Exploring composite Higgs scenarios with mass-split models

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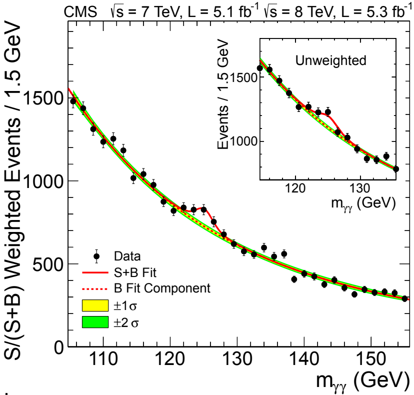
motivation

Experimental observations

- Discovery of the Higgs boson in 2012
  [Atlas PLB 716 (2012) 1] [CMS PLB 716 (2012) 30]
- Mass of the Higgs boson is 125 GeV
- No other states found
  - ⇒ must be much heavier, likely > 1.5 TeV
- Standard Model not UV complete
- What is the origin of the electro-weak sector?

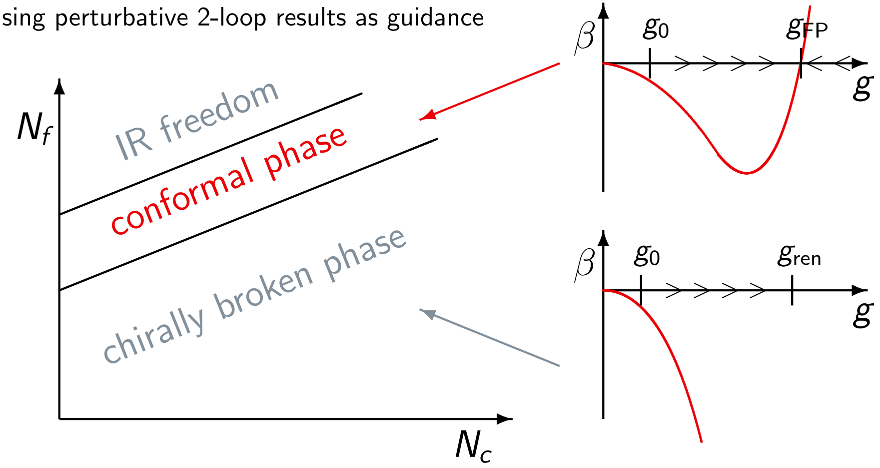
⇒ Seek a model exhibiting a large separation of scales

⇝ Near-conformal gauge theories / composite Higgs model



Near-conformal gauge theories

- Gauge-fermion system with $N_c \geq 2$ colors and N_f flavors in some representation
- Using perturbative 2-loop results as guidance



Composite Higgs models

- New, strongly interacting gauge fermion system
- Effective theory describing part of the dynamics
- Coupled to the Standard Model

Higgs-less, massless SM $\longrightarrow$ "full" SM

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

Composite Higgs models

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Add new strong dynamics coupled to SM

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

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

This construction gives mass to:

- the SM gauge fields
- the SM fermions fields: 4-fermion interaction or partial compositeness

Composite Higgs models

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

↑

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

This construction gives 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: $\mathcal{L}_{UV}$

Candidates for $\mathcal{L}_{SD}$

- Promising candidates are chirally broken in the IR but conformal in the UV
  [Luty and Okui JHEP 09(2006)070], [Dietrich and Sannino PRD75(2007)085018], [Vecchi arXiv:1506.00623], [Ferretti and Karateev JHEP 1403 (2014) 077], ...

UV ——— conformal ——— chirally broken ——→ IR

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

- One possible implementation: mass-split models (see also talk by Dan Hackett)
  → Example: SU(3) gauge theory with "heavy" and "light" (massless) fundamental flavors
  - Add heavy flavors to push the system near an IRFP of a conformal theory
  - 4 light flavors are chirally broken in the IR

- Composite Higgs can emerge as dilaton or pseudo-Nambu Goldstone boson

Two possibilities for a composite Higgs (IR sector)

- Spontaneous breaking of scale symmetry: Higgs is a dilaton
  - → Possibly light 0^{++} scalar
  - → F_π = SM vev $\sim$ 246 GeV
  - → ideal 2 massless flavors in the IR
  - → closer to old technicolor ideas

- Spontaneous breaking of flavor symmetry: Higgs is a pNGB
  - → Mass emerges from its interactions
  - → Non-trivial vacuum alignment $F_\pi = (\text{SM vev})/\sin(\chi) > 246$ GeV
  - → ideal 4 massless flavors in the IR
  - → Vecchi: UV-complete models requiring at least two types of fermions in two different gauge group representations [arXiv:1506.00623]
  - → Ferretti: Classification of models with custodial symmetry and partial compositeness [JHEP 1403 (2014) 077] [JHEP 1606 (2016) 107]
  - → Ma and Cacciapaglia: Fundamental composite 2HDM with 4 flavors in SU(3) gauge [JHEP 03 (2016) 211]

Mass-split models

- Constructed to exhibit large scale separation ("walking coupling")
  - → Tunable by the mass m_h of the heavy flavors
- Highly predictive: inherit hyperscaling from the IRFP
  - → dilaton-like Higgs (2+N): no free parameter
  - → pNGB Higgs (4+N): only angle of vacuum alignment to be fixed
- Anomalous dimensions correspond to the conformal IRFP
  - → Total number of flavors should be inside but close to the lower edge of the conformal window
- Strongly coupled, chirally broken but not QCD-like

- Numerical results
  - → four light and eight heavy flavors (4+8)
  - → four light and six heavy flavors (4+6) — exploratory

4+8 model

based on

R. Brower, A. Hasenfratz, C. Rebbi, E. Weinberg, O.W. PRD 93 (2016) 075028

A. Hasenfratz, C. Rebbi, O.W. PLB 773C (2017) 86-90

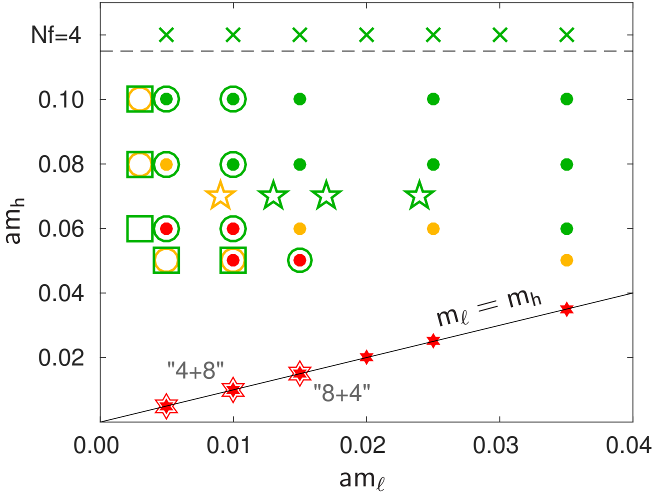
On the lattice

- Setup
  - SU(3) gauge group
  - Fundamental adjoint gauge action with $\beta_a = -\beta/4$ [Cheng et al. arXiv:1311.1287][Cheng et al. PRD 90 (2014) 014509]
  - nHYP smeared staggered Fermions [Hasenfratz et al. JHEP 05 (2007) 029]
  - Most simulations/measurements performed with FUEL [J. Osborn]
- Goals
  - Explore near conformal or conformal dynamics
  - Compute the iso-singlet 0^{++}
- References

  [JETP 120 (2015) 3, 423] [PoS Lattice2014 254] [CCP proceedings 2014] [PRD 93 (2016) 075028] [PLB 773C (2017) 86-90]

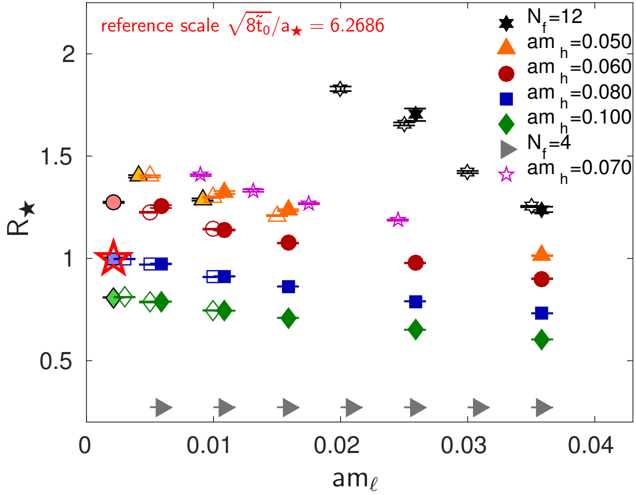
  (a longer, detailed paper is in preparation)

Performed simulations



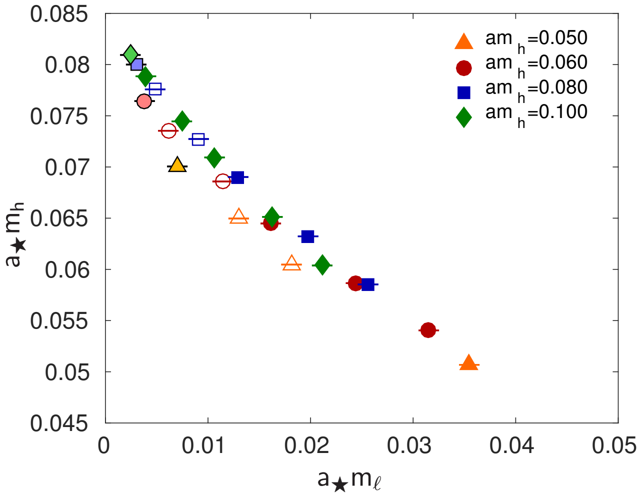
- Symbols indicate volumes and colors finite volume effects
  red: squeezed
  yellow: marginal
  green: OK
- $\beta = 4.0$
  □: $48^3 \times 96$ or $36^3 \times 64$
  ○: $32^3 \times 64$
  ●: $24^3 \times 48$
- $\beta = 4.4$
  ☆: $32^3 \times 64$
- Up to 40k MDTU

Four light and eight heavy flavor are not QCD like



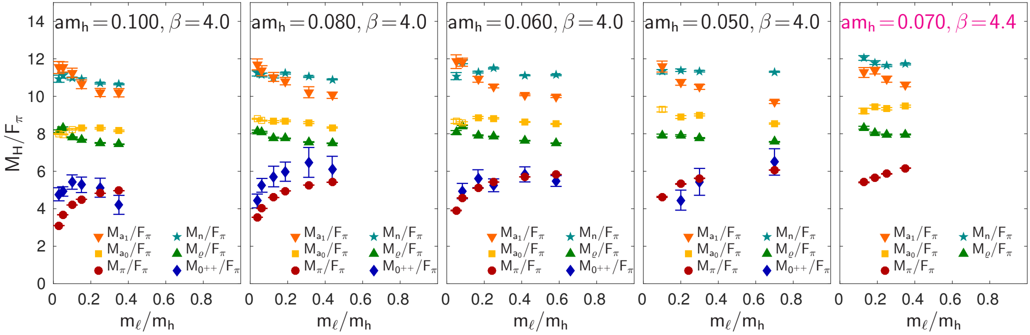
- Use the Wilson flow ($\sqrt{8\tilde{t}_0}$) to define a relative lattice spacing
  $$R_\star = \left[\sqrt{8\tilde{t}_0}/a\right] / \left[\sqrt{8\tilde{t}_0}/a_\star\right]$$
- $N_f = 12$ (conformal): scale breaks down for $m_\ell = m_h \to 0$
- 4+8: scale exhibits strong dependence on m_ℓ and m_h
- QCD: scale largely independent of m_ℓ $\to$ define scale in the chiral limit

Four light and eight heavy flavor are not QCD like



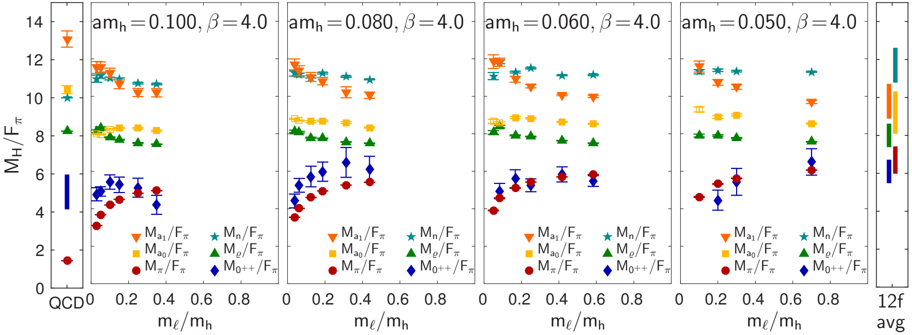
- "Naive conversion" of bare input quark masses to physical units
- Hyperscaling predicts quark masses scale according to the anomalous dimension
- QCD: scale largely independent of m_ℓ and m_h

Light-light spectrum: ratios of M_H/F_π



- Pion, rho, a_0, a_1, nucleon, and 0^{++} scalar (statistical errors only)
- 0^{++} is light ($M_{0^{++}} < M_\varrho$), it tracks the pion. Chiral limit?
- M_π/F_π bends down $\Rightarrow$ indicates system is chirally broken
- Dimensionless ratios! No scale setting needed

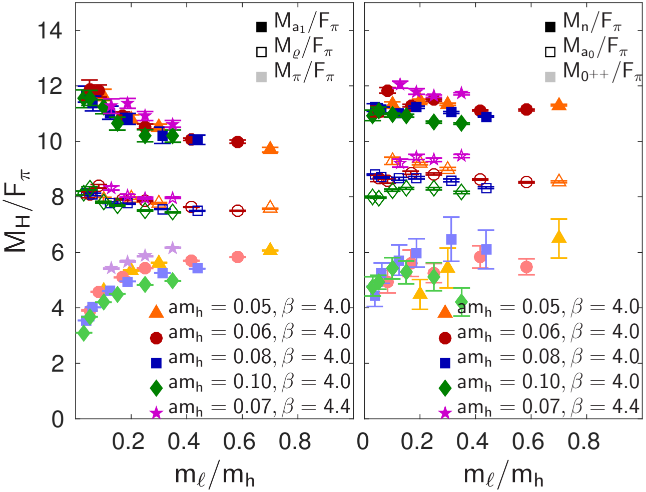
Light-light spectrum: ratios of M_H/F_π



- For increasing m_h and $m_\ell \to 0$ we approach QCD [PDG values]
- For decreasing m_h and $m_\ell \sim m_h$ we approach degenerate 12 flavors

[LatHC PLB 703(2011) 348][LatKMI PRD86 (2012) 059903][LatKMI PRL 111 (2013) 162001][Cheng et al. PRD 90 (2014) 014509]

Hyperscaling at work

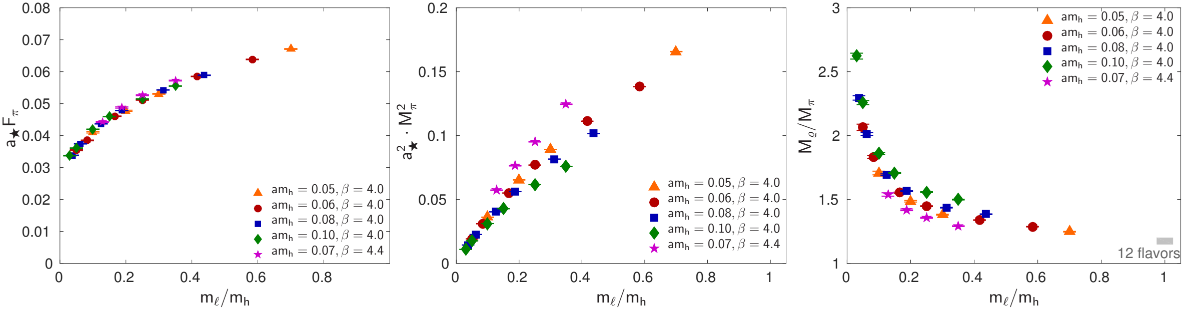


- $M_n/F_\pi \approx 11$
- $M_\varrho/F_\pi \approx 8$
- $M_{0^{++}}/F_\pi \approx 4 - 5$
  (taking the chiral limit is difficult but 0^{++} well separated from the ϱ)

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

- Gauge coupling is irrelevant

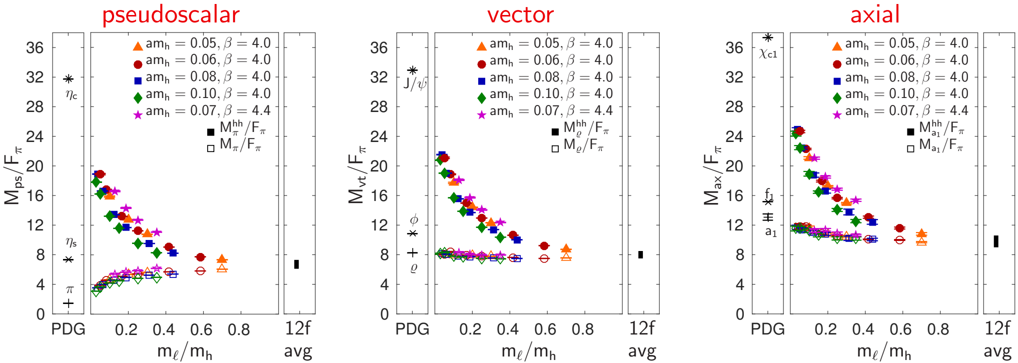
The system is chirally broken



- All data points in $a_\bigstar$ units
- $a_\bigstar F_\pi$ 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

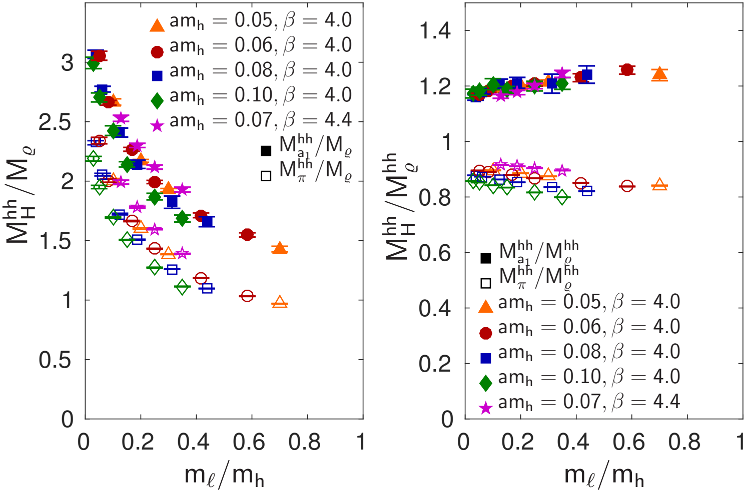
[Cheng at al. 2014]

Light-light and heavy-heavy spectrum



- 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

Ratios over M_ϱ and M_ϱ^{hh}



- Heavy-heavy states increase mostly due to a light-light quantity in the denominator
- Hyperscaling is also expected for heavy-light states
  → directly coupled to SM

4+6 model

(Lattice Strong Dynamics Collaboraton)

Why moving to 4+6?

- 4+8 is built on IRFP of the conformal system with 12 fundamental flavors
  - → 12 flavors has a small anomalous dimension (∼0.25)
  - → Phenomenologically not that attractive
- Indications of conformality of 10-flavors [Chiu 1603.08854][PoS LATTICE2016 (2017) 228]
  - → Closer to the lower edge of the conformal window
    - ⇒ larger anomalous dimension
  - → Further investigations needed (see talk by Anna Hasenfratz)

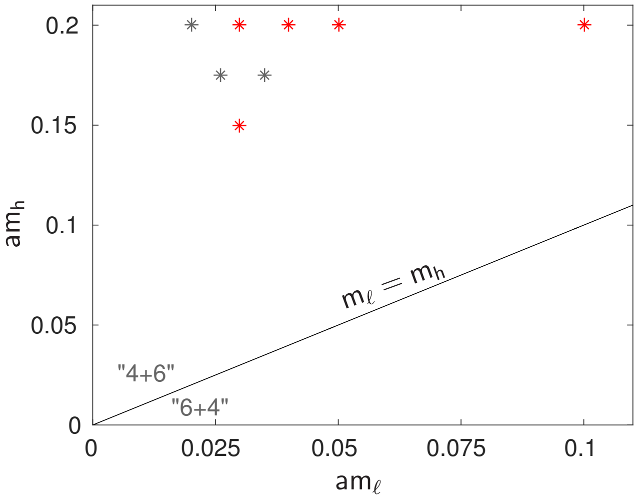
Simulating 4+6

- Set-up
  - → SU(3) gauge group
  - → Symanzik gauge action with stout-smeared Möbius domain-wall fermions
    [Peardon et al. PRD80 (2009) 054506][Brower et al. CPC 220 (2017) 1]
  - → Simulations performed with `iroiro++` and `Grid` [Boyle et al. PoS LATTICE2015 023]
  - ⇝ Targeting BG/Q; CPU, KNL, and in the future GPU clusters

- Domain-wall fermions feature continuum-like symmetries and expressions
  - → Simplifies to investigate mass generation of SM fermions
    - ⇝ partial compositeness or four-fermion interactions
  - → Easier to calculate the Higgs potential, S-parameter, scattering processes, ...
  - → Avoids issues of rooting or fermion universality near an IRFP [arXiv:1710.08970]

- Simulations are costly ...

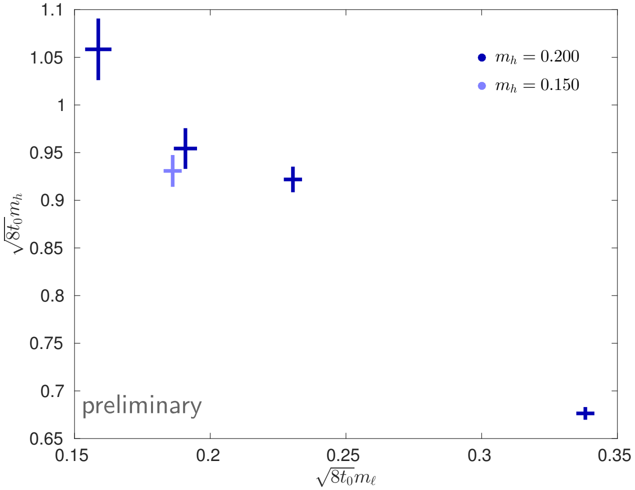
Exploratory $4+6$ simulations on $16^3 \times 32$ lattices



- Identified $\beta = 4.03$ to be promising
- Exploratory simulations
  - $\rightarrow$ Low statistics
  - $\rightarrow$ Small volumes
  - $\Rightarrow$ Maybe significant systematic effects
- Too difficult to extract $M_\pi^{\ell\ell}$ and $F_\pi^{\ell\ell}$
- Only "sufficient" data for $*$;

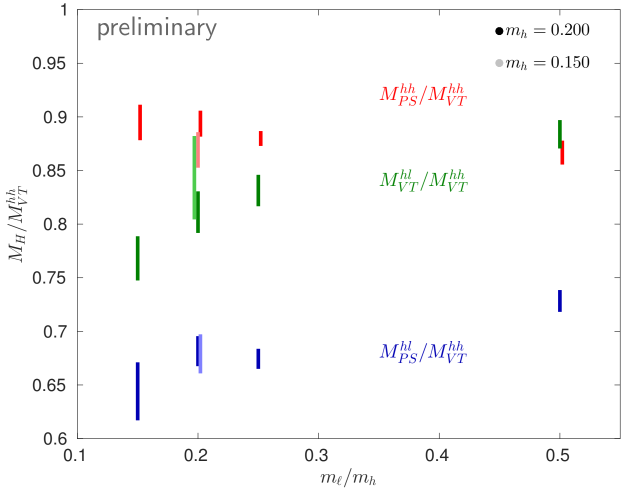
  $*$ in progress

Naive conversion of bare input quark masses to physical units



- No data points; likely not free of systematic effects
- Hyperscaling predicts quark masses scale according to the anomalous dimension
- QCD: scale largely independent of m_ℓ and m_h
- Ignoring effect due to am_{res}

Ratios over M_{VT}^{hh}



- No data points; likely not free of systematic effects (ignoring m_{res})
- Large uncertainties and too few data points for firm conclusions
- Nevertheless we might see first signs of hyperscaling for 4+6
- If 4+6 shows hyperscaling, it is a strong indication that $N_f = 10$ is conformal

Concluding remarks

- Our model with four light and eight heavy flavors exhibits
  - → a large separation of scales, walking gauge coupling
  - → $M_\pi \sim M_{0^{++}} < M_\varrho$
  - → hyperscaling: ratios depend only on m_ℓ/m_h
  - → predictive: only scale to be set using e.g. F_π
  - → main results derived/shown for dimensionless ratios!
- Heavy-heavy (and heavy-light) spectrum accessible but not QCD-like

Future: four light and six heavy flavors

- → Closer to boundary of the conformal window; larger anomalous dimension
- → Theoretically clean, but expensive domain-wall fermions
- → mass generation of SM fermions, Higgs potential, S-parameter, ...

Resources

4+8:

- USQCD: Ds, Bc, and pi0 cluster (Fermilab)
- BU: engaging and scc (MGHPCC)
- XSEDE: stampede (TACC) and supermic (LSU)
- U Colorado: summit

4+6:

- USQCD: Ds, Bc, and pi0 cluster (Fermilab); qcd16p (Jlab); sdcc (BNL)
- LLNL: vulcan
- U Colorado: summit
- BU: scc (MGHPCC)