Exploring a composite Higgs scenario in a model with four light and six heavy flavor

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Composite Higgs scenario: 4+6 model [LSD PRD103(2020)014504][Witzel et al. PoS ICHEP2020 675]

- Extend the Standard Model by a new, strongly coupled gauge-fermion system
  - → SU(3) gauge with $N_\ell = 4$ light flavors chirally broken in the IR
    - ⇝ fundamental composite 2HDM [Ma, Cacciapaglia JHEP03(2016)211]
  - → $N_h = 6$ heavy flavors push the system near an IRFP of a conformal theory
    - ⇝ maybe invisible to SM
- Higgs boson arises as bound state of this new sector
  - → dilaton-like 0^{++} or pNGB scenario
- Large separation of scales ⇒ light Higgs boson but other states are much heavier
- Inherits hyperscaling constraining particle spectrum ⇝ highly predictive
- Described by extended dilaton chiral perturbation theory (dChPT)

▲ Needs mechanism to generate masses for SM fermions and gauge bosons

▲ Needs to be in agreement with electro-weak precision constraints (S-parameter)

Determine y_m from hyperscaling relation [LSD PRD103(2020)014504]

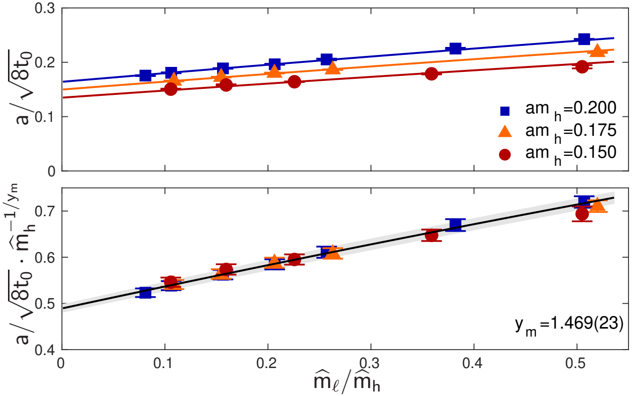
- Example: $a/\sqrt{8t_0}$

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

- 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 $\widehat{m}_h^{1/y_m}\cdot(c_2(\frac{\widehat{m}_l}{\widehat{m}_h})^2 + c_1(\frac{\widehat{m}_l}{\widehat{m}_h}) + c_0)$ to all 17 data points at three $\widehat{m}_h$ values and determine $y_m = 1.469(23)$



- Note: $\Phi_{\sqrt{8t_0}}(0) \approx 0.48$

- Hyperscaling of $\sqrt{8t_0}$ **not** a general prediction of dChPT

Determine y_m from hyperscaling relation [LSD PRD103(2020)014504]

- Example: aF_{ps}

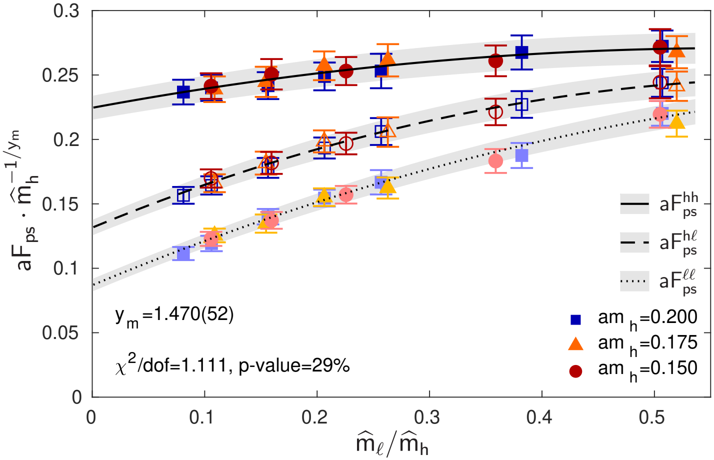
$$aM_H = \widehat{m}_h^{1/y_m}\,\Phi_H(\widehat{m}_\ell/\widehat{m}_h)$$

- 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



Low energy effective description

- At $\widehat{m}_h(a\mu)^{-y_m} \approx 1$:
  heavy flavors decouple, light flavors condense and chiral symmetry breaks spontaneously
- Define hadronic or chiral symmetry breaking scale $\Lambda_H = \widehat{m}_h^{1/y_m} a^{-1}$
  → chiral limit $a = (\widehat{m}_h)^{1/y_m} \cdot \Phi_{\sqrt{8t_0}}(0) \cdot \sqrt{8t_0}|_{m_\ell=0}$ ⇒ $\Lambda_H^{-1} = \Phi_{\sqrt{8t_0}}(0) \cdot \sqrt{8t_0}|_{m_\ell=0}$
- Below Λ_H, the 4+6 system reduces to chirally broken $N_f = 4$ with running fermion mass m_f

- Seek chiral effective Lagrangian for the light sector (dropping superscript $\ell\ell$)
  → Smoothly connected to the hyperscaling relation valid at $\mu = \Lambda_H$
  → Express lattice scale a in terms of Λ_H: $M_H/\Lambda_H = (aM_H) \cdot \widehat{m}_h^{-1/y_m} = \Phi_H(\widehat{m}_\ell/\widehat{m}_h)$

- 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

Dilaton chiral perturbation theory (dChPT)

[Golterman, Shamir PRD94(2016)054502] [PRD98(2018)056025] [Golterman, Neil, Shamir PRD102(2020)034515]
[Appelquist, Ingoldby, Piai JHEP03(2018)039] [JHEP07(2017)035] [PRD101(2020)075025]

- Derived for chirally broken systems just below the conformal window with a 0^{++} (dilaton) as light as the pseudoscalar
- Can be adapted for (the light sector of) mass-split systems: $m_f \to (\frac{\widehat{m}_\ell}{\widehat{m}_h}) \cdot \Lambda_H$
- 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 PRD102(2020)034515]

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

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

Fit to the general dChPT scaling relation [LSD PRD103(2020)014504]

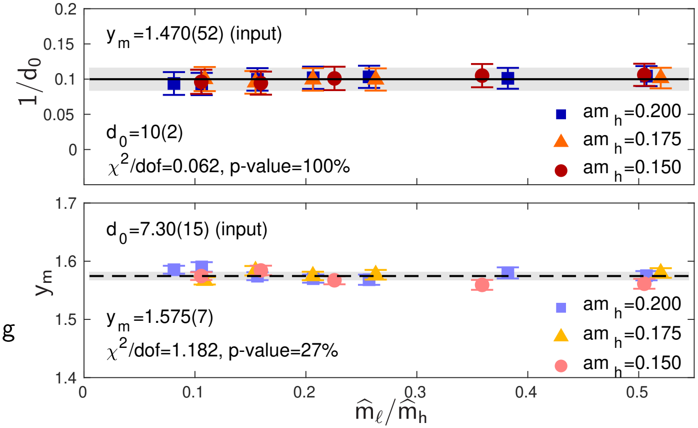
- Fitting

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

  → 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")

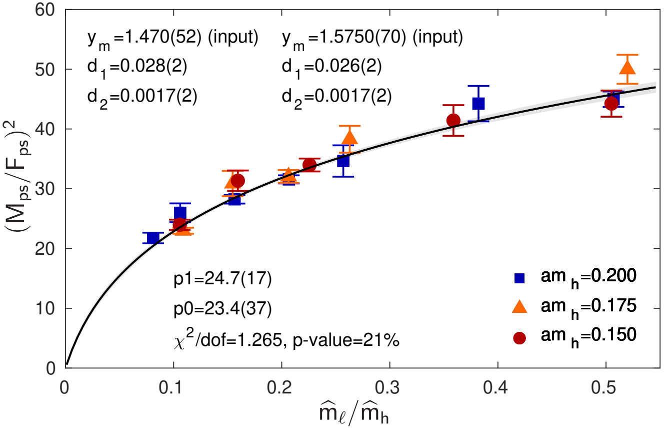


Fit assuming a specific dilaton potential [LSD PRD103(2020)014504]

- Fitting

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

→ Determine $p0 = y_m d_1$ and $p1 = y_m d_1/d_2$

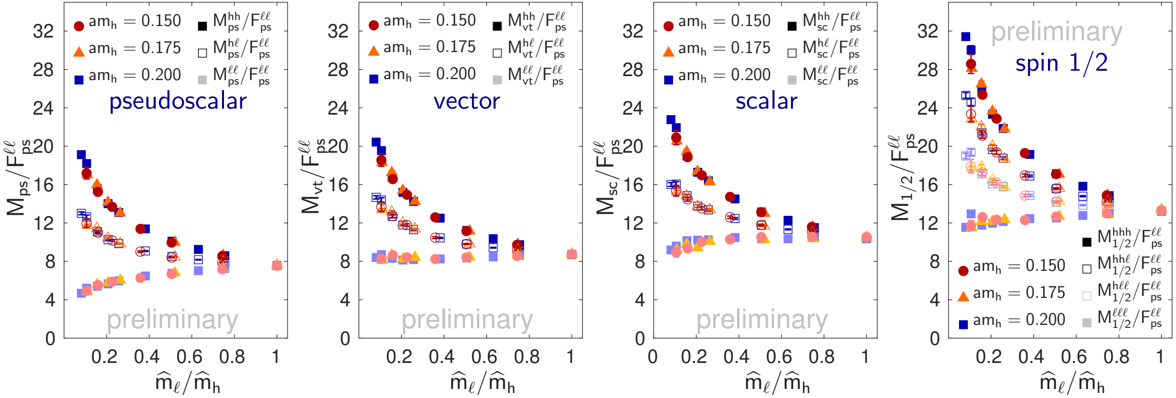


Update 2021

- Improved statistics on existing ensembles
- Including data from 7 new ensembles

$$\frac{m_\ell}{m_h} = \begin{cases} \frac{0.125}{0.200}, \frac{0.150}{0.200}, \frac{0.200}{0.200} \\ \frac{0.130}{0.175}, \frac{0.175}{0.175} \\ \frac{0.111}{0.150}, \frac{0.150}{0.150} \end{cases}$$

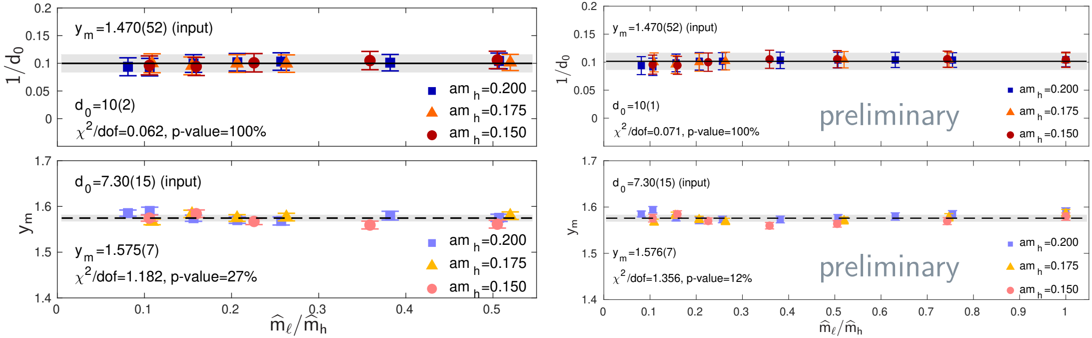
Ratios over $F^{\ell\ell}_{ps}$



- Hyperscaling relation: $aM_H = \widehat{m}_h^{1/y_m}\,\Phi_H(\widehat{m}_\ell/\widehat{m}_h) \Rightarrow \dfrac{M_{H1}}{M_{H2}} = \dfrac{\Phi_{H1}(\widehat{m}_\ell/\widehat{m}_h)}{\Phi_{H2}(\widehat{m}_\ell/\widehat{m}_h)}$ (depend only on $\widehat{m}_l/\widehat{m}_h$)
- light-light ($\ell\ell$), heavy-light ($h\ell$), heavy-heavy (hh) states

General dChPT scaling relation

- Repeating general dChPT fit using the same y_m values as input



Summary

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

- Extended dChPT describes our mass-split system very well
  - → $\widehat{m}_\ell/\widehat{m}_h$ takes the role of m_f in regular dChPT
  - → Range of validity (need of higher order terms) can be tested in dependence of continuous $\widehat{m}_\ell/\widehat{m}_h$
  - ▲ Need to measure the 0^{++} for additional validation

- $N_f = 10$ 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^* might be too small for phenomenological applications

Outlook

- Numerically measure the isosinglet scalar 0^{++}
- Push simulations deeper into the chiral regime
- Determine phenomenologically interesting quantities
  - → Baryonic anomalous dimension
  - → Calculate the S-parameter
  - → Determine the Higgs potential
  - → Explore mechanism to generate fermion masses

Thank you

Tom Appelquist, Peter Boyle, Maarten Golterman,
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Resources

LLNL: vulcan, lassen
ALCF (ANL): mira, theta
USQCD: qcd16p/18p (Jlab)
sdcc (BNL)
U Colorado: summit
BU: engaging and scc
(MGHPCC)

Software

GRID [Boyle et al. PoS Lattice2015 023]
Qlua [Pochinsky PoS Lattice2008 040]

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

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

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

→ 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]

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

⇝ 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)

  → 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]

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

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