Review on Composite Higgs Models

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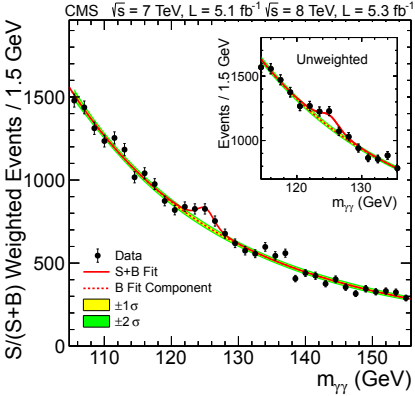
overview

Experimental observations

- Discovery of the Higgs boson in 2012
  [Atlas PLB716(2012)1] [CMS PLB716(2012)30]

- Higgs boson
  - → $M_{H^0} = 125.18(16)$ GeV [PDG 2018]
  - → Spin 0 preferred over spin 2; spin 1 excluded ($H^0 \to \gamma\gamma$)
  - → CP difficult to determine (mixing of e/o eigenstates)
  - → SM decay width too small for LHC measurement
  - → Improving precision on coupling to SM particles

- So far no other states found
  - ⇒ No supersymmetric particles
  - ⇒ No heavier resonances
  - → What is the origin of the electro-weak sector?
  - ⇝ Maybe new resonances of a few TeV?



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
  → 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)?

Composite Higgs models

- Aim: describe states of the SM as well as particles originating from new physics

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

Composite Higgs models

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

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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

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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

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

- Leads to an effective theory giving mass to
  - $\to$ the SM gauge fields
  - $\to$ 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

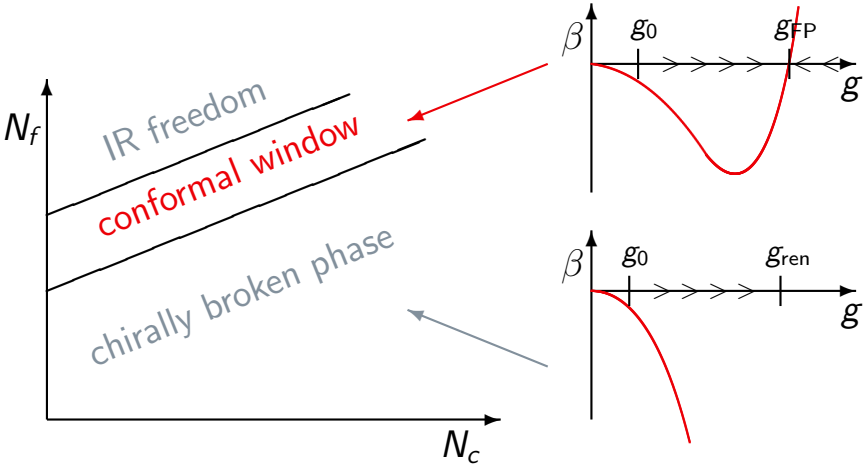
- Light iso-singlet scalar (0^{++})
  - → "Dilaton-like"
  - → Scale: F_π = SM vev $\sim$ 246 GeV
  - → ideal 2 massless flavors
    - ⇒ giving rise to 3 Goldstone bosons
    - ⇒ longitudinal components of $W^\pm$ and Z^0
- 2-flavor sextet [LatHC, CP3] (Kuti Wed 2:00 PM, Wong Wed 2:20 PM)
- 8-flavor fundamental [LatKMI, LSD] (Rebbi Thu 11:00 AM, Neil Thu 12:00 PM)
- 2-flavor fundamental [Drach et al.] see appendix

- 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
- Two-representation model by Ferretti [TACoS] (Jay Thu 12:20 PM)
- Mass-split models [4+8, LSD]
- SU(4)/Sp(4) composite Higgs [Bennett et al.] (Lee Tue 2:20 PM) see appendix

near-conformal gauge theories

Near-conformal gauge theories

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



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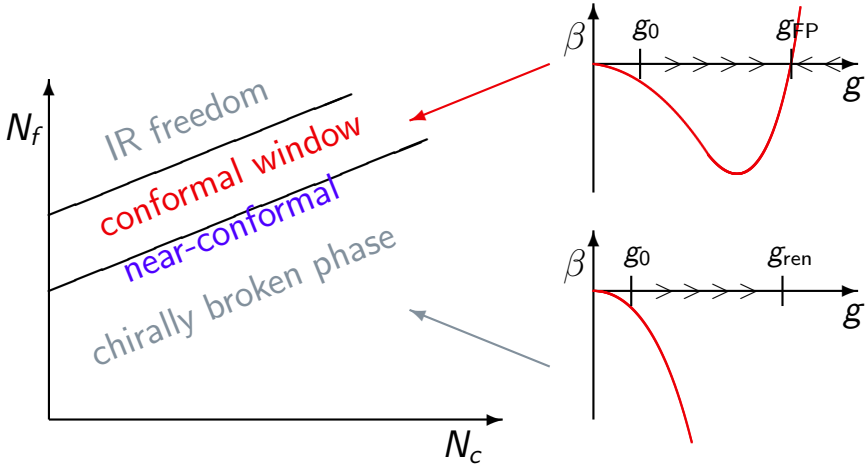
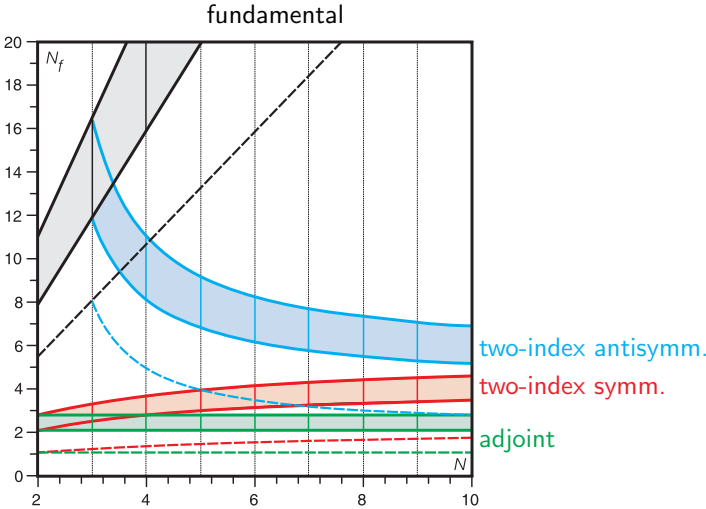


Conformal window

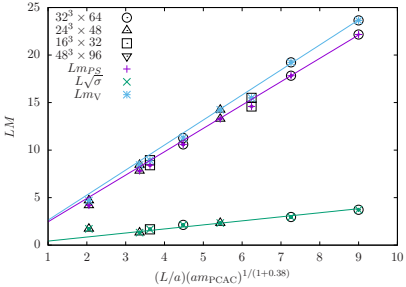
- Indications of the conformal window for different representations, N_c, and N_f [Dietrich, Sannino PRD75(2007)085018]
- Derived from perturbative and Schwinger-Dyson arguments
- Lower bonds of conformal window typically require nonperturbative calculations



SU(2) gauge theory with fermions in the adjoint representation

- Nonperturbative investigations include e.g.
  - → Scaling of hadron masses
  - → Mode number of Dirac operator
  - ⇒ Determination of the anomalous dimension
- Conclusions
  - → $N_f = 2$ is conformal [Bergner et al. PRD96(2017)034504]
  - → $N_f = 1$ likely conformal [Athenodorou et al. PRD91(2015)114508]
  - → $N_f = 1/2$ (1 Majorana fermion) is QCD-like [Bergner et al. JHEP03(2016)080]
  - → $N_f = 3/2$ (3 Majorana fermions) is conformal
    Mode number: $\gamma^* \approx 0.38(2)$; fit spectrum $\gamma^* \approx 0.37(2)$
- Mixed fundamental-adjoint action (Bergner Fri 5:10 PM)
  - ⇝ Investigations of supersymmetric QCD

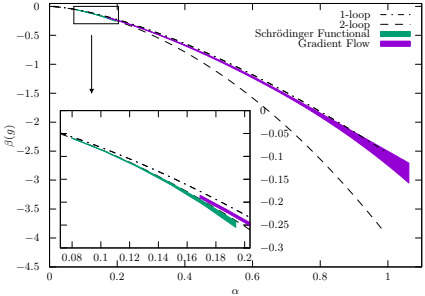
(Scior poster)



[Bergner et al. JHEP01(2018)119]

The step-scaling β-function

- IRFP: β function has zero for $g^2 > 0$
- For large g^2 nonperturbative methods are required
- Calculate discretized β function (step scaling)
  - → Requires calculations on a set of different volumes
  - → Well established in QCD [Lüscher et al. NPB359(1991)221]



[Dalla Brida et al. PRD95(2017)014507]

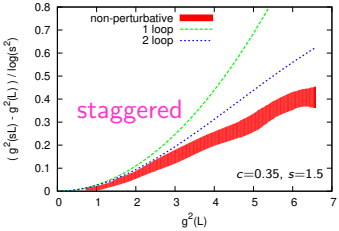
- Gradient flow step scaling [Lüscher JHEP08(2010)071] [Fodor et al. JHEP11(2012)007][Fodor et al. JHEP09(2014)018]

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

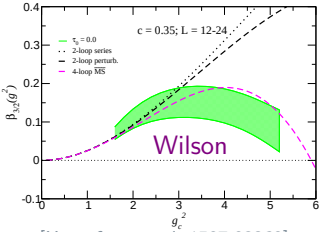
- Extrapolate $L \to \infty$ to remove discretization effects and take the continuum limit
- Expect to find agreement for results based on different actions, flows, operators ...

The challenge of establishing an IRFP

[Fodor et al. JHEP09(2015)039]

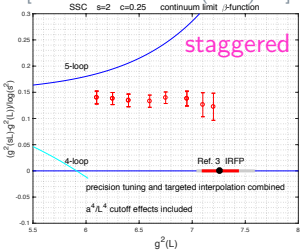


$N_f = 2$ sextet

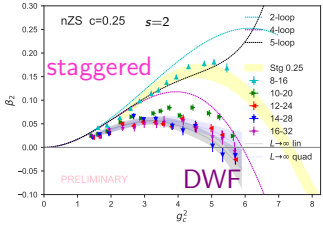


[Hasenfratz et al. 1507.08260]

[Fodor et al. PLB779(2018)230]

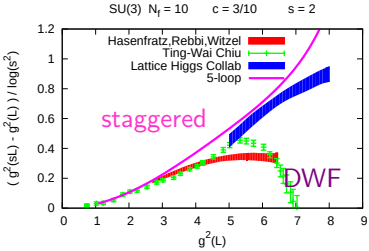


$N_f = 12$ fundamental

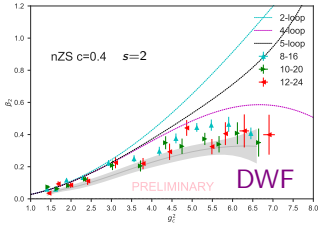


(Hasenfratz poster)

(Nogradi Wed 3:00 PM)



$N_f = 10$ fundamental



[Hasenfratz, Rebbi, Witzel 1710.11578]

Active research

- Larger volumes might be required for $L \to \infty$ extrapolation
  - → Small c-values certainly require larger volumes than larger c-values
    - ⇝ Larger c-values have larger statistical uncertainties
  - → Different actions have different discretization errors

- DWF with Symanzik gauge action feature a fully $O(a^2)$ improved set-up à la Symanzik
  - → Zeuthen flow [Ramos, Sint EPJC76(2016)15]
  - → Symanzik operator
  - → Perturbative tree-level normalization [Fodor et al. JHEP09(2014)018] works for $N_f = 12$ and 10

⇝ Perturbative improvement breaks down for staggered with $N_f = 8$ [Fodor et al JHEP06(2015)19]

- [Rooted] Staggered Fermions: Good, Bad or Ugly? [Sharpe Plenary Lattice 2006]
  - ⇝ Are staggered and DW/Wilson fermions in conformal systems in the same universality class?

(Hasenfratz poster, Kuti Wed 2:00 PM, Holland Wed 2:40 PM, Nogradi Wed 3:00 PM)

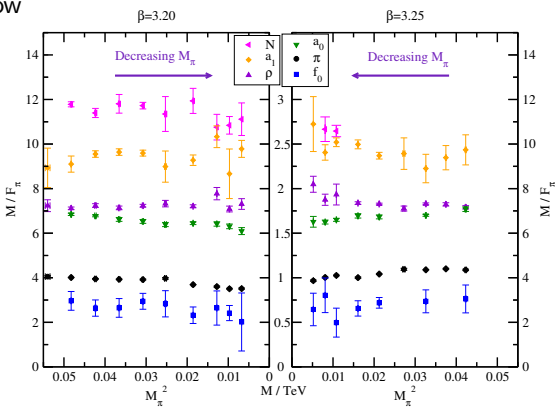
Higgs as a light 0^{++} scalar

SU(3) with $N_f = 2$ sextet flavors (two-index symmetric representation)

- Minimal flavor content to describe EW symmetry breaking
- Likely very close to the onset of the conformal window

- LatHC
  - → Chirally broken spectrum [Fodor et al. PLB718(2012)657]
  - → 0^{++} (f_0) is light
  - → No IRFP in the explored range of the β-function [Fodor et al. JHEP09(2015)039]

(Kuti Wed 2:00 PM, Wong Wed 2:20 PM)



[Fodor et al. PoS LATTICE2015 219]

SU(3) with $N_f = 2$ sextet flavors (two-index symmetric representation)

- Minimal flavor content to describe EW symmetry breaking
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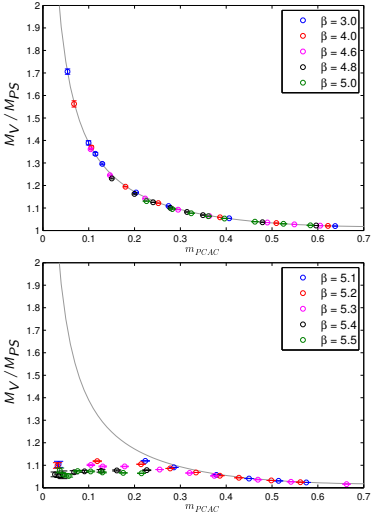
- Hansen, Drach, Pica
  → Two different phases one chirally broken, one looking IR conformal [Hansen, Drach, Pica PRD96(2017)0345]

- Hasenfratz, Liu, Yu-Han Huang
  → Indications for a possible IRFP [Hasenfratz et al. 1507.08260]



[Hansen, Drach, Pica PRD96(2017)0345]

SU(3) with $N_f = 8$ fundamental flavors

- Theory considered to be chirally broken but close to the onset of the conformal window
  - → Step scaling analysis of the discrete β function
    [Hasenfratz et al. JHEP06(2015)143][Fodor et al. JHEP06(2015)019]
  - → Finite temperature phase diagram
    [Deuzeman et al. PLB670(2008)41][Jin, Mawhinney PoS LATTICE2010 055][Schaich et al. PoS LATTICE2012 028]
  - → Studies of the low-lying meson spectrum
    [Aoki et al. PRD89(2014)111502][Appelquist et al. PRD93(2016)114514][Aoki et al. PRD96(2017)014508]
    [Appelquist et al. 1807.08411]

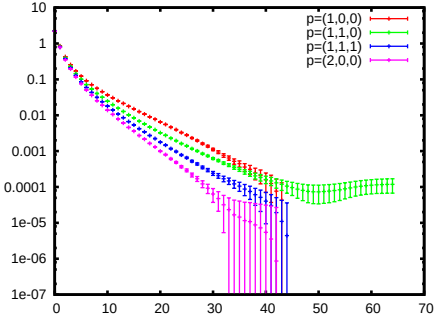
- Theory has 63 Goldstone boson — not an ideal candidate to explain EW symmetry breaking
  - → Allows to investigate qualitative features of near-conformal gauge theories
  - → Reduce number of light Goldstones by assigning e.g. mass or charge to some flavors

- 0^{++} is light, degenerate with the pion!

Determining the iso-singlet scalar 0^{++}

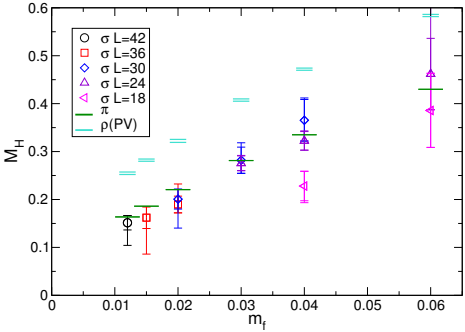
- Receives quark line connected and disconnected contributions
  - → Stochastic estimator (noisy)
- Its quantum numbers are the same vacuum
  - → Large vacuum subtraction
- Lighter in near-conformal systems than in QCD
  - → Easier to determine, stable particle (energetically protected from decaying)
- Nevertheless most expensive state in the spectrum

- Idea: take advantage of correlators at non-zero momenta to avoid the vacuum subtraction (Rebbi Thu 11:00 PM)



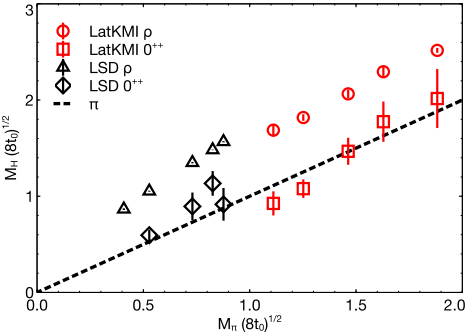
Iso-singlet scalar (0^{++})

LatKMI



[Aoki et al. PRD96(2017)014508]

LSD

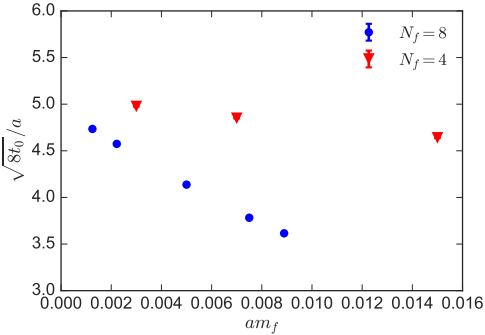


[Appelquist et al. PRD93(2016)114514]

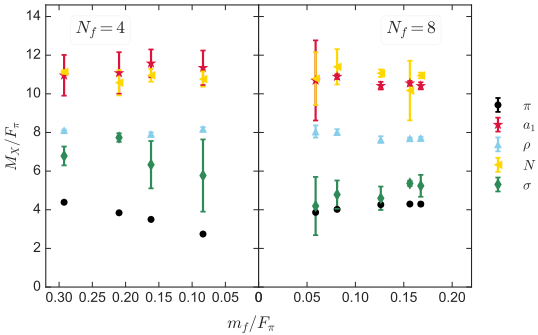
- 0^{++} is light, degenerate with the pion $\Rightarrow$ χPT not applicable

Comparison of SU(3) with $N_f = 4$ and 8 fundamental flavors

(Neil Thu 12:00 PM, Cushman poster)



[Appelquist et al. 1807.08411]



- Wilson flow scale $\sqrt{8t_0}$ vs fermion mass am_f
- Strong mass-dependence for $N_f = 8$
  - ⇒ Show quantities in units of $\sqrt{8t_0}$ or dimensionless ratios
- Spectrum in units of F_π
- $N_f = 8$: pion and σ (0^{++}) degenerate rather different than in $N_f = 4$

Effective field theories (a selection of recent work)

Holdom, Koniuk: A bound state model for a light scalar [Holdom, Koniuk JHEP12(2017)102]

→ Existence of light scalar, well separated from heavier states related to existence of near conformal gauge dynamics extending over a wide range

→ Scalar mass and form factor close to parity doubled limit

→ Light scalar has characteristics different from light dilaton

Appelquist, Ingoldby, Piai: Dilaton EFT [Appelquist, Ingoldby, Piai JHEP07(2017)035][JHEP03(2018)039]

→ Light singlet scalar interpreted as dilaton (spontaneous breaking of conformal symmetry)

→ Treat dilaton together with pions (spontaneous breaking of chiral symmetry)

→ Add general form for the dilaton potential to be determined from lattice data

→ EFT "fits" lattice data ($N_f = 8$ fundamental and $N_f = 2$ sextet)

Effective field theories (a selection of recent work)

Golterman, Shamir: The large-mass regime of the dilaton-pion low-energy effective theory
[Golterman, Shamir 1805.00198]

- Investigate dilaton-pion EFT in the Veneziano limit ($N_f \to \infty$ for N_f/N_c *fixed*)
- Expand around $n_f - n_f^*$, with $n_f = N_f/N_c$ and n_f^* onset of conformal window in Veneziano limit

  → Small mass region: dilaton decouples from pions, typical chiral behavior

  → Large mass region: hadron masses, decay constants scale with $m_f^{1/(1+\gamma^*)}$ (hyperscaling)

  ⇒ LSD $N_f = 8$ data is in the large mass region

  → Explains characteristics of LSD data

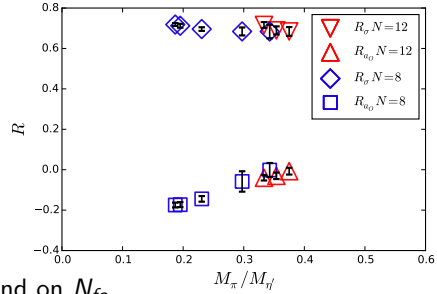
  → To reach small mass region: reduce $m_f \to m_f/100$

  ⇝ Small mass region may show that $N_f = 8$ is indeed confining

(Golterman Thu 11:20 PM)

Effective field theories (a selection of recent work)

[Meurice PRD96(2017)114507]



Meurice: Linear sigma model for multiflavor gauge theories

→ EFT describing σ, a_0, η', π

→ Explicit breaking of axial $U_A(1)$ symmetry depends on N_f

⇒ Effect on spectrum and onset of conformal window

→ Tree-level spectrum leads to dimensionless ratios:

$$R_\sigma = (M_\sigma^2 - M_\pi^2)/M_{\eta'}^2 + (1 - 2/N_f)(1 - M_\pi^2/M_{\eta'}^2)$$
$$R_{a_0} = (M_{a_0}^2 - M_\pi^2)/M_{\eta'}^2 - (2/N_f)(1 - M_\pi^2/M_{\eta'}^2)$$

→ LatKMI data: almost flat, no N_f dependence ⇝ e.g. bound on N_{fc}

De Floor, Gustafson, Meurice: Mass splittings in a linear sigma model for multiflavor gauge theories

- Consider flavors with two masses m_1 and $m_2 = m_1 + \delta_m$ (δ_m small)

→ Spectrum exhibits light-light, heavy-light, and heavy-heavy mesons

→ If $M_{\pi ll}^2 < M_{\pi hl}^2 < M_{\pi hh}^2$, then inverse ordering for scalars $M_{a_0 ll}^2 > M_{a_0 hl}^2 > M_{a_0 hh}^2$

[Floor, Gustafson, Meurice, 1807.05047] (Gustafson poster)

Higgs as a pseudo Nambu-Goldstone boson

Ferretti's Model [Ferretti JHEP06(2014)142]

- SU(4) gauge theory with fermions in two representations
  - → $N_6^W = 5$ Weyl massless flavors of sextet (Q) (two-index antisymmetric) fermions with EW charge
  - → $N_4 = 3$ fundamental Dirac flavors (q) with color charge

- Mesons
  - → sextet QQ, $Q\bar{Q}$, $\bar{Q}\bar{Q}$ pNGBs, vectors
  - → fundamental $q\bar{q}$ pNGBs, vectors

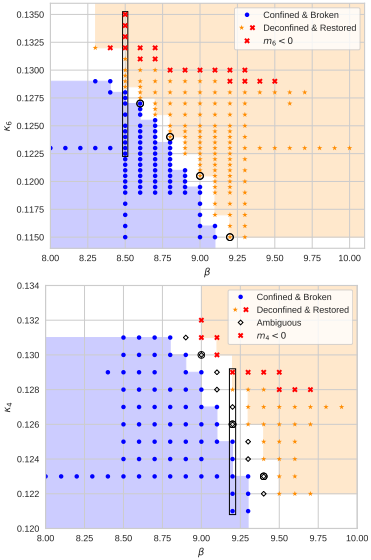
- Baryons
  - sextet $QQQQQ$ bosons
  - fundamental $qqqq$ bosons
  - chimera Qqq fermions

- Ferretti limit ($m_6 \to 0$) Higgs is a massless sextet NGB, its potential arises from SM interactions
- Fermion acquire mass from quartic mixing $u\bar{u}H \to u\bar{u}QQ$
- Non-anomalous superposition of $U_{A(4)}(1)$ and $U_{A(6)}(1)$ → axial singlet pNGB (ζ meson)
- top quark mixes linearly with chimera ⇒ large m_t

Adaption of Ferretti's model on the lattice

[Ayyar et al. PRD97(2018)074505][PRD97(2018)114502][PRD97(2018)114505]

- SU(4) gauge theory
  - → $N_6 = 2$ Dirac flavors ($N_6^4 = 4$ Weyl) sextet flavors
  - → $N_4 = 2$ fundamental Dirac flavors
- Finite temperature phase diagram: only two phases
  - Low-temperature
    - both fermion species confined and chirally broken
  - High-temperature
    - both fermion species deconfined and chirally restored
- Single phase transition appears to be first order as theoretically predicted

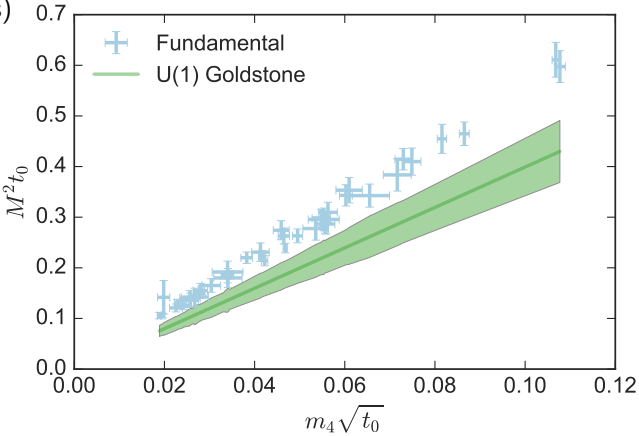


[Ayyar et al. PRD97(2018)114502]

Results in the Ferretti limit ($m_6 \to 0$)

- ζ meson
  - $\to$ $M_{PS6} = 0$ (sextet pNGB exactly massless)
  - $\to$ $M_\zeta < M_{PS4}$
  - $\to$ ζ meson lightest, massive state
  - $\to$ Reconstruct M_ζ from chiral fit (function of m_4 and m_6)

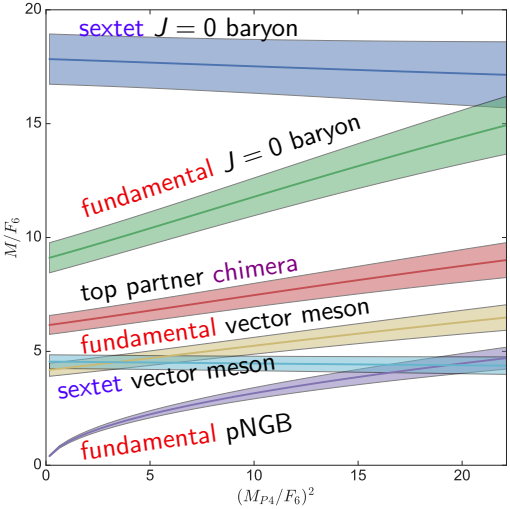
[Ayyar et al. PRD97(2018)074505]



Results in the Ferretti limit ($m_6 \to 0$)

- Spectrum in units of F_6
  - → (1/2,0) chimera (Qqq) is top partner and lightest baryon
  - → Experimental constraint: $F_6 \gtrsim 1.1$ TeV
    - ⇒ Mass of top partner chimera $M \gtrsim 6.5$ TeV

- Further details (Jay Thu 12:20 PM)



[Ayyar et al. PRD97(2018)114505]

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
  - $N_\ell = 4$ light flavors are chirally broken in the IR

heavy flavors could be invisible to SM

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)

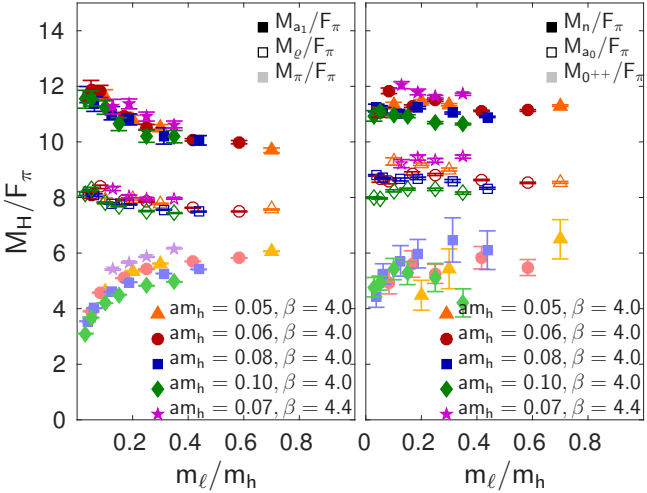
- Theory with degenerate $N_f = N_h + N_\ell$ is (mass-deformed) conformal and exhibits an IRFP
  - All ratios of hadron masses scale with the anomalous dimension (hyperscaling)
  - → Continuum limit is taken by sending fermion mass $m_f \to 0$

- 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, Witzel PLB773(2017)86]

Results for four light and eight heavy flavors

- Hyperscaling in the light-light sector



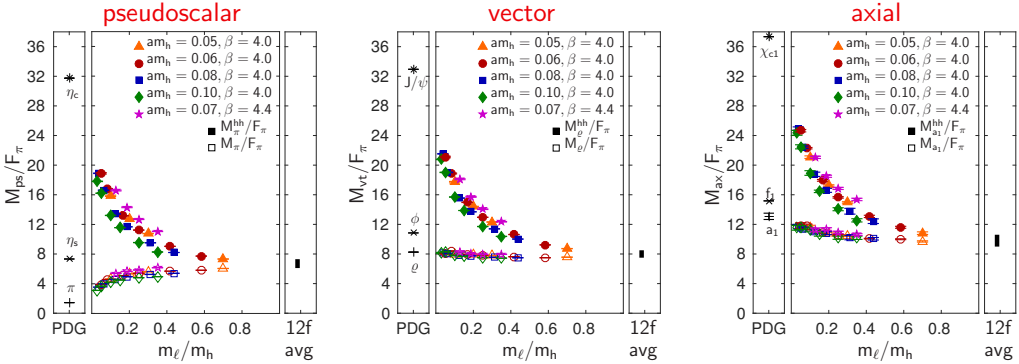
- $M_n/F_\pi \approx 11$
- $M_\varrho/F_\pi \approx 8$
- $M_{0^{++}}/F_\pi \approx 4-5$
  $\rightarrow$ taking the chiral limit is difficult but 0^{++} well separated from the ϱ and degenerate with the pion

- Statistical errors only
- "Scatter" indicates corrections to scaling

- Gauge coupling is irrelevant

[Brower et al. PRD 93 (2016) 075028]

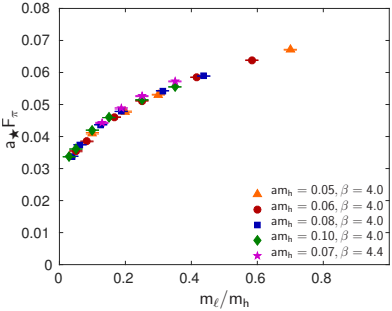
Results for four light and eight heavy flavors

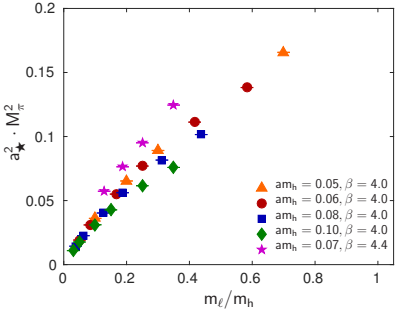


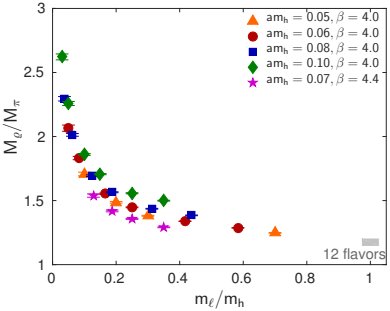
- 4+8 heavy-heavy spectrum is not QCD-like; QCD is not hyperscaling
- M^{hh}/F_π increases but F_π is finite in the chiral limit
- $M_\varrho^{hh} \sim 3M_\varrho \Rightarrow$ could be accessible at the LHC
- Data at $\beta = 4.0$ and 4.4: gauge coupling is irrelevant [Hasenfratz, Rebbi, Witzel PLB773(2017)86]

Results for four light and eight heavy flavors

- The system is chirally broken







- All data points in $a_\star$ units
- $a_\star F_\pi$ is finite

- Linearity in M_π^2 for small m_ℓ
- QCD: $m_d/m_s = 4.7/96 \approx 0.05$

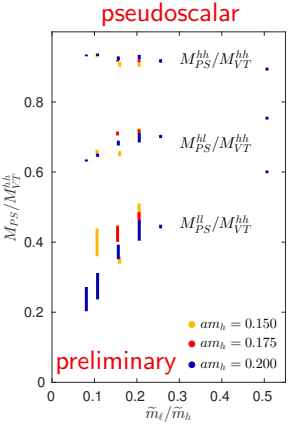
- $N_f = 4$ (QCD-like): ratio diverges
- $N_f = 12$: almost constant ratio

[Cheng at al. PRD90(2014)014509]

Outlook

- Mass-split models using 4 light and 6 heavy flavors of MDWF
  - → If degenerate $N_f = 10$ is conformal, expect to see hyperscaling
  - → First data with eventually large systematics look promising
  - → $N_f = 10$ would have larger anomalous dimension

- Simpler to calculate phenomenologically interesting 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] (Hasenfratz Fri 4:50 PM)
  - → S-parameter [Appelquist et al. PRL106(2011)231601], Higgs-potential, ...



- Combine two representations with mass-split model

summary

Summary

- The experiments will tell us whether the Higgs is a composite particle
  - → Performing nonperturbative simulations we can guide experimentalists and model builders
  - → Even (old) QCD calculations can be useful (DeGrand Thu 11:40 AM)
- Proposal of a new, alternative Higgs mechanism based on dynamical mass generation (Garofalo Mon 3:00 PM and Frezzotti Mon 3:20 PM), appendix
- Simulating near-conformal systems is more costly than QCD but can be as controversial
  - → Particular challenge: identifying an IRFP at strong coupling
- Simulations of near-conformal systems revealed a light 0^{++} with mass $M_{0^{++}} \sim M_\pi$
  - → Different effective field theories are required/explored
- Models based on two representations or mass-split systems exhibit novel features
  - → E.g. chimera baryons, hyperscaling in a chirally broken system

Acknowledgments

Step-scaling

A. Hasenfratz, K. Holland, J. Kuti, D. Nogradi

$N_f = 8$

A. Hasenfratz, G.T. Fleming, E.T. Neil, E. Rinaldi, C. Rebbi, D. Schaich

EFTs

T. Appelquist, M. Golterman, R. Koniuk, Y. Meurice

Ferretti model

T. DeGrand, D.C. Hackett, W.I. Jay, E.T. Neil

SU(2) adjoint

G. Bergner

Dynamical mass generation

M. Garofalo, R. Frezzotti

Fundamental Higgs

A. Maas

Mass-split models

A. Hasenfratz, C. Rebbi

SU(2) fundamental

V. Drach

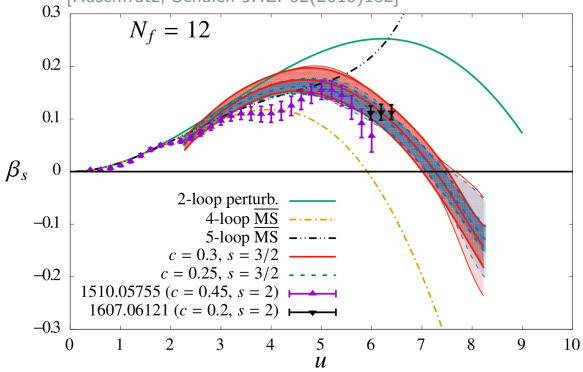
SU(4)/Sp(4)

J.W. Lee

appendix

$N_f = 12$ step-scaling

[Hasenfratz, Schaich JHEP02(2018)132]



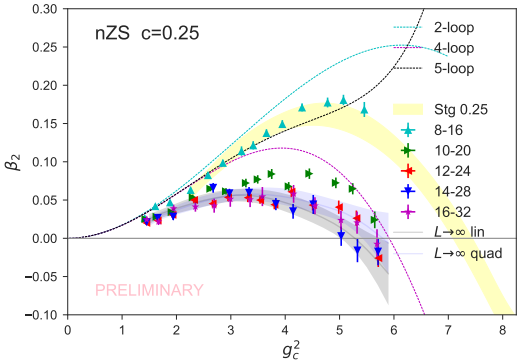
- Hasenfratz, Schaich
  nHYP-smeared staggered,
  Wilson gauge w/ adjoint term
  Wilson flow, clover operator

- Lin, Ogawa, Ramos
  unimproved staggered, Wilson gauge, twisted BC
  Wilson flow, clover operator

- Fodor et al.
  3× stout smeared staggered Symanzik gauge
  Symanzik flow, clover operator
  Newer results discussed in a moment!

$N_f = 12$ step-scaling

[Hasenfratz, Rebbi, Witzel 1710.11578]



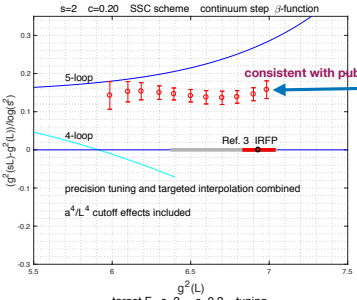
(Hasenfratz poster)

- Hasenfratz, Rebbi, Witzel
  Möbius domain-wall fermions, Symanzik gauge
  Zeuthen flow, Symanzik operator
  → Perturbative tree-level normalization
  [Fodor et al. JHEP09(2014)018]
  (working for $N_f = 12$ and 10)

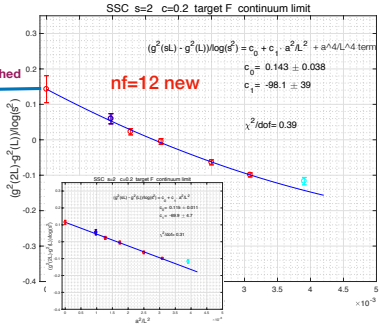
- Result robust
  → Alternative flow/operators
  → Without tree-level normalization
  → Alternative $L \to \infty$ extrapolation
  → Changing scheme, e.g., $c = 0.3$

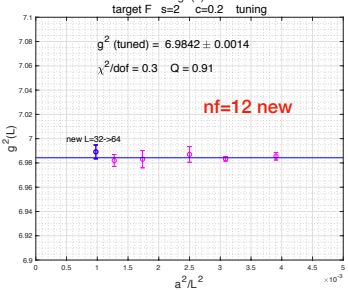
$N_f = 12$ step-scaling

- Page provided by Julius Kuti



consistent with published





LatHC PLB B779 (2018) 230-236 arXiv:1710.09262
confirmed with new updated results:

L=32 -> L=64 step at several targets
adds evidence against nf=12 IRFP

Talk: J. Kuti Wed. 14:00 BSM room 104

Dynamical generation of elementary particle masses — an alternative to the Higgs mechanism

[Dimopoulos, Frezzotti, Garofalo, Kostrzewa, Pittler, Rossi, Urbach]

- Non-abelian strongly interacting fermions coupled via Yukawa couplings to a scalar field and a Wilson-like term
  - $\rightarrow$ Exact symmetry acting on fermions and scalars prevents power divergent fermion mass terms
  - $\rightarrow$ Fermionic chiral invariance broken by Yukawa and Wilson-like term, but restored at critical Yukawa coupling
- Scalar field with double-well potential
  - $\rightarrow$ Left-over breaking of chiral symmetry at cutoff scale polarizes vacuum
  - $\Rightarrow$ spontaneous chiral symmetry breaking dynamically generates PCAC fermion mass
- Dynamical fermion mass can be naturally "small" and fermion masses exhibit natural hierarchy
- Higgs boson is a composite state in $WW + ZZ$ channel bound by new strongly interacting particles

Dynamical generation of elementary particle masses — an alternative to the Higgs mechanism

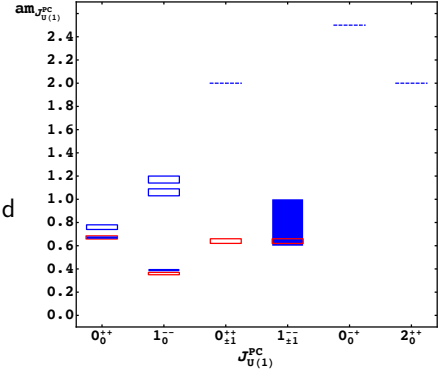
- Dynamical generation of fermion mass demonstrated by numerical simulations
  (Garofalo Mon 3:00 PM)

- Electro-weak interactions and how electro-weak boson acquire mass by this mechanism
  → Dynamical EW symmetry breaking due to a super-strongly sector
  → No "unnatural" fine tuning of effective four-fermion coupling
  (Frezzotti Mon 3:20 PM)

Effects of a fundamental Higgs

[Maas, Törek]

- Physical spectrum must be gauge invariant (in QCD guaranteed by confinement)
- Weak sector: perturbative description BRST-invariant, but gauge dependent
  - → Experimental results match predictions due to the Fröhlich-Morchio-Strocchi (FMS) mechanism [Fröhlich, Morchio, Strocchi PLB97 (1981)249][NPB160(1981)553]
  - → SM: weak gauge group matches global custodial symmetry
  - → Not guaranteed for BSM models
    - ⇒ discrepancy between physical and elementary spectrum

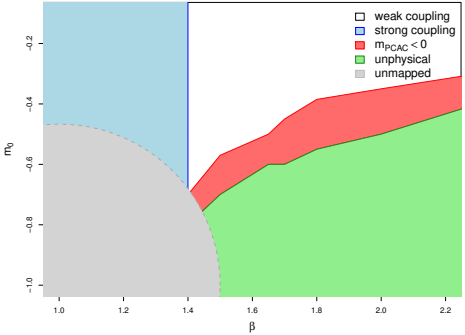


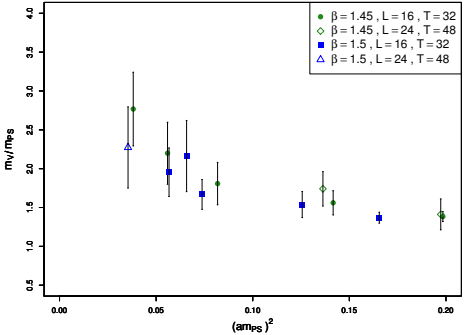
- Investigate SU(3) gauge theory with a fundamental Higgs field [Maas, Törek 1804.04453]
  - → Blue gauge invariant spectrum
  - → Red predictions from gauge-invariant PT [Maas 1712.04721]
  - → Standard PT fails

SU(2) with $N_f = 2$ fundamental flavors

[Drach, Janowski, Pica, Prelovsek]

- Starting new investigations using Wilson-clover fermion with Symanzik gauge action
- Improving on earlier work with (unimproved) Wilson fermions and plaquette gauge action





- Little changes w.r.t. unimproved setup
- Approaching the chiral limit
- Investigate scattering and $\rho\pi\pi$ coupling

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

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

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

→ One doublet plays the role of the Higgs doublet field

→ 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)

SU(4)/Sp(4) composite Higgs

[Bennett, Hong, Lee, Lin, Lucini, Piai, Vadacchino]

- Systematic program to investigate Sp(2N) gauge theories for $N_f = 2$ fund. flavors and $N > 1$
  - → Quenched results for Sp(4) published [Bennett et al. JHEP 1803(2018)185]
  - → First dynamical results for masses and decay constants (Lee Thu 2:20 PM)
  - → Qualitative agreement between quenched and dynamical results
  - → Comparison between $N_f = 2$ fundamental and anti-symmetric