell/\widehat{m}_h$ fixed
- Only considering light-light quantities, dropping superscript $\ell\ell$

Dilaton chiral perturbation theory (dChPT)

[Golterman, Shamir PRD94 (2016) 054502] [PRD98 (2018) 056025]

[Appelquist, Ingoldby, Piai JHEP03 (2018) 039] [JHEP07 (2017) 035] [PRD101 (2020) 075025]

[Golterman, Neil,Shamir arXiv:2003.00114]

- Derived for chirally broken systems just below the conformal window with a 0^{++} (dilaton) as light as the pseudoscalar
- Can be adapted for mass-split systems: $m_f \to \left(\frac{\widehat{m}_\ell}{\widehat{m}_h}\right) \cdot \Lambda_H$
- General dChPT scaling relation

$$d_0 \cdot F_{ps}^{2-y_m} = M_{ps}^2 / m_f \qquad \to \qquad d_0 \cdot (aF_{ps})^{2-y_m} = (aM_{ps})^2 / \widehat{m}_\ell$$

- Assuming a specific form of the dilaton potential [Golterman, Neil,Shamir arXiv:2003.00114]

$$\frac{M_{ps}^2}{F_{ps}^2} = \frac{1}{y_m d_1} W_0\left(\frac{y_m d_1}{d_2} m_f\right) \qquad \to \qquad \frac{M_{ps}^2}{F_{ps}^2} = \frac{1}{y_m d_1} W_0\left(\frac{y_m d_1}{d_2} \frac{\widehat{m}_\ell}{\widehat{m}_h} \cdot \Lambda_H\right)$$

with W_0 Lambert W-function and low energy coefficients d_0, d_1, d_2

Fit to the general dChPT scaling relation

- Fitting

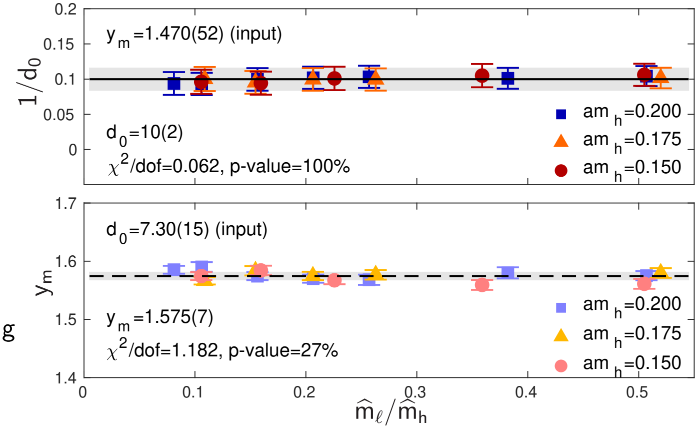
$$d_0 \cdot (aF_{ps})^{2-y_m} = (aM_{ps})^2/\widehat{m}_\ell$$

→ M_{ps} and F_{ps} have similar size, correlated uncertainties

→ To avoid complicated fit

1) Use $y_m = 1.470(52)$ as input, fit only d_0

2) Scan range of d_0, fit y_m, seeking minimal χ^2 ("curve collapse")

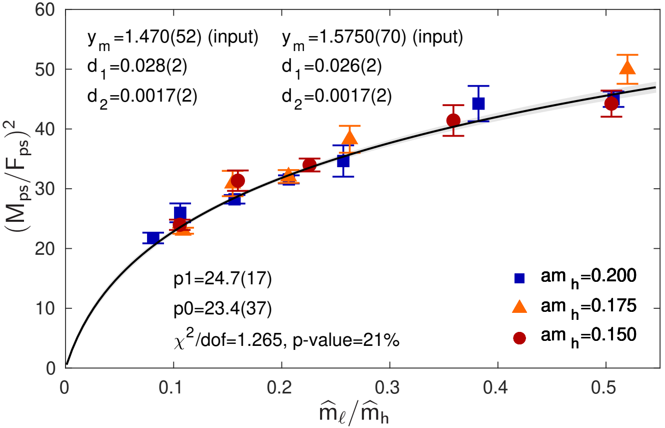


Fit assuming a specific dilaton potential

- Fitting

$$\frac{M_{ps}^2}{F_{ps}^2} = \frac{1}{y_m d_1} W_0 \left(\frac{y_m d_1}{d_2} \frac{\widehat{m}_\ell}{\widehat{m}_h} \cdot \Lambda_H \right)$$

$\rightarrow$ Determine $p0 = y_m d_1$ and $p1 = y_m d_1 / d_2$



summary and outlook

Summary

- Mass-split simulations with 4 light and 6 heavy flavors
  - → Exhibit hyperscaling in $\widehat{m}_\ell/\widehat{m}_h$
  - → Allow to extract y_m corresponding to the $N_f = 10$ infrared fixed point

- dChPT describes our mass-split system very well
  - → Need to measure the 0^{++} for additional validation
  - → $\widehat{m}_\ell/\widehat{m}_h$ is a continuous parameter similar to the mass in regular χPT
    i.e. can vary range to test need for higher order terms

- $N_f = 10$ anomalous dimension $\gamma_m^* \approx 0.47$ is small
  - → Consistent with findings for $N_f = 12$ ($\gamma_m^* \approx 0.24$) and $N_f = 8$ ($\gamma_m^* \sim 1$)
  - → γ_m^* likely too small for phenomenological applications
  - → Suggests models based on $N_f = 8$ or 9 could be closer to the sill of the conformal window

Outlook

- Numerically measure the isosinglet scalar 0^{++}
- Push simulations deeper into the chiral regime
- Connect simulations to the degenerate $N_f = 10$ conformal limit
- Determine phenomenologically interesting quantities
  - → Baryonic anomalous dimension
  - → Calculate the S-parameter
  - → Determine the Higgs potential
- Investigate finite temperature phase structure

Resources

LLNL: vulcan, lassen

ALCF (ANL): mira, theta

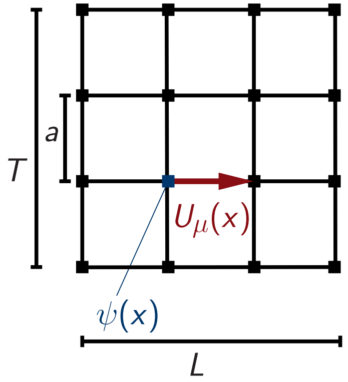
USQCD: Ds, Bc, and pi0 cluster (Fermilab); qcd16p/18p (Jlab); sdcc (BNL)

U Colorado: summit

BU: engaging and scc (MGHPCC)

Numerical Simulations

- Lattice field theory
- Hypercubic lattices with $(L/a)^3 \times (T/a)$ with $L/a = 24$, 32 and $T/a = 64$
- Simulate SU(3) gauge system with four light and six heavy flavors
  - $\rightarrow$ Three times stout-smeared ($\varrho = 0.1$) Möbius domain wall fermions (MDWF) with Syamnzik gauge action
- MDWF are simulated with a fifth dimension L_s to create chiral fermions in four dimensions
  - $\rightarrow$ $L_s = 16 \Rightarrow$ small residual chiral symmetry breaking $O(10^{-3})$
- Parameters
  - $\rightarrow$ $\beta = 4.03$
  - $\rightarrow$ $0.015 \leq am_\ell \leq 0.100$
  - $\rightarrow$ $am_h = 0.200, 0.175, 0.150$



Gradient flow step-scaling β-function

[Lüscher JHEP08(2010)071][Fodor et al. JHEP11(2012)007][Fodor et al. JHEP09(2014)018]

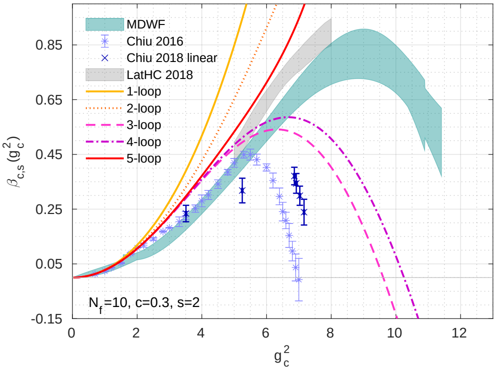
$$\beta_s^c(g_c^2; L) = \frac{g_c^2(sL) - g^2(L)}{\log(s^2)} \qquad \text{(negative of continuum } \beta \text{ function)}$$

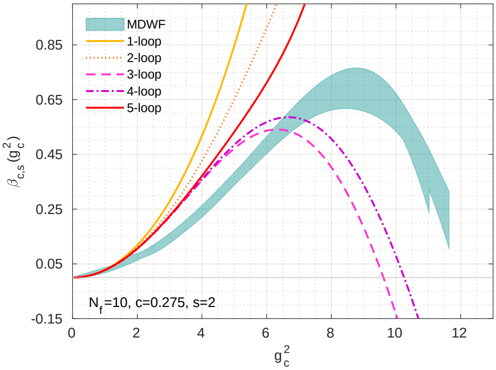
$$g_c^2(L) = \frac{128\pi^2}{3(N_c^2 - 1)} \, \frac{1}{C(c, L)} t^2 \langle E(t) \rangle \quad \text{with } \sqrt{8t} = c \cdot L$$

- → $C(c, L)$ perturbative tree-level improvement term [Fodor et al. JHEP09(2014)018] or zero mode correction $(1 + \delta(t/L^2))$ [Fodor et al. JHEP11(2012)007]
- → Generate ensembles of dynamical gauge field configurations with L^4 and $(s \cdot L)^4$ volumes
- → Extrapolate $L \to \infty$ to remove discretization effects and take the continuum limit
- → Expect to find agreement for results based on different actions, operators . . .

$N_f = 10$ step-scaling β-function

[Hasenfratz, Rebbi, OW PRD101 (2020) 114508]





- Gradient flow scheme $c = 0.300$
- Gradient flow scheme $c = 0.275$

Two scenarios for a composite Higgs

- Light iso-singlet scalar (0^{++})
  - → "Dilaton-like"
  - → Scale: F_{ps} = SM vev $\sim$ 246 GeV
  - → ideal 2 massless flavors
    - ⇒ giving rise to 3 Goldstone bosons
    - ⇒ longitudinal components of $W^{\pm}$ and Z^0

- pseudo Nambu Goldstone Boson (pNGB)
  - → Spontaneous breaking of flavor symmetry
    - ⇒ $N_f \geq 3$
  - → Mass emerges from its interactions
  - → Non-trivial vacuum alignment

    $F_{ps} = (\text{SM vev})/\sin(\chi) > 246$ GeV

Mass-split models can accommodate both scenarios

→ Requires to find a light 0^{++}

i.e. $M_{ps} \sim M_{0^{++}} < M_{vt}$

→ Fundamental composite 2HDM

[Ma, Cacciapaglia JHEP03(2016)211]

Fundamental composite 2HDM with four flavors

[Ma, Cacciapaglia JHEP03(2016)211]

- Global symmetry at low energies:

$$SU(4) \times SU(4) \text{ broken to } SU(4)_{\text{diag}}$$

- 15 pNGB transform under custodial symmetry

$$SU(2)_L \times SU(2)_R$$

$$\Rightarrow \mathbf{15}_{SU(4)_{\text{diag}}} = (2,2) + (2,2) + (3,1) + (1,3) + (1,1)$$

$\rightarrow$ One doublet plays the role of the Higgs doublet field

$\rightarrow$ Other doublet and triplets are stable; could play role of dark matter

- Vecchi: "choose the right couplings to RH top" [Edinburgh talk]

$$\Rightarrow (2,2) + \cancel{(2,2)} + \cancel{(3,1)} + \cancel{(1,3)} + (1,1)$$

$\rightsquigarrow$ effectively SU(4)/Sp(4)