

Large scale separation and hadronic resonances from a new strongly interacting sector

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based on

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

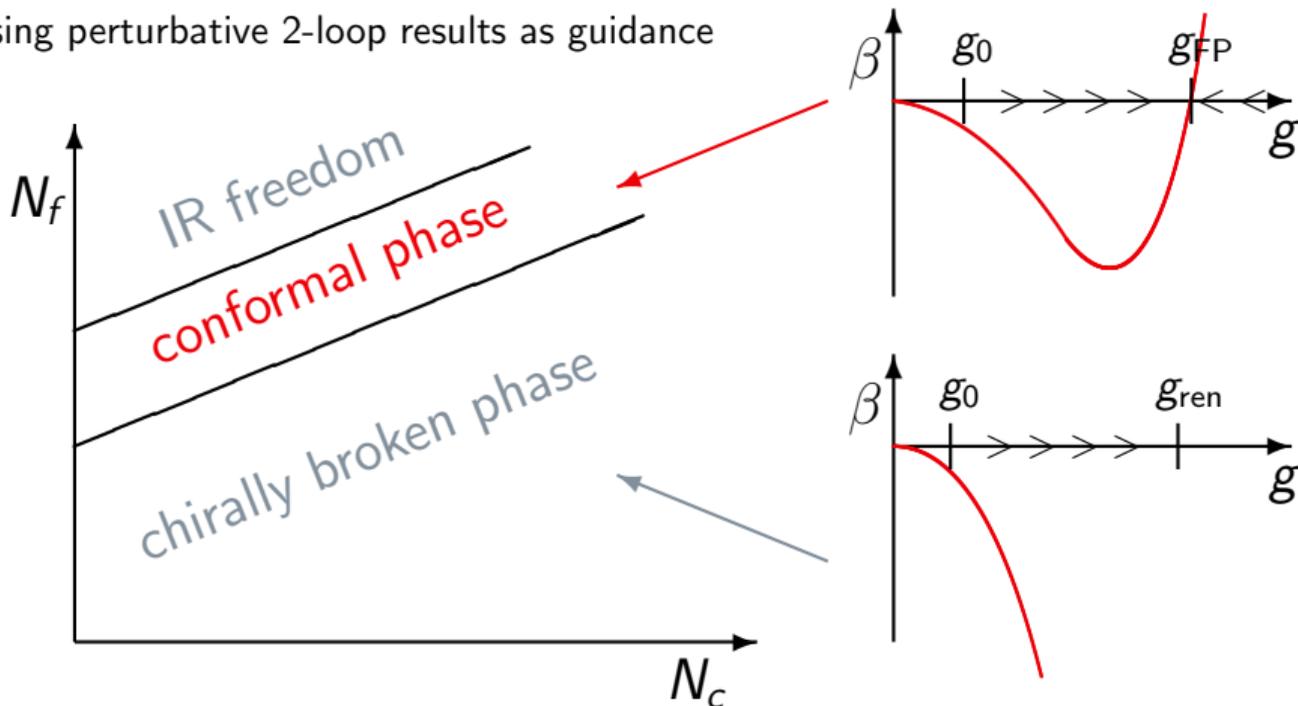
A. Hasenfratz, C. Rebbi, O.W. arXiv:1609.01401

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?
- ⇒ 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 \rightarrow “full” SM

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

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Add new strong dynamics coupled to SM

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



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

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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], . . .

- ▶ SU(3) gauge theory with 4 light (massless) and 8 heavy fundamental flavors



- ▶ Add 8 “heavy” fundamental flavors
- ▶ $N_f = 4 + 8 = 12$: conformal dynamics
- ▶ SU(3) gauge theory with 4 light flavors
- ▶ Chirally broken in the IR

↪ 4, 8, 12 are preferred for simulations with unrooted staggered fermions

→ “Walking” gauge coupling, tunable by changing m_h

→ Anomalous dimensions correspond to the conformal IRFP

→ Model features both pNGB or dilaton-Higgs scenarios

Two possibilities for a composite Higgs (IR sector)

▶ Spontaneous breaking of **scale** symmetry: Higgs is a dilaton

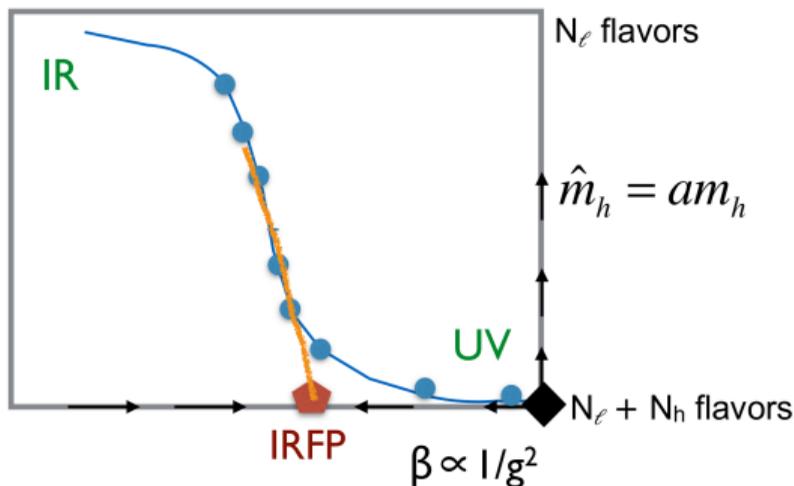
- Possibly light 0^{++} scalar
- $F_\pi = \text{SM vev} \sim 246 \text{ GeV}$
- ideal 2 massless flavors in the IR
- closer to old technicolor ideas

▶ Spontaneous breaking of **flavor** symmetry: Higgs is a pNGB

- Mass emerges from its interactions
- Non-trivial vacuum alignment $F_\pi = (\text{SM vev})/\sin(\chi) > 246 \text{ GeV}$
- 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] (→ appendix)

Implementation on the lattice

- ▶ Choose N_f flavors above the conformal window
- ▶ Split the masses: $N_f = N_\ell + N_h$
 - ▶ N_ℓ flavors are massless, extrapolate $m_\ell \rightarrow 0 \Rightarrow$ chirally broken
 - ▶ N_h flavors are massive, we will vary $m_h \rightarrow$ decouple in the IR
 - \rightarrow Choose m_h to feel the attraction of the IRFP of $N_f = 12$



- ▶ We have 3 parameters:
 - $\rightarrow g$ irrelevant coupling
 - $\rightarrow m_\ell \rightarrow 0$ (chiral limit)
 - $\rightarrow m_h$: sets the scale

Derivation of hyperscaling from Wilson RG

- ▶ Scale change: $\mu \rightarrow \mu' = \mu/b$, with $b > 1$
 - ⇒ bare masses increase: $\widehat{m}(\mu) \rightarrow \widehat{m}(\mu') = b^{y_m} \widehat{m}(\mu)$
 - ⇒ bare coupling approaches its fixed point: $g \rightarrow g^*$
 - ⇒ any 2-point correlator: $C_H(t; g, \widehat{m}, \mu) \rightarrow b^{-2y_H} C_H(t/b; g_i^*, b^{y_m} \widehat{m}, \mu)$

- ▶ Now $C_H(t) \propto \exp(-M_H t) \Rightarrow aM_H \propto (\widehat{m})^{1/y_m}$ (hyperscaling)

- ▶ Likewise amplitudes (F_π) show hyperscaling $\Rightarrow M_H/F_\pi$ are constant

[Del Debbio and Zwicky PRD82 (2010) 014502][PLB 734 (2014) 107]

- ▶ Light flavors of mass \widehat{m}_ℓ and heavy flavors of mass \widehat{m}_h :

$$C_H(t; g, \widehat{m}_h, \widehat{m}_\ell, \mu) \rightarrow b^{-2y_H} C_H(t/b; g^*, b^{y_m} \widehat{m}_h, b^{y_m} \widehat{m}_\ell, \mu)$$

$$\equiv b^{-2y_H} C_H(t/b; g^*, b^{y_m} \widehat{m}_h, \widehat{m}_\ell / \widehat{m}_h, \mu)$$

⇒ $aM_H \propto (\widehat{m})^{1/y_m} f_H(m_\ell/m_h)$ with $f_H(m_\ell/m_h)$ a universal function

⇒ ratios depend only on m_ℓ/m_h

QCD:

- chirally broken, simulate at finite $\beta = 6/g^2$
- correlation functions show (at large distance) exponential behavior
- for $\beta \rightarrow \infty$, $aF_\pi \rightarrow 0$; ratios will approach well defined limits
- β is relevant; take continuum limit by $\beta \rightarrow \infty$

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 $N_f = 12$:

- (it appears) theory is conformal and choose $\beta > \beta_{cr}$
- correlation functions show (at large distance) power law behavior
- rescaling lengths results in the same long range behavior for any two β values
- under RG transformations theory runs to an IRFP
- β is irrelevant, masses or amplitudes show hyperscaling

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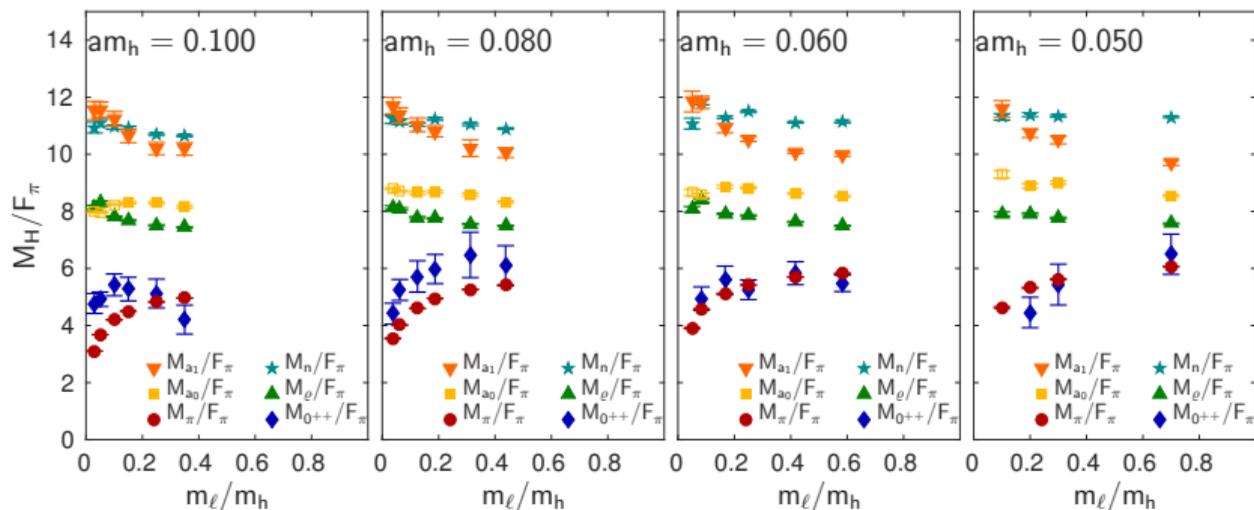
4+8:

- four flavors are massless ($m_\ell = 0$), eight are massive with mass m_h
- correlation functions show (at large distance) exponential behavior
- for m_h sufficiently small, β is irrelevant
- m_h is relevant; take continuum limit by $m_h \rightarrow 0$ for fixed m_ℓ/m_h
- ratios will be independent of m_h and β (hyperscaling)

 $N_f = 12$:

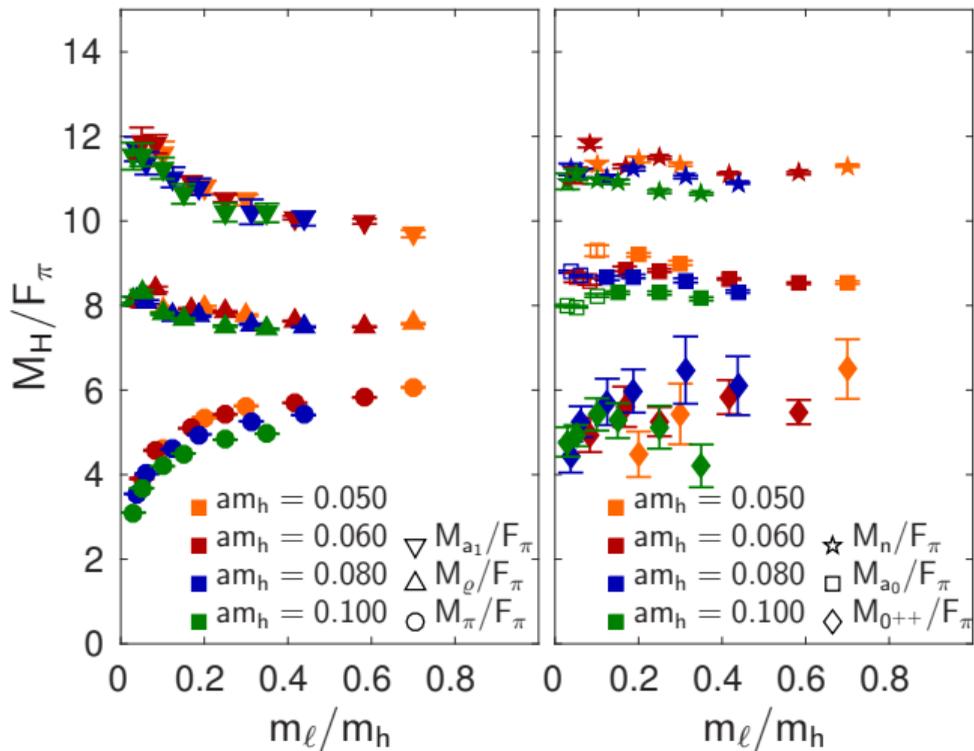
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Light-light spectrum: ratios of M_H/F_π



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

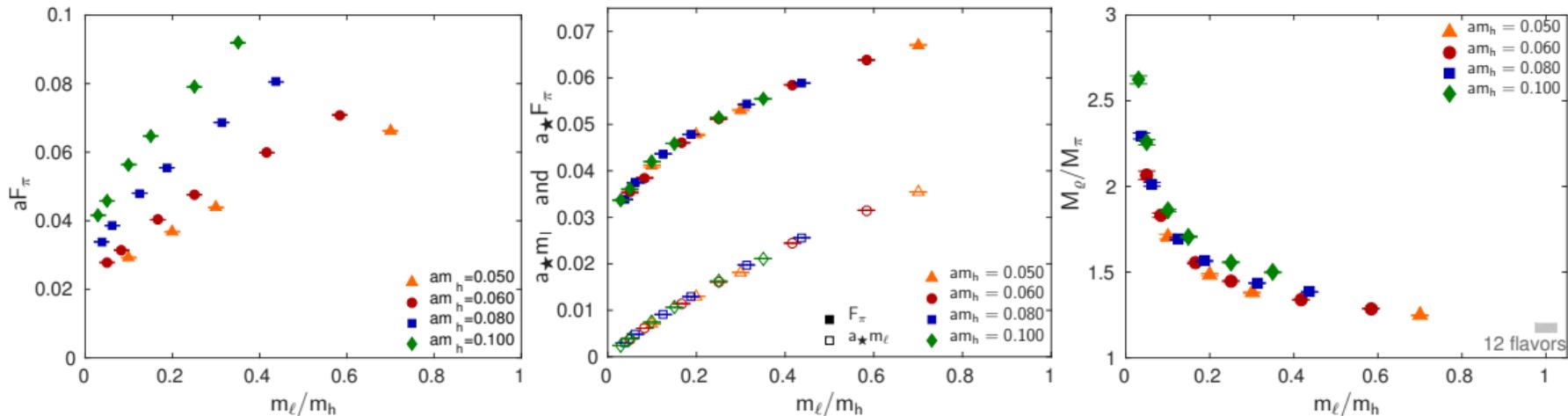
Hyperscaling at work



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

- ▶ “Scatter” indicates corrections to scaling

The system is chirally broken



▶ Each point shown in its own lattice units

▶ For $m_h \rightarrow 0$, $aF_\pi \rightarrow 0$

▶ All data points in a_* units

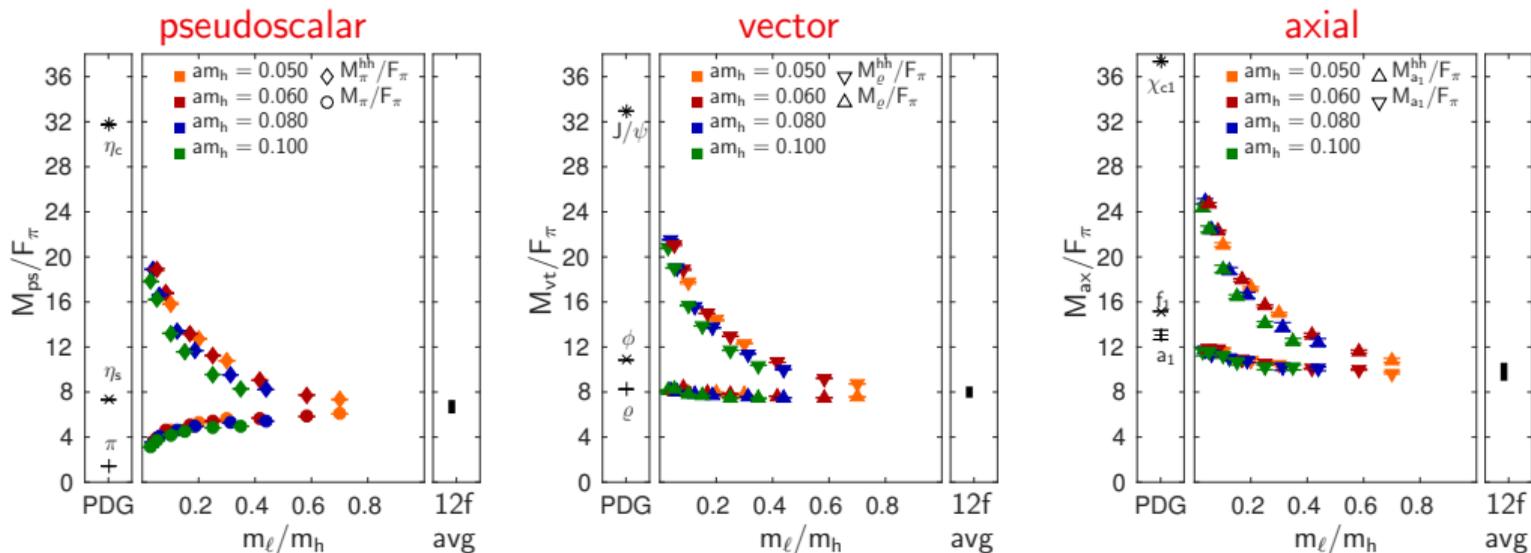
▶ a_*F_π is finite

▶ $N_f = 4$ (QCD-like): ratio diverges

▶ $N_f = 12$: almost constant ratio

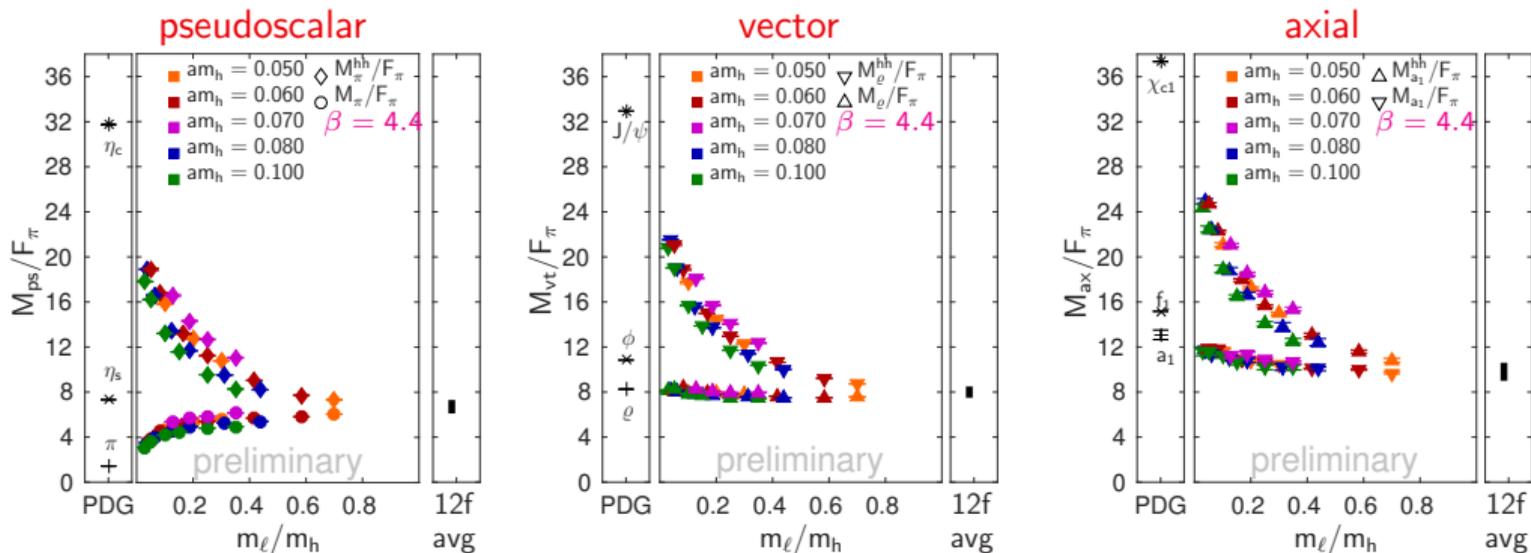
[Cheng et al. 2014]

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
- ▶ $M_\rho^{hh} \sim 3M_\rho \Rightarrow$ could be accessible at the LHC

Irrelevance of coupling $\beta = 6/g^2$



- ▶ Data with $am_h = 0.100, 0.080, 0.060, 0.050$ simulated at $\beta = 4.0$
- ▶ Additional simulations at $\beta = 6/g^2 = 4.4$ and $am_h = 0.070$ [arXiv:1611.07427]

Concluding remarks

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

Outlook

- ▶ Simulate four light and six heavy flavors
 - closer to boundary of the conformal window; **larger anomalous dimension**
 - theoretically clean, but expensive domain-wall fermions \Rightarrow test of fermion universality near IRFP

Resources and Acknowledgments

USQCD: Ds, Bc, and pi0 cluster (Fermilab)

BU: engaging (MGHPCC)

XSEDE: Stampede (TACC) and SuperMic (LSU)



appendix

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]

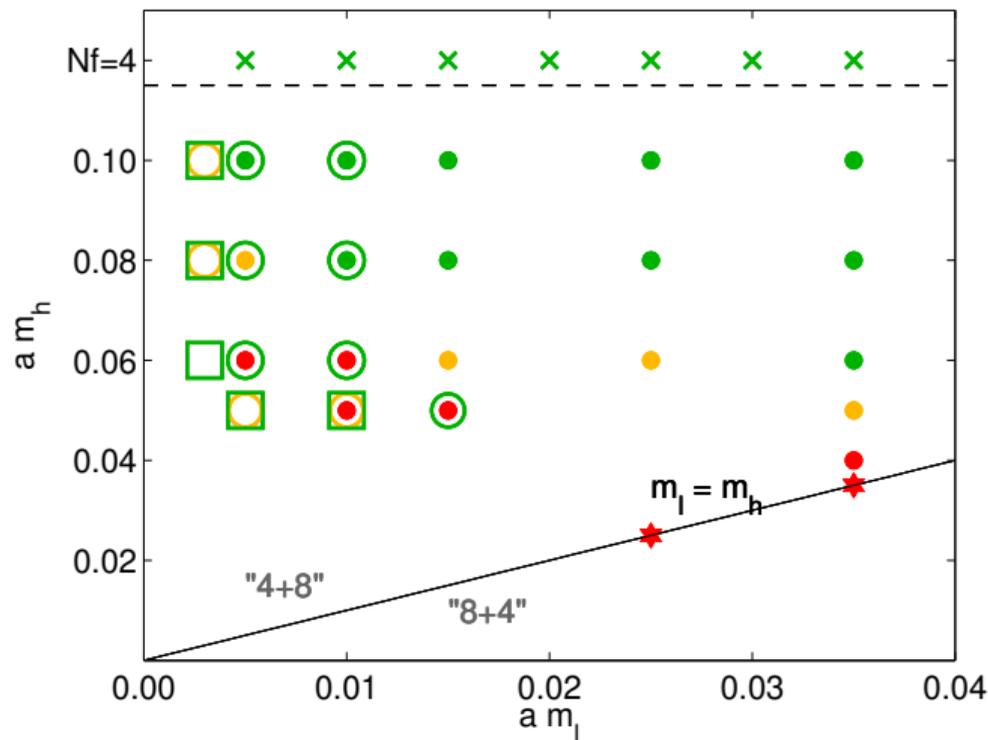
▶ Goals

- ▶ 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] [arXiv:1609.01401]
(a longer, detailed paper is in preparation)

Performed simulations ($\beta = 4.0$)



► Symbols indicate volumes and colors finite volume effects

red: squeezed

yellow: marginal

green: OK

□: $48^3 \times 96$

or $36^3 \times 64$

○: $32^3 \times 64$

●: $24^3 \times 48$

► Up to 40k MDTU

Fundamental composite 2HDM with 4 flavors [Ma and Cacciapaglia JHEP 03 (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]
 - ⇒ $(2, 2) + \cancel{(2, 2)} + \cancel{(3, 1)} + \cancel{(1, 3)} + (1, 1)$
 - ↪ effectively $SU(4)/Sp(4)$

running coupling

Running coupling form gradient flow

- ▶ Gradient flow defines the renormalized coupling

[Narayanan and Neuberger JHEP 03 (2006) 064], [Lüscher JHEP 08 (2010) 071]

$$g_{GF}^2(\mu = 1/\sqrt{8t}) = t^2 \langle E(t) \rangle / \mathcal{N}$$

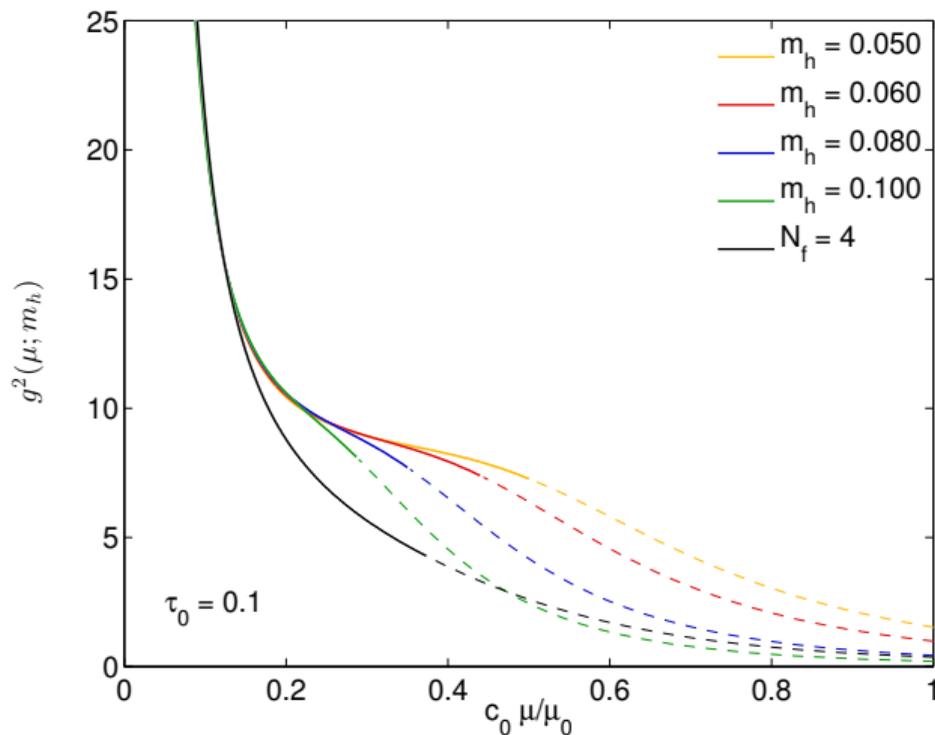
t : flow time; $E(t)$ energy density

- ▶ g_{GF}^2 is used for scale setting

$$g_{GF}^2(t = t_0) = 0.3/\mathcal{N} \quad (\text{"}t_0\text{-scale"})$$

- ▶ Can determine renormalized running coupling on large enough volumes and large enough flow times in the continuum limit

Running coupling form gradient flow: 4+8 flavors



- ▶ Extrapolated to $m_\ell = 0$
- ▶ $N_f = 4$ shows fast running
- ▶ “Shoulder” increases for smaller m_h
 \Rightarrow walking
- ▶ Walking range is tuned as function of m_h
- ▶ Data with error bars!

The 0^{++}

Computationally challenging

- ▶ 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

Calculating the disconnected spectrum (0^{++} scalar)

Numerical measurement on the lattice

- ▶ 6 U(1) sources with dilution on each time slice, color and even/odd spatially
- ▶ Variance reduced $\langle \bar{\psi}\psi \rangle$

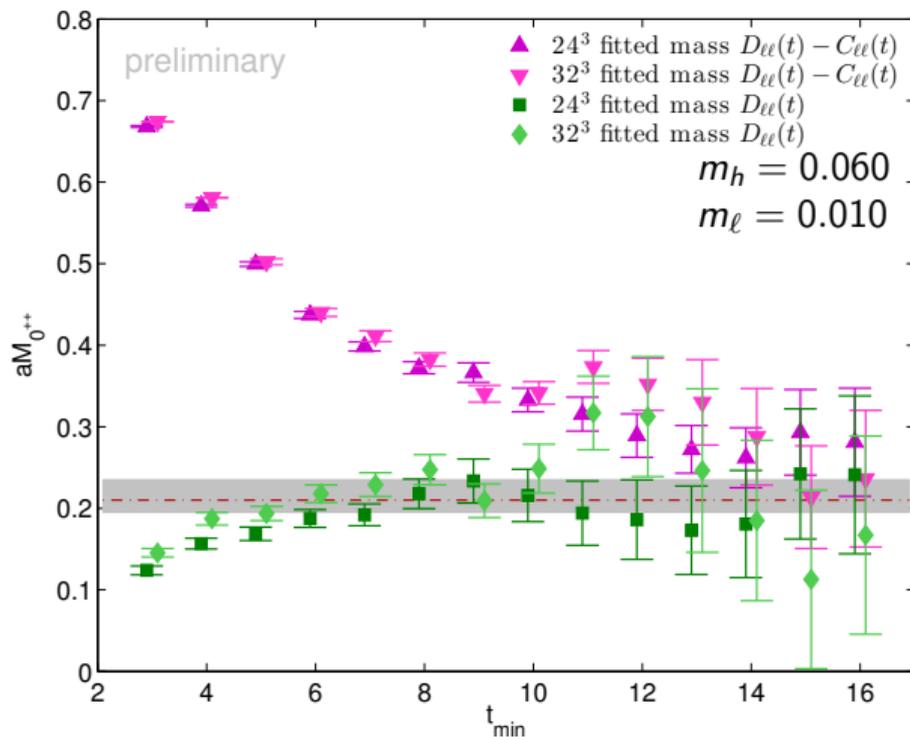
Analysis strategy

- ▶ Correlated fit to both parity states (staggered)
- ▶ **Vacuum subtraction** introduces very large uncertainties
- ▶ Advantageous to fit additional constant

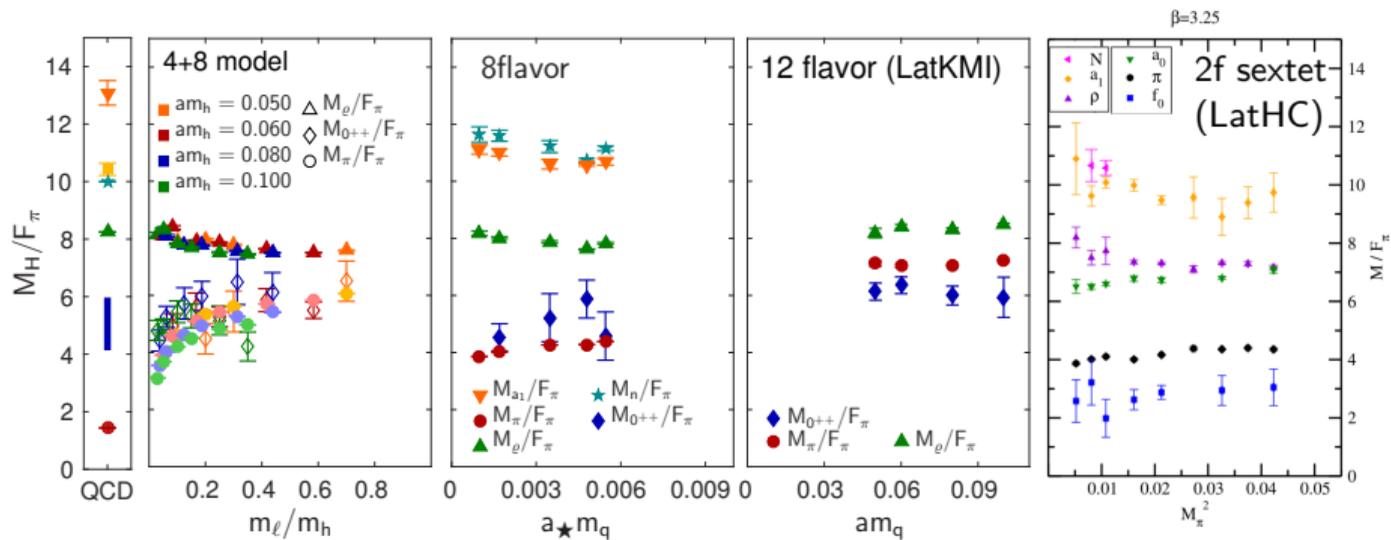
$$C(t) = c_{0^{++}} \cosh \left(M_{0^{++}} \left(\frac{N_T}{2} - t \right) \right) + c_{\pi_{sc}} (-1)^t \cosh \left(M_{\pi_{sc}} \left(\frac{N_T}{2} - t \right) \right) + \nu$$

- ▶ Equivalent to fitting the finite difference: $C(t+1) - C(t)$

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



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

0^{++} 

[PDG]

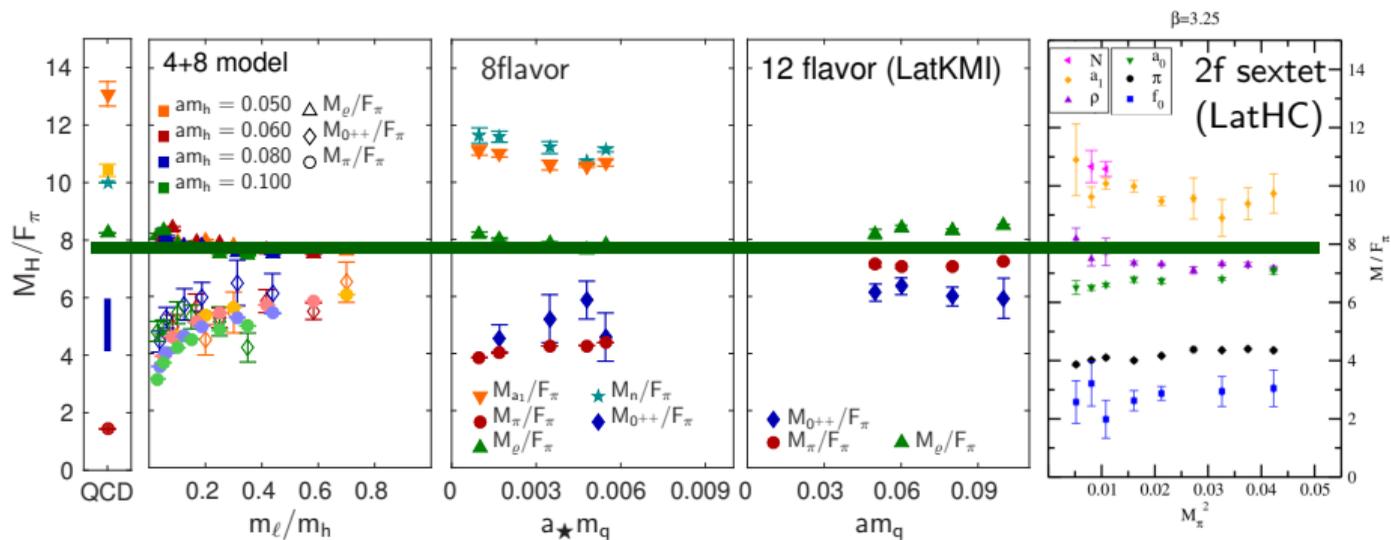
[PRD 93 (2016) 075028]
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[LSD PRD 93 (2016) 114514]

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

[J. Kuti, Argonne 2016]

Magic 8



[PDG]

[LSD PRD 93 (2016) 114514]

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