# Composite Higgs from mass-split models

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## Motivation

- What is the nature of the Higgs boson?
- What is the origin of electro-weak symmetry breaking?
- Is there new physics below the Planck-scale? How could it look like?

| experiment | theory |
|---|---|
| • Higgs is a light scalar with mass 125 GeV | • Standard Model is not UV complete |
| • No other resonances discovered so far | • Spectrum cannot be QCD-like |

large separation of scales

e.g. strongly coupled conformal gauge theories

→ Higgs is a composite particle
→ Other resonances predicted in the few TeV range
→ Nonperturbative simulations using lattice field theory

## Framework of composite Higgs models

- Start from Higgs-less Standard Model $\mathcal{L}_{\mathrm{SM}_0}$
- Add new strongly interacting gauge fermion system $\mathcal{L}_{\mathrm{SD}}$
- Add interactions between new sector and Standard Model $\mathcal{L}_{\mathrm{int}}$

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

→ $\mathcal{L}_{\mathrm{SD}}$ triggers EW symmetry breaking and a light Higgs emerges
→ Give mass to SM gauge fields and fermions (4-fermion interaction, partial compositeness, . . . )
→ Effective ansatz: theory in the UV required to explain mass of $\mathcal{L}_{\mathrm{SD}}$ fermions

## Mass-split models as candidates for $\mathcal{L}_{\mathrm{SD}}$

- Promising candidates are chirally broken in the IR but conformal in the UV [1]


→ Conformal many flavor system in the UV
→ Allow some of the masses to decouple in the IR
→ Arrive at a chirally broken few-flavor system
e.g. SU(3) gauge theory with 12 or 10 flavors

- Mass-split system are non-QCD like:
  chirally broken, but dimensionless ratios show conformal hyperscaling i.e. IRFP governs UV dynamics
- Physical quantities depend only on $m_\ell/m_h$
- Gauge coupling is irrelevant, takes the value at the IRFP
- For $m_\ell \to 0$, only $m_h$ is relevant, effectively setting the scale
- The Higgs boson can emerge as dilaton-like particle or pseudo Nambu Goldstone boson (pNGB)

### dilaton-like Higgs

- Ideal two massless flavors in the IR
- Possibly a light $0^{++}$ could emerge from conformal FP
- Trivial vacuum alignment:
  $F_\pi \equiv$ vev SM $\sim 246$ GeV

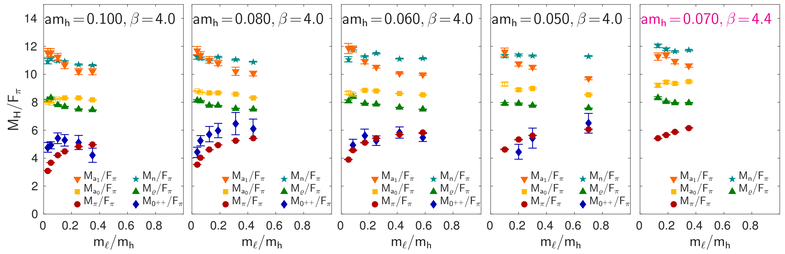
### pNGB Higgs

- Ideal four massless flavors in the IR
- Mass emerges from its interactions
- Non-trivial vacuum alignment:
  $F_\pi \equiv$ (vev SM)/ $\sin(\chi) > 246$ GeV

## Example: 4+8 mass-split model [2]

- Plaquette gauge action with negative adjoint term and nHYP smeared staggered fermions [3]
- $\beta = 4.0$ and 4.4, $\beta_a/\beta = -0.25$, $L^3 \times T = 24^3 \times 48$, simulations performed using FUEL [4]
- $am_\ell = 0.003, 0.005, 0.010, 0.015, 0.025, 0.35$; $am_h = 0.05, 0.06, 0.07, 0.08, 0.10$
- Connected spectrum from wall-sources and point-sinks, $O(500)$ configurations
- Disconnected spectrum from stochastic sources with time-slice dilution, $O(1000)$ configurations

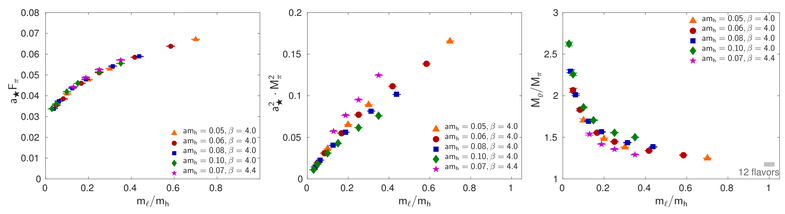
## Light-light spectrum




- Dimensionless ratios — no scale setting
- Iso-singlet scalar $0^{++}$ is light, almost degenerate with the pion
- Ratios do neither depend on heavy flavor mass $m_h$ nor on gauge coupling $\beta$

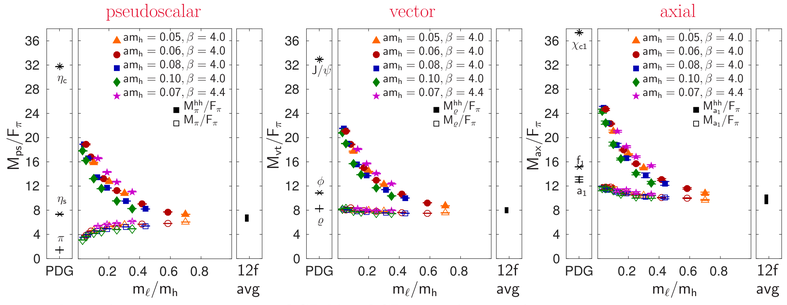
⇒ the system exhibits hyperscaling

## The light-light sector is chirally broken




- Using the same lattice units, $F_\pi$ shows hyperscaling and approaches a finite value
- $M_\pi^2$ in lattice units shows linear behavior for small $m_\ell$ (cf. QCD: $m_d/m_s = 4.7/96 \approx 0.05$)
- As in QCD like theories, $M_\varrho/M_\pi$ diverges for $m_\ell \to 0$

## Hyperscaling in the light-light and heavy-heavy sector

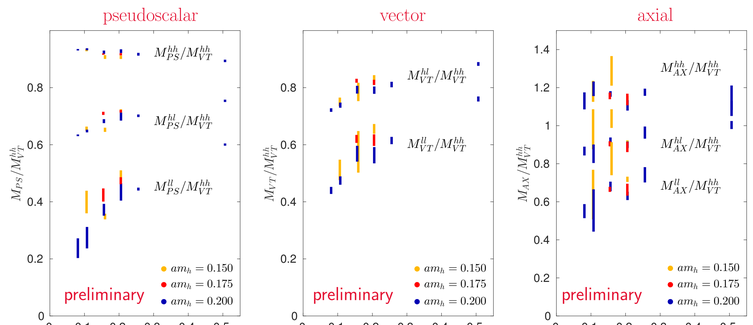



- 4+8 heavy-heavy spectrum is not QCD-like; QCD is not hyperscaling
- $M^{hh}/F_\pi$ increases but $F_\pi$ is finite in the chiral limit
- $M^{hh}_\varrho \sim 3M_\varrho \Rightarrow$ could be accessible at the LHC
- Data at $\beta = 4.0$ and 4.4: gauge coupling is irrelevant

## Outlook: 4+6 mass-split model (Lattice Strong Dynamics collaboration)

- Tree-level improved Symanzik gauge action with stout-smeared Möbius domain-wall fermions [5]
- Simulations performed with `Grid` [6] or `IroIro++` [7] to utilize state-of-the-art supercomputers
- Domain-wall fermions feature continuum-like symmetries simplifying calculations
  → Easier to calculate the Higgs potential, S-parameter, scattering processes, . . .
  → Easier to investigate partial compositeness or four-fermion interactions
  → Avoids issues of staggered fermions (e.g. rooting, symmetry breaking)
- Likely larger anomalous dimension if $N_f = 10$ is indeed conformal [8, 9, 10]

## Exploring the parameter space




- No data points — possibly large systematic effects: low statistics, excited states, FV, etc.
- Identified promising parameters for numerical simulations
- First signs of hyperscaling, starting to push into the chiral regime

## Summary

Mass-split models in the basin of attraction of an IRFP

- Exhibit a large scale separation
- Have a non-QCD like spectrum
  → Light $0^{++}$ iso-singlet scalar
  → Ratios show hyperscaling independent of coupling or heavy flavor mass
- Feature composite Higgs scenarios with a dilaton-like or pNGB Higgs boson
- Are highly predictive: at most one free parameter (due to hyperscaling)

## References

[1] Luty and Okui, JHEP 09 (2006) 070, Dietrich and Sannino PRD 75 (2007) 085018, Vecchi arXiv:1506.00623, Ferretti and Karateev JHEP 1403 (2014) 077
[2] R.C. Brower, A. Hasenfratz, C. Rebbi, E. Weinberg, and O. Witzel, J.Exp.Theor.Phys. 120 (2015) 423; PRD 93 (2016) 075028; A. Hasenfratz, C. Rebbi, and O. Witzel, PLB 773 (2017) 86
[3] A. Cheng, A. Hasenfratz, D. Schaich, PRD 85 (2012) 094509
[4] J. Osborn et al., `http://usqcd-software.github.io/FUEL.html`
[5] T. Kaneko, S. Aoki, G. Cossu, H. Fukaya, S. Hashimoto, and J. Noaki (JLQCD), PoS LATTICE2013 (2014) 125
[6] P. Boyle, G. Cossu, A. Portelli, and A. Yamaguchi, `https://github.com/paboyle/Grid`; PoS LATTICE2015 (2015) 023
[7] G. Cossu et al., `https://github.com/coppolachan/IroIro`
[8] T.-W. Chiu(2016), arXiv:1603.08854; PoS LATTICE2016, 228 (2017)
[9] A. Hasenfratz, C. Rebbi, and O. Witzel, arXiv:1710.11578
[10] Z. Fodor, K. Holland, J. Kuti, D. Nogradi, and C. H. Wong, PLB 779 (2018) 230

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