Numerical exploration of a mass-split model with four light and eight heavy flavors

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Bound states in strongly coupled systems
Florence, Italy, March 14, 2018

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

Motivation

- Mass of the Higgs boson is 125 GeV
- Other states must be much heavier, likely > 1.5 TeV
- Standard Model not UV complete
- What is the origin of the electro-weak sector?

$\Rightarrow$ Seek a model exhibiting a large separation of scales

$\rightsquigarrow$ Near-conformal gauge theories / composite Higgs model

Mass-split models

- Constructed to exhibit large scale separation ("walking coupling")
- Highly predictive
  - → dilation-like Higgs (2+N): no free parameter
  - → pNGB Higgs (4+N): only angle of vacuum alignment to be fixed
- 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

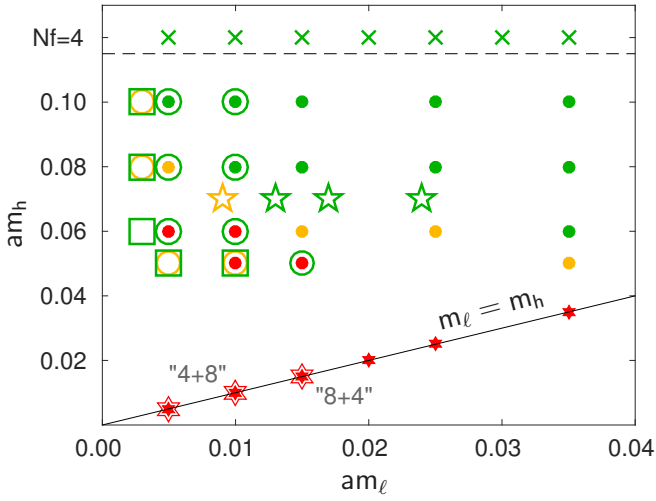
On the lattice

- 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]

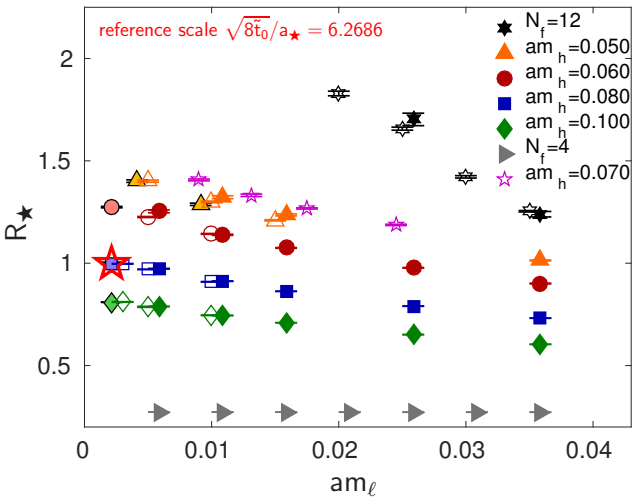
  (a longer, detailed paper is in preparation)

Performed simulations



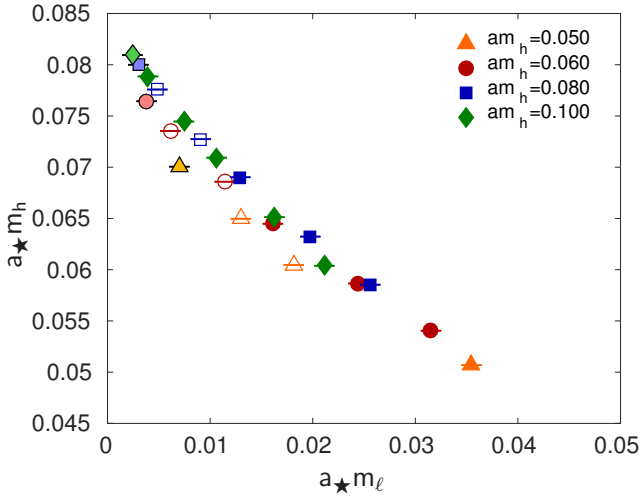
- Symbols indicate volumes and colors finite volume effects
  - red: squeezed
  - yellow: marginal
  - green: OK
- $\beta = 4.0$
  - □: $48^3 \times 96$ or $36^3 \times 64$
  - ○: $32^3 \times 64$
  - ●: $24^3 \times 48$
- $\beta = 4.4$
  - ☆: $32^3 \times 64$
- Up to 40k MDTU

Four light and eight heavy flavor are not QCD like



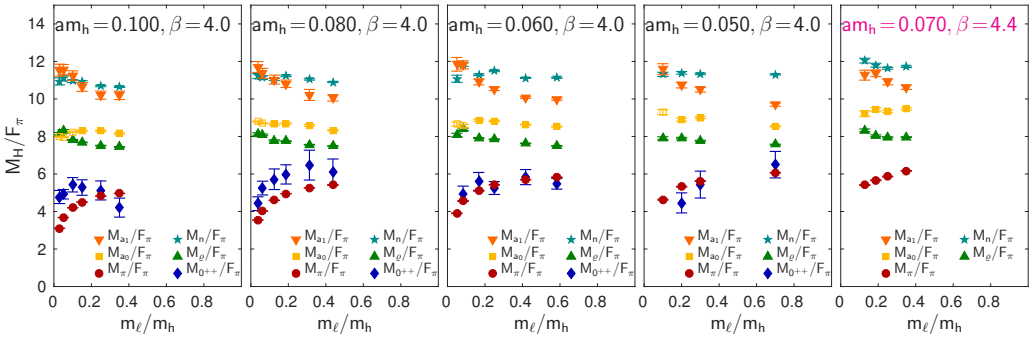
- Use the Wilson flow ($\sqrt{8\tilde{t}_0}$) to define a relative lattice spacing
  $$R_\star = \left[\sqrt{8\tilde{t}_0}/a\right] / \left[\sqrt{8\tilde{t}_0}/a_\star\right]$$
- $N_f = 12$ (conformal): scale breaks down for $m_\ell = m_h \to 0$
- 4+8: scale exhibits strong dependence on m_ℓ and m_h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

Four light and eight heavy flavor are not QCD like



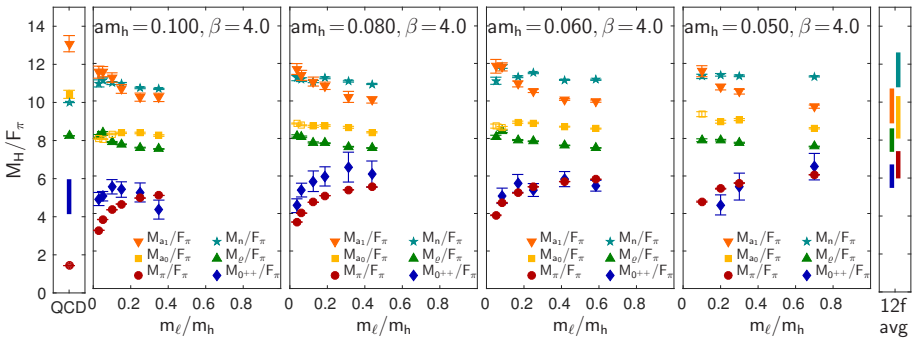
- "Naive conversion" of bare input quark masses to physical units
- Hyperscaling predicts quark masses scale according to the anomalous dimension
- QCD: scale largely independent of m_ℓ and m_h

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

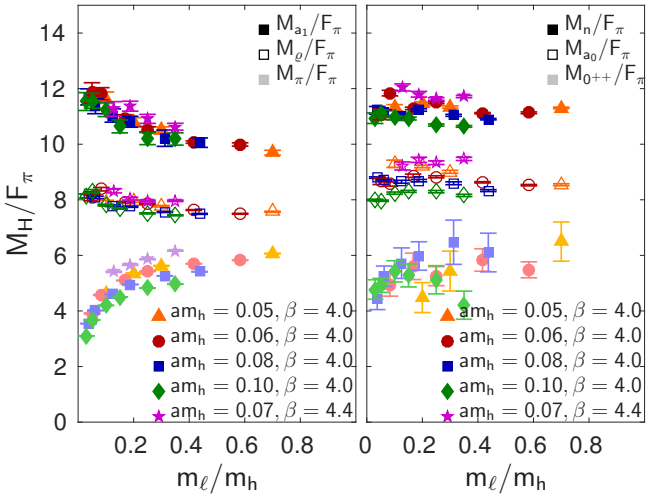
Light-light spectrum: ratios of M_H/F_π



- 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

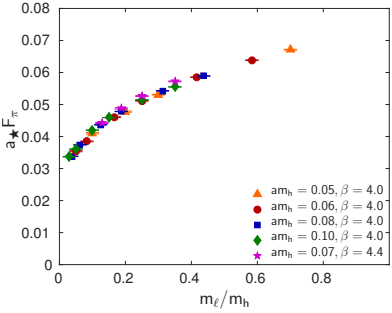


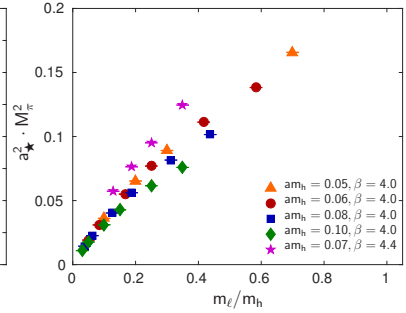
- $M_n/F_\pi \approx 11$
- $M_\varrho/F_\pi \approx 8$
- $M_{0^{++}}/F_\pi \approx 4-5$
  (taking the chiral limit is difficult but 0^{++} well separated from the ϱ)

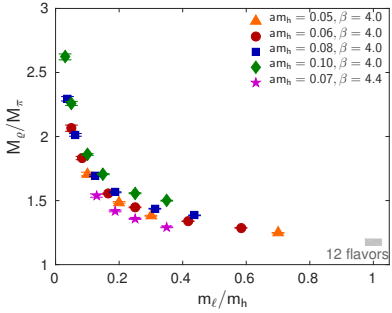
- Statistical errors only
- "Scatter" indicates corrections to scaling

- Gauge coupling is irrelevant

The system is chirally broken







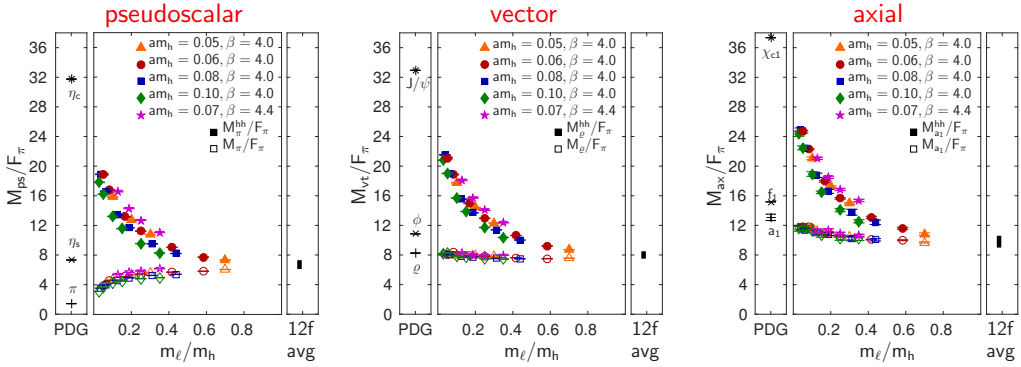
- All data points in $a_\star$ units
- $a_\star F_\pi$ is finite

- 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

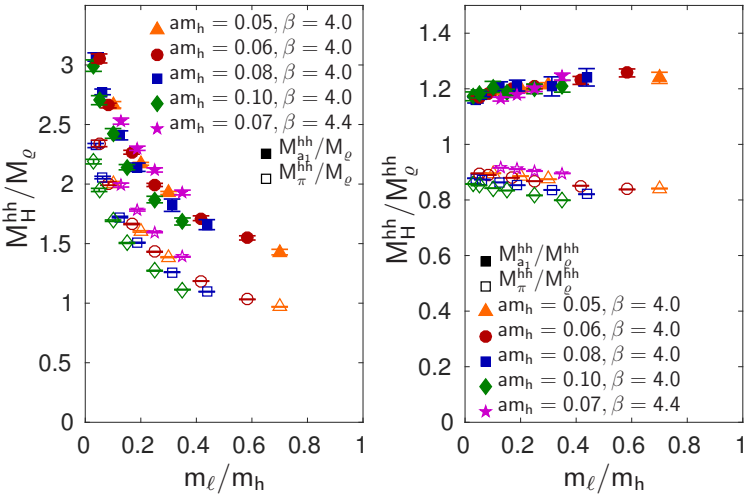
[Cheng at al. 2014]

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 light-light quantity in denominator
- Hyperscaling also expected for heavy-light states (directly coupled to SM)

The challenge of computing the 0^{++}

- Same quantum numbers as the vacuum (large background)

- Fermionic states can mix with glueballs
  → Computing the glueball spectrum is a challenge on its own

- Connected and disconnected (only gluon-lines) contributions
  → For large t: disconnected part dominates
  → Stochastic determination of disconnected parts
  → Mass-split systems: light-light, heavy-light and heavy-heavy 0^{++} can mix
  ⇒ More expensive but noisier than connected meson spectrum

- Easier to compute in some BSM theories if 0^{++} is "light"
  → $aM_{0^{++}} < 2aM_\pi$ i.e. not as difficult as in QCD

σ or $f_0(500)$ in QCD

- Caprini, Colangelo, Leutwyler: $M_\sigma = 441\,\binom{+16}{-8}$ MeV, $\Gamma_\sigma = 544\,\binom{+18}{-25}$ MeV (based on Roy equation) [PRL 96 (2006) 132001]
- Garcia-Martin et al. (dispersive analysis) confirms existence of σ and $f_0(980)$ [PRL 107 (2011) 072001]

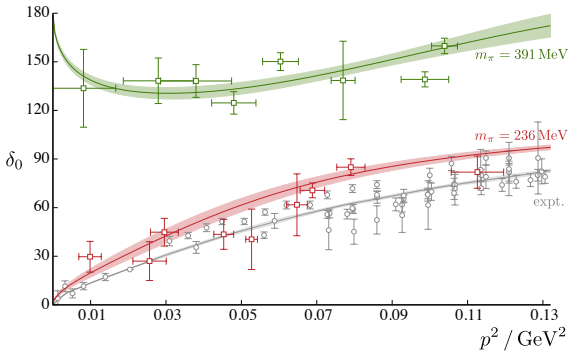
- Hadron spectrum calculation
  [Briceño et al., PRL 118 (2017) 022002]

  → $\pi - \pi$ scattering phase shift calculation

  → Qualitatively different behavior

  ⇝ $M_\pi = 391$ MeV: bound state, $M_\sigma = 758(4)$ MeV

  ⇝ $M_\pi = 236$ MeV: broad resonance

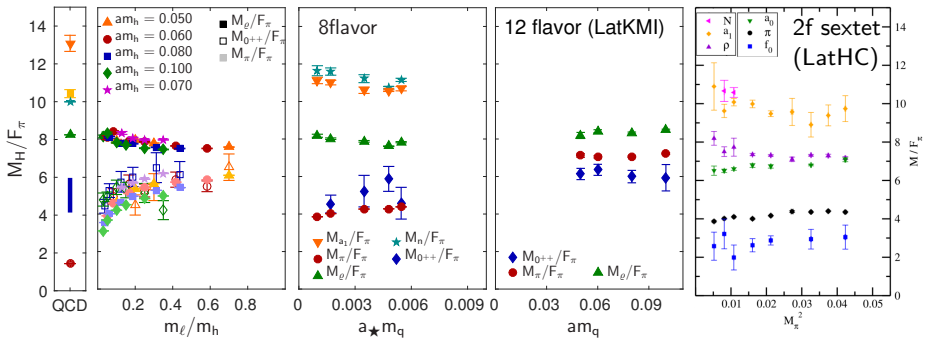


0^{++}

[PDG] [LSD PRD 93 (2016) 114514] [J. Kuti, Argonne 2016]

[PRD 93 (2016) 075028]
[PLB 773C (2017) 86-90]

[LatKMI PRD86 (2012) 059903]
[LatKMI PRL 111 (2013) 162001]



[QCD] $M_\sigma = 400 - 550$ MeV
$> 2M_\pi = 276$ MeV

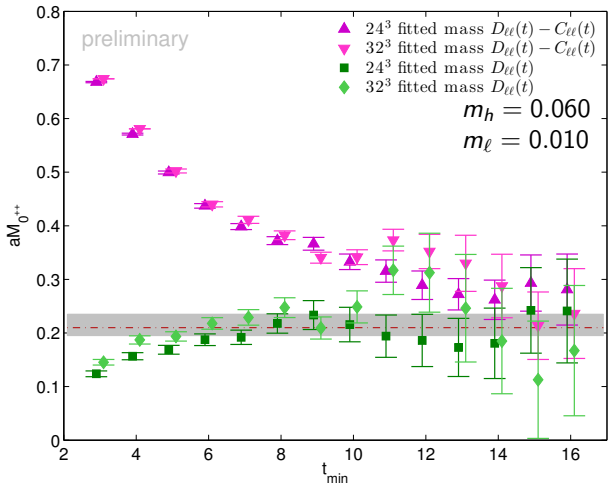
[8f] $aM_{0^{++}} \sim aM_\pi$
Conformal? Chirally broken?

[2f sextet] $aM_{0^{++}} < aM_\pi$
Is the theory conformal?

[4+8] $aM_{0^{++}} \gtrsim aM_\pi$
Is the 0^{++} "peeling off"?

[12f] $aM_{0^{++}} < aM_\pi$
Theory is conformal

Comparison of $D_{\ell\ell}$ and $D_{\ell\ell} - C_{\ell\ell}$



- For $t \to \infty$: $D_{\ell\ell}$ and $D_{\ell\ell} - C_{\ell\ell}$ should agree (up to mixing effects)
- Compare fits with different t_{min} and $t_{\text{max}} = N_T/2$
- Compare results for two volumes

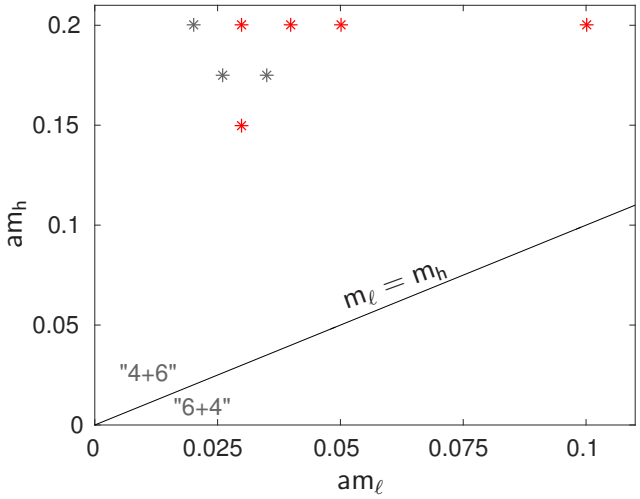
$\Rightarrow$ Consistent for large t_{min}

$\rightarrow$ $D_{\ell\ell} - C_{\ell\ell}$: troubled by excited states
$\rightarrow$ $D_{\ell\ell}$ may underestimate the value

Why moving to 4+6?

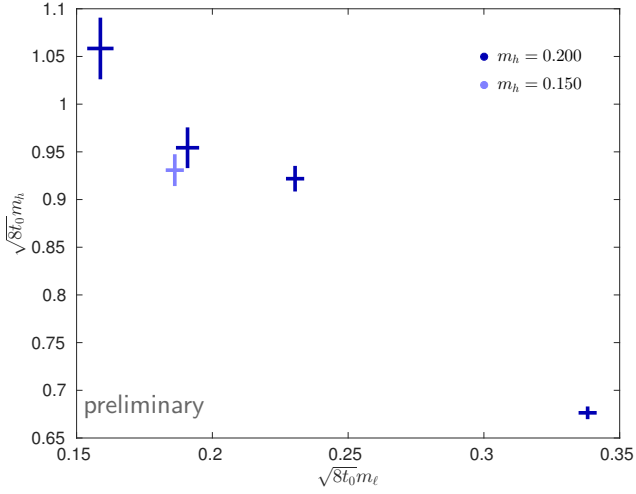
- 4+8 is built on IRFP of conformal 12-flavors which has small anomalous dimension ($\sim$0.25)
- Indications of conformality of 10-flavors [Chiu 1603.08854][PoS LATTICE2016 (2017) 228]
  - $\rightarrow$ Closer to the lower edge of the conformal window $\Rightarrow$ larger anomalous dimension
- Set-up
  - $\rightarrow$ SU(3) gauge group
  - $\rightarrow$ Symanzik gauge action with stout-smeared Möbius domain-wall fermions [Peardon et al. PRD80 (2009) 054506][Brower et al. CPC 220 (2017) 1]
  - $\rightarrow$ Simulations performed with `Grid` [Boyle et al. PoS LATTICE2015 023]
- Domain-wall fermions feature continuum-like symmetries and expressions
  - $\rightarrow$ Simplifies to investigate mass generation of SM fermions
    - $\rightsquigarrow$ partial compositeness or four-fermion interactions
  - $\rightarrow$ Avoids issues of rooting or fermion universality near an IRFP [1710.08970]
  - $\rightarrow$ Simulations are costly ...

Exploratory $4 + 6$ simulations on $16^3 \times 32$ lattices (LSD collaboration)



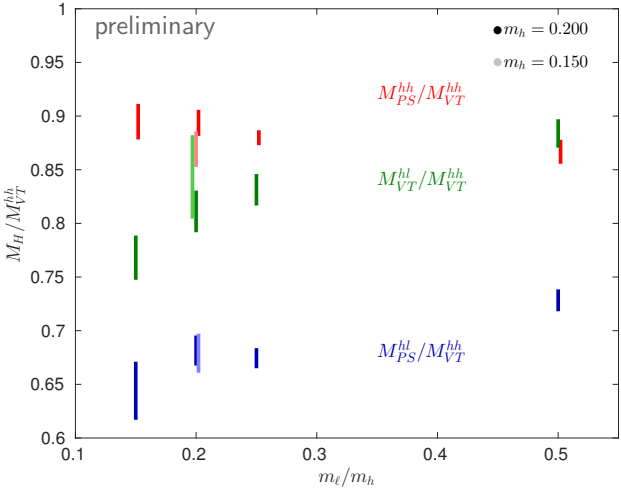
- Identified $\beta = 4.03$ to be promising to feel attraction of IRFP
- Exploratory simulations
  - $\rightarrow$ Low statistics
  - $\rightarrow$ Small volumes
  - $\Rightarrow$ Maybe significant systematic effects
- Too difficult to extract $M_\pi^{\ell\ell}$ and $F_\pi^{\ell\ell}$
- Only "sufficient"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

Ratios over M_{VT}^{hh}



- No data points; likely not free of systematic effects
- 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 (Anna's talk)
  - → $M_\pi \sim M_{0^{++}} < M_\varrho$
  - → 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
- 0^{++}: challenging to compute, several models exhibit $M_{0^{++}} \sim M_\pi$

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

Resources

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

BU: engaging and scc (MGHPCC)

XSEDE: Stampede (TACC) and SuperMic (LSU)

U Colorado: Summit