Mass-split Composite Higgs Model with Large Scale Separation

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introduction

General idea: composite Higgs models

- Extend the Standard Model by a new, strongly coupled gauge-fermion system

- The Higgs boson arises as bound state of this new sector
  $\rightarrow$ Mass and quantum numbers match experimental values
  when accounting for SM interactions/corrections

- System exhibits a large separation of scales
  $\rightarrow$ Explaining why a 125 GeV Higgs boson but no other states have been found
  $\rightarrow$ Indications that such a system cannot be QCD-like (e.g. quark mass generation)
  $\rightsquigarrow$ 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)?

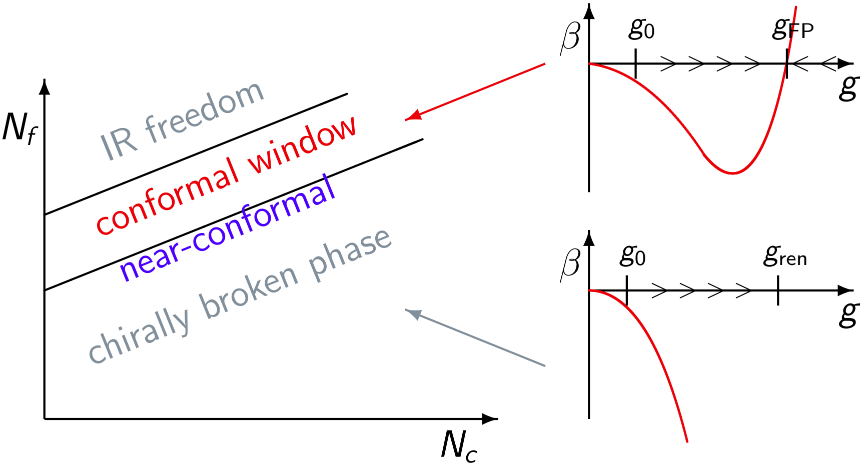
Outline

1. Explore β function of SU(3) with twelve or ten fundamental flavors
2. Build a composite Higgs model with large scale separation
3. First results for the mass-split system with 4 light and 6 heavy flavors

β function

Near-conformal gauge theories

- Gauge-fermion system with $N_c \geq 2$ colors and N_f flavors in some representation



Renormalization group β function

- Conformal theories exhibit an IRFP i.e. $\beta(g^2) = 0$ for $g^2 > 0$

- Perturbative calculations up to 5-loop in $\overline{MS}$ scheme
  [Baikov et al. PRL118(2017)082002][Ryttov and Shrock PRD94(2016)105015]
  → Fixed point may occur at strong coupling where PT is not reliable

- Nonperturbative calculation of the step-scaling function
  → Schrödinger functional [Lüscher et al. NPB359(1991)221]
  → Gradient flow [Lüscher JHEP08(2010)071][Fodor et al. JHEP11(2012)007]

- New: continuous gradient flow β function with all steps detailed
  [Hasenfratz, Witzel in preparation] [Poster ($N_f = 12$)][Talk Anna ($N_f = 2$)]

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]

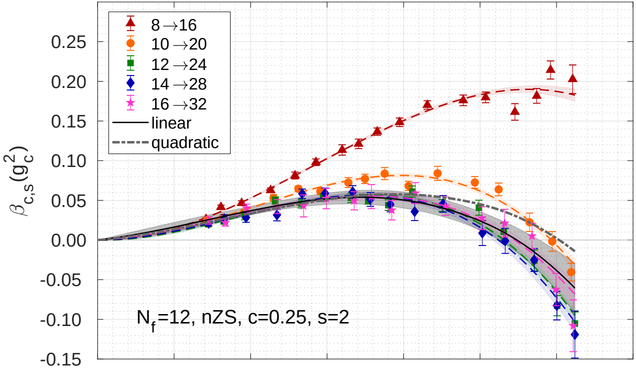
→ Generate ensembles of dynamical gauge field configurations with L^4 and $(s\cdot L)^4$ volumes

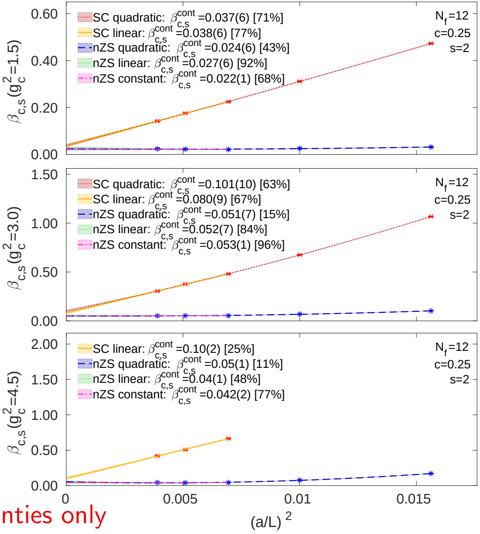
→ Extrapolate $L\to\infty$ to remove discretization effects and take the continuum limit

→ Expect to find agreement for results based on different actions, operators ...

Step-scaling β-function for SU(3) with 12 fundamental flavors

[Hasenfratz, Rebbi, OW PLB 798(2019)134937]



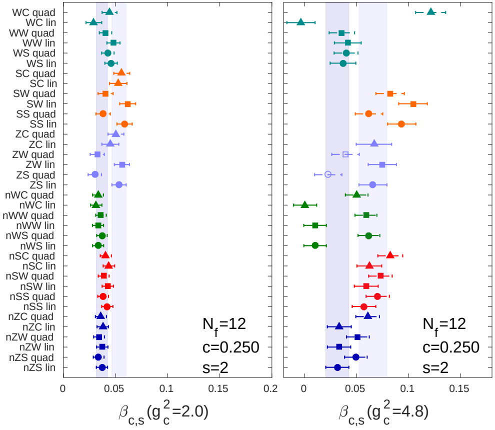


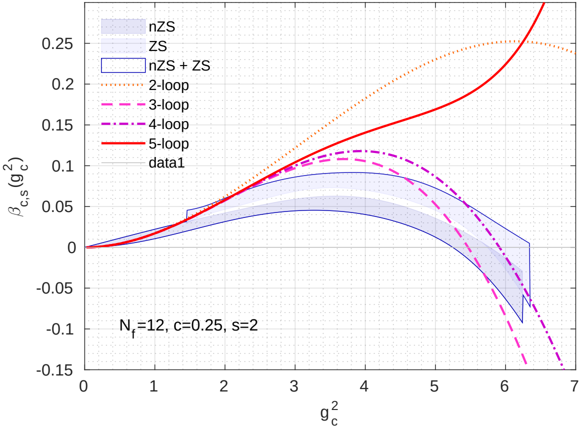
statistical uncertainties only

Step-scaling β-function for SU(3) with 12 fundamental flavors

- Estimate systematic effects due to different flows/operators, extrapolation, tree-level normalization

[Hasenfratz, Rebbi, OW arXiv:1909.05842]





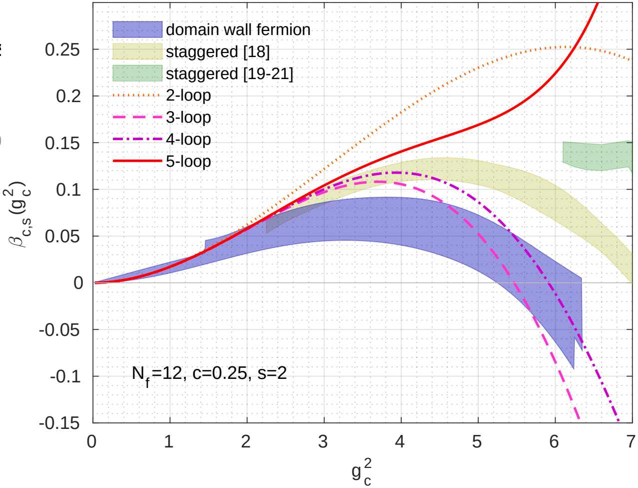
Step-scaling β-function for SU(3) with 12 fundamental flavors

[Hasenfratz, Rebbi, OW arXiv:1909.05842]

- $c = 0.250$ scheme
- Comparison to other determination
  [Hasenfratz and Schaich JHEP02(2018)132]

  [Fodor et al. PRD94(2016)091501]
  [PLB779(2018)230][EPJ WebConf175(2018)0

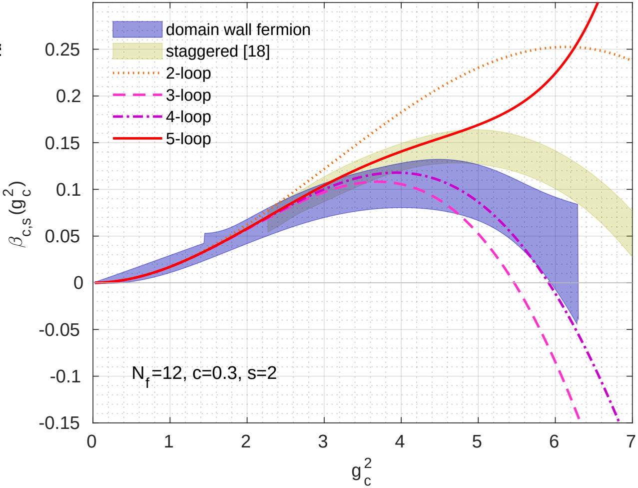
  [Baikov et al. PRL118(2017)082002]
  [Ryttov and Shrock PRD94(2016)105015]
  [PRD95(2017)105004]
- IRFP: $5.2 \leq g_c2 \leq 6.4$



Step-scaling β-function for SU(3) with 12 fundamental flavors

- $c = 0.300$ scheme
- Comparison to other determinations
  [Hasenfratz and Schaich JHEP02(2018)132]

  [Baikov et al. PRL118(2017)082002]
  [Ryttov and Shrock PRD94(2016)105015]
  [PRD95(2017)105004]



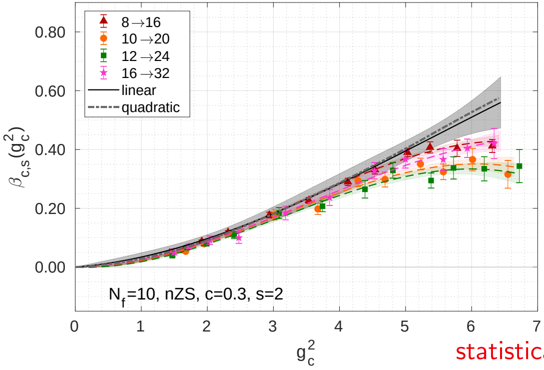
Step-scaling β-function for SU(3) with 10 fundamental flavors

- Simulations at stronger couplings in progress
- Statistical uncertainties only

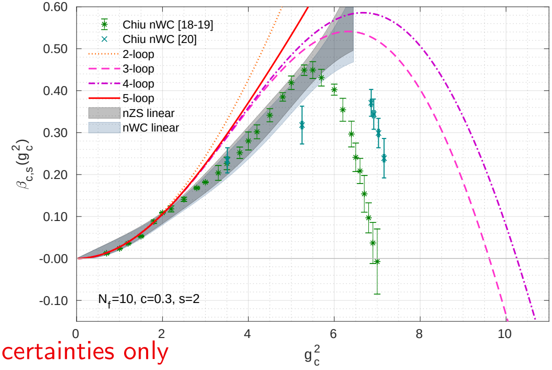
- So far perfect agreement with Chiu (optimal DWF, Wilson gauge action, Wilson flow, clover operator)

[Chiu arXiv:1603.08854][PoS Lattice2016 228][PRD99(2019)014507]

[Hasenfratz, Rebbi, OW PLB 798(2019)134937]



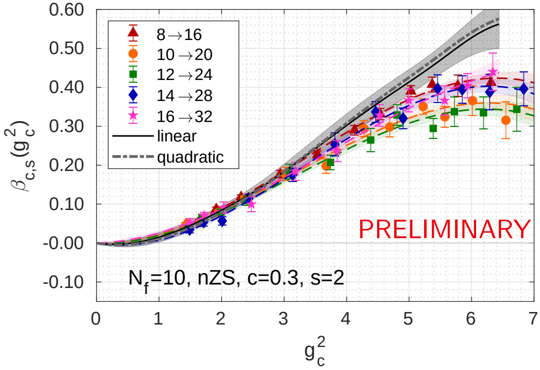
[Hasenfratz, Rebbi, OW PLB 798(2019)134937]

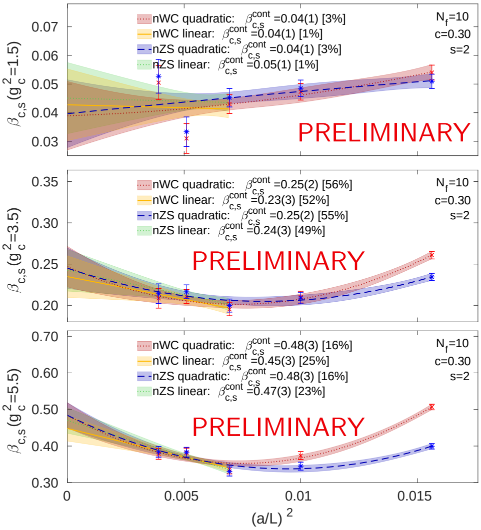


statistical uncertainties only

Step-scaling β-function for SU(3) with 10 fundamental flavors

- Adding preliminary data at weak coupling for $14 \to 28$ volume pair
- Statistical uncertainties only

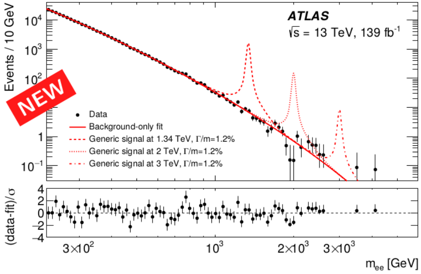




composite Higgs models

Experimental observations

- Discovery of the Higgs boson in 2012
  [Atlas PLB716(2012)1] [CMS PLB716(2012)30]
- Higgs boson
  - $\to$ $M_{H^0} = 125.18(16)$ GeV [PDG 2018]
  - $\to$ Spin 0 preferred over spin 2; spin 1 excluded ($H^0 \to \gamma\gamma$)
  - $\to$ CP difficult to determine (mixing of e/o eigenstates)
  - $\to$ SM decay width too small for LHC measurement
  - $\to$ Improving precision on coupling to SM particles
- So far no other states found
  - $\Rightarrow$ No supersymmetric particles
  - $\Rightarrow$ No heavier resonances
  - $\to$ What is the origin of the electro-weak sector?
  - $\rightsquigarrow$ Maybe new resonances of a few TeV?
- ATLAS generic Z' search in dileptonic resonances
  [Zucchetta EW Moriond 2019]



Composite Higgs models

- Aim: describe states of the SM as well as particles originating from new physics
- Start with a Higgs-less, massless SM
- Add new strong dynamics coupled to SM

$$\mathcal{L}_{UV} \to \mathcal{L}_{SD} + \mathcal{L}_{SM_0} + \mathcal{L}_{int} \to \mathcal{L}_{SM} + \dots$$

full SM + states from $\mathcal{L}_{SD}$

- Leads to an effective theory giving mass to
  - → the SM gauge fields
  - → the SM fermions fields: 4-fermion interaction or partial compositeness
- Does not explain mass of $\mathcal{L}_{SD}$ fermions and 4-fermion interactions: $\mathcal{L}_{UV}$

Two scenarios for a composite Higgs

- Light iso-singlet scalar (0^{++})
  - → "Dilaton-like"
  - → Scale: F_π = 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_π = (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]

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 — conformal — chirally broken → IR

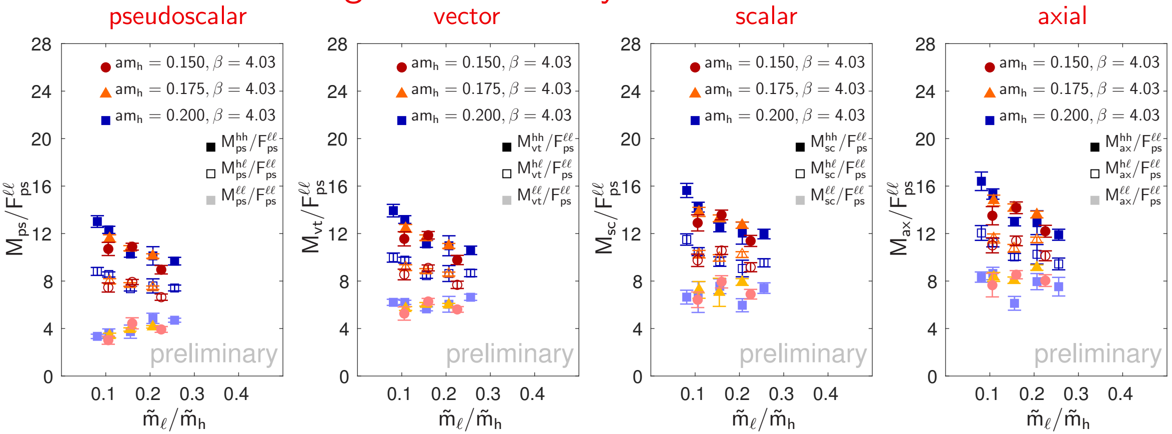
Λ_{UV} fermion masses Λ_{IR} Higgs dynamics

- Mass-split models e.g. SU(3) gauge theory with "heavy" and "light" (massless) fundamental flavors
  - Add N_h 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

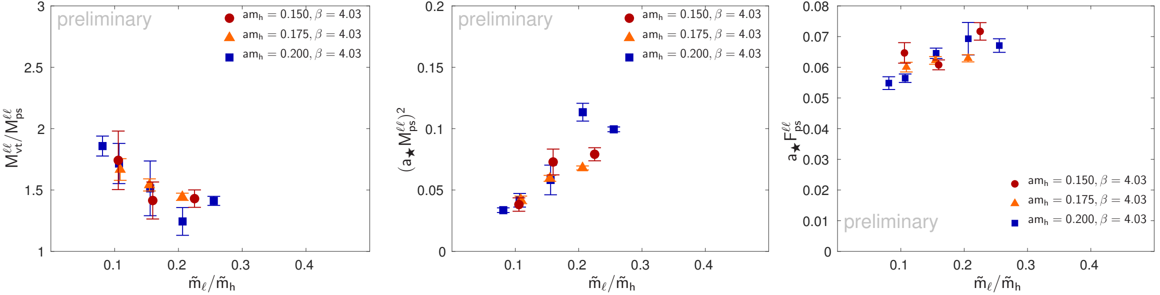
    fundamental composite 2HDM with 4 flavors in SU(3) gauge [Ma, Cacciapaglia JHEP03(2016)211] results 4+6

First results for four light and six heavy flavors



- First signs of hyperscaling, starting to push into the chiral regime
- $F^{\ell\ell}_{ps}$ not renormalized, but Z_A of $O(1)$

First results for four light and six heavy flavors



- $M^{\ell\ell}_{vt}/M^{\ell\ell}_{ps}$ increases for $\tilde{m}_\ell/\tilde{m}_h \to 0$ (diverges for chirally broken theories
- $(M^{\ell\ell}_{ps})^2$ is close to linear in $\tilde{m}_\ell/\tilde{m}_h$
- $F^{\ell\ell}_{ps}$ looks finite for $\tilde{m}_\ell/\tilde{m}_h \to 0$

summary

Summary

- RG β function for SU(3) with ten fundamental flavors
  - → Step-scaling calculation up to $g_c^2 \sim 6$ in excellent agreement with Chiu ($c = 0.300$)
  - → Simulations at stronger coupling in progress to explore possibility of an IRFP
  - → New method to determine of continuous GF β function looks very promising
  - → Systematic effects to be investigated

- Mass-split simulations with 4 light and 6 heavy flavors
  - → Exhibit hyperscaling in $\tilde{m}_\ell/\tilde{m}_h$ ($\rightsquigarrow$ hint that $N_f = 10$ is conformal)
  - → Generating additional ensembles to probe deeper in the chiral limit
  - → Measuring the iso-singlet scalar 0^{++} is work in progress

- Explore phenomenologically relevant processes/quantities
  - → Generation of mass for SM fermions (partial compositeness, four-fermion interaction)
  - → Baryon anomalous dimension e.g. via new gradient flow method [Carosso et al. 1806.01385]
  - → S-parameter [Appelquist et al. PRL106(2011)231601], Higgs-potential, ...

Resources

Step-scaling

XSEDE: stampede2 (TACC)

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

U Colorado: summit

BU: engaging and scc (MGHPCC)

4+6 (LSD):

LLNL: vulcan

ALCF (ANL): mira, theta

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

U Colorado: summit

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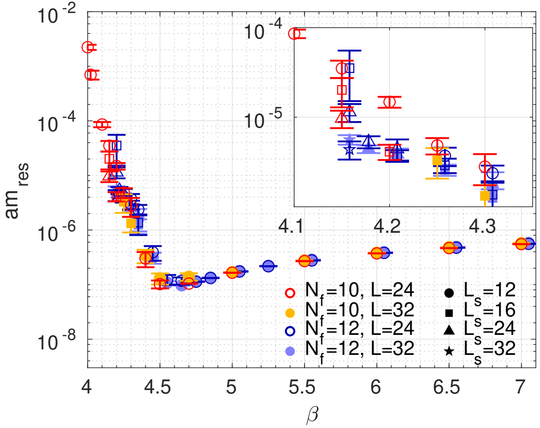
appendix

Numerical details

- Symanzik gauge action with three times stout smeared Möbius domain wall fermions
- L^4 volumes with $L = 8, 10, 12, 14, 16, 20, 24, 28, 32$
- Periodic BCs for the gauge fields; anti-periodic BCs for the fermions
- $am_f = 0$, L_s such that am_{res} is negligible (numerically verified)
- Bare gauge couplings $7.00 \geq \beta \gtrsim 4.15$ ($N_f = 10$: calculations with $\beta \geq 4.02$ in progress)
- Simulations performed using `Grid` [Boyle et al. PoS Lattice2015 023]
- Measuring Zeuthen flow, Symanzik flow, and Wilson flow in `Qlua` [Pochinsky PoS Lattice2008 040]

Residual chiral symmetry breaking

- Parametrized in terms of the residual mass am_{res}
- Numerically determined using the mid-point – pseudoscalar correlator



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)

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)
  - $\rightarrow$ 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
  - $\rightarrow$ Inherit hyperscaling of ratios of hadron masses but are chirally broken
  - $\rightarrow$ Continuum limit: $m_h \to 0$ keeping m_ℓ/m_h fixed
  - $\rightarrow$ Chiral limit: $m_\ell \to 0$ i.e. $m_\ell/m_h \to 0$
  - $\rightarrow$ Gauge coupling is irrelevant
  - $\rightarrow$ 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]