Large scale separation and resonances within LHC range from a prototype model for new physics

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Barcelona, December 16, 2016

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

experimental findings

The Standard Model of Elementary Particle Physics

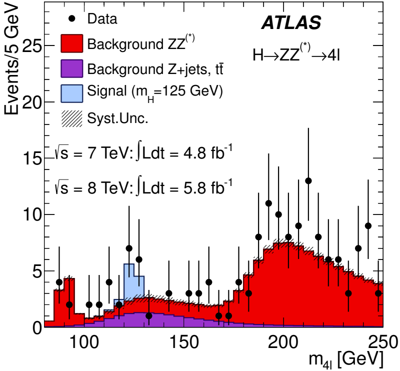
	generations I	II	III	gauge forces	Higgs boson
quarks	u	c	t	g	H
	d	s	b	γ	
leptons	ν_e	ν_μ	ν_τ	Z^0	
	e	μ	τ	$W^\pm$	

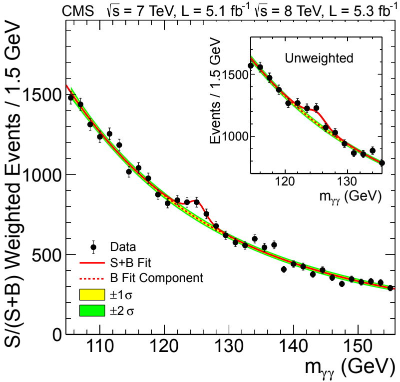
- Gravitation, dark matter, or dark energy not included
- Matter/antimatter asymmetry

- Is the Higgs boson a fundamental scalar?
- What happens up to $M_{\text{Planck}} \approx 1.2 \cdot 10^{19}$ GeV?

The Higgs boson

- Discovery of the Higgs boson in 2012 [Atlas PLB 716 (2012) 1] [CMS PLB 716 (2012) 30]

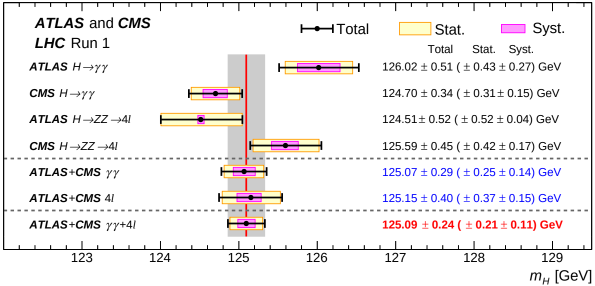




The Higgs boson

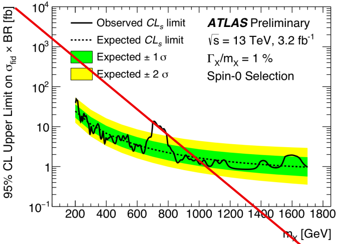
- Combined analysis 2015: [Atlas and CMS PRL 114 (2015) 191803]

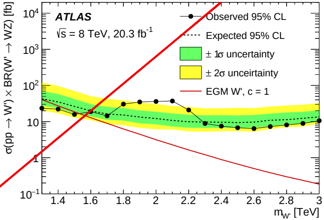
  $m_H = 125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})$ GeV, spin 0, parity +1

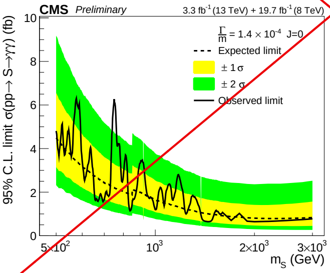


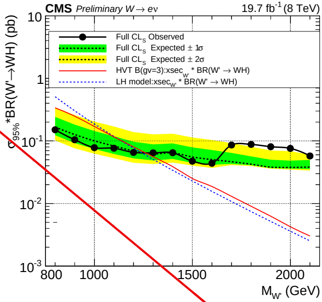
- We still do not know:
  - → What is the Higgs boson / Standard Model UV completion?
  - → What is the nature of electro-weak symmetry breaking?

Too good to be true?
ICHEP 2016: no bump at 750 GeV; no bump at 2 TeV









Large scale separation

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

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

composite Higgs models

Composite Higgs models

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

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

Composite Higgs models

- New, strongly interacting gauge fermion system
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Higgs-less, massless SM $\rightarrow$ "full" SM

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

Composite Higgs models

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

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

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

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], ...

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UV → IR: conformal (Λ_{UV}, fermion masses) → chirally broken (Λ_{IR}, Higgs dynamics)

Many possibilities:

- SU(3) gauge with 4 flavors
- SU(4) with 2 diff. representations
- SU(3) gauge with 8 flavors
- SU(3) gauge with 2 sextet
- SU(2) gauge with 2 flavors

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UV → IR

conformal: Λ_{UV} fermion masses

chirally broken: Λ_{IR} Higgs dynamics

- Add fermions to push system into the conformal window
- If fermions are massive, they decouple at Λ_{IR}
- Dynamics beyond Λ_{UV} gives mass to add. fermions

Many possibilities:

- SU(3) gauge with 4 flavors
- SU(4) with 2 diff. representations
- SU(3) gauge with 8 flavors
- SU(3) gauge with 2 sextet
- SU(2) gauge with 2 flavors

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 1606 (2016) 107]
  - → Ma and Cacciapaglia: Fundamental composite 2HDM with 4 flavors [JHEP 03 (2016) 211]

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

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

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

$\rightarrow$ One doublet plays the role of the Higgs doublet field

$\rightarrow$ Other doublet and triplets are stable; could play role of dark matter

- Vecchi: "choose the right couplings to RH top" [Edinburgh talk]

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

$\rightsquigarrow$ effectively SU(4)/Sp(4)

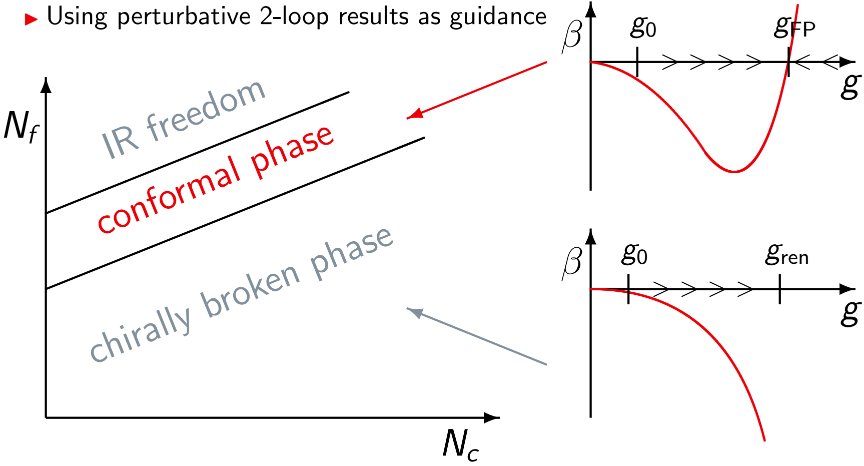
Investigate specific models

- Choose N_c color and N_f flavors in a given representation
- Hopefully close to the conformal boundary but chirally broken
- Two candidates
  - → SU(3) gauge with $N_f = 2$ sextet fermions (LatHC)
  - → SU(3) gauge with $N_f = 8$ fundamental fermions (LatKMI, LSD)

- Certainly these two models are near the conformal boundary but are they still chirally broken?
  - → Nonperturbative computation of the β function
  - → Phase diagram at zero and finite temperature
  - → Determine the hadron spectrum: χPT vs. hyperscaling fits
  - → ...

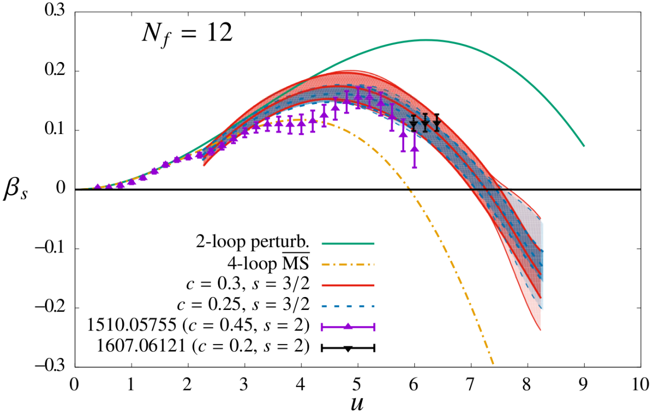
Investigate specific models

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



Investigate specific models

- $N_f = 12$, $N_c = 3$, fundamental fermions: $g_\star^2 = 7.3\binom{+3}{-2}_{c=0.25}$
  [Hasenfratz and Schaich arXiv:1610.10004]

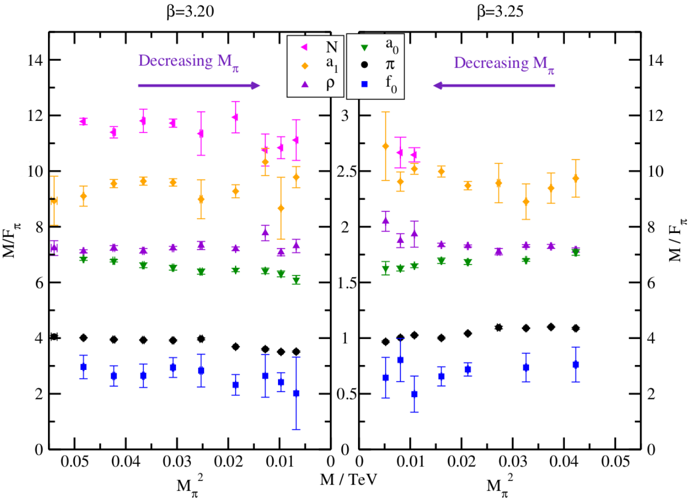


- Discrete β-function for scale change s

$$\beta_s(\tilde{g}_c^2, L) = \frac{\tilde{g}_c^2(sL;a) - \tilde{g}_c^2(L;a)}{\log(s^2)}$$

- $u \equiv \tilde{g}_c^2(L;a)$
- Defined to be positive

$N_f = 2$ sextet model (LatHC) [J. Kuti, Argonne 2016]

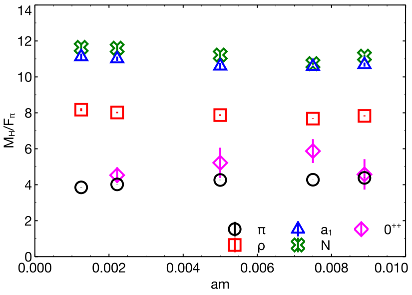


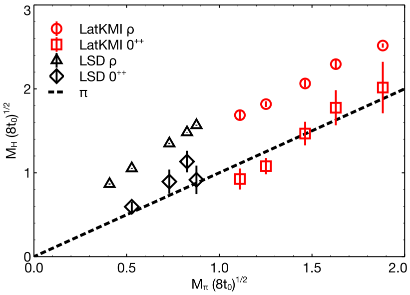
- $M_{0^{++}} < M_\pi$
- Very little curvature in M_π/F_π
- But "hyperscaling does not fit"

- β function is small
- Baryons candidates for dark matter? [PRD 94 (2016) 014503]

$N_f = 8$ fundamental

- LSD [PRD 93 (2016) 114514]
  → nHyp smeared staggered fermions
- LatKMI[PRD 87 (2013) 094511][arXiv:1610.07011]
  → HISQ fermions





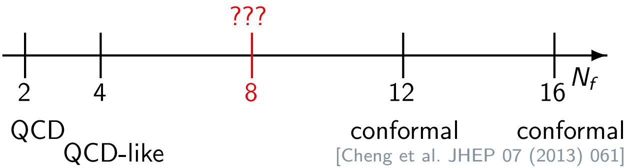
- Spectrum matches despite different actions ⇝ small discretization errors
- Very little curvature in M_π/F_π; cannot say whether system is chirally broken
- Pallante et al. [arXiv:1506.06396] and Iwasaki et al. [PLB 748 (2015) 289] claim it is conformal

4+8 model

Alternatively: build a model on a conformal fixed point

- Built in features (e.g. [Luty and Okui JHEP 09 (2006) 070])
  - → Conformal in the UV (non-perturbative)
  - → Chirally broken in the IR
  - → Walking gauge coupling

- SU(3) gauge theories with N_f fundamental fermions
- Staggered fermions come in multiplicities of 4 (no rooting)



[Cheng et al. JHEP 07 (2013) 061]
[Itou arXiv:1311.2998][Itou et al. arxiv:1411.1155]
[Cheng et al. PRD 90 (2014) 014509]
[Lombardo et al. JHEP 12 (2014) 183]
[Hasenfratz and Schaich arXiv:1610.10004]

⇒ 4, 8, 12, 16 are preferred N_f

4+8 model as a candidates for $\mathcal{L}_{SD}$

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

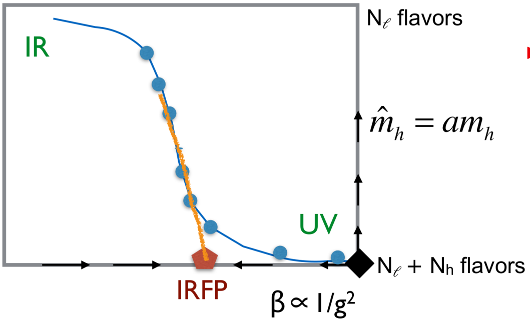
- Add 8 "heavy" fundamental flavors
- $N_f = 4 + 8 = 12$: conformal dynamics

- SU(3) gauge theory with 4 light, fundamental flavors
- Prototype pNGB or dilaton-Higgs

→ Ensures chiral symmetry breaking in the IR
→ Tune "walking" by changing m_h
→ Anomalous dimensions correspond to the conformal IRFP
⇝ *One implementation; many other possibilities*

Implementation on the lattice

- Choose N_f flavors above the conformal window
- Split the masses: $N_f = N_\ell + N_h$
  - N_h flavors are massive, we will vary m_h → decouple in the IR
  - N_ℓ flavors are massless, extrapolate $m_\ell \to 0$ ⇒ chirally broken



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

    allows to tune walking

Running coupling form gradient flow

- Gradient flow defines the renormalized coupling
  [Narayanan and Neuberger JHEP 03 (2006) 064], [Lüscher JHEP 08 (2010) 071]

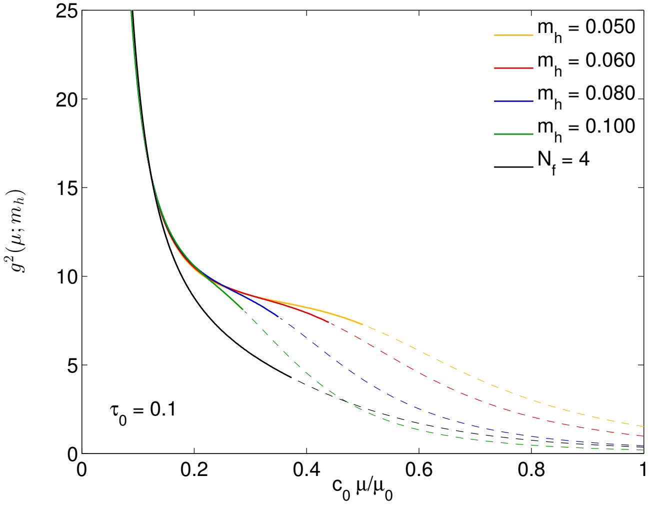
$$g^2_{GF}(\mu = 1/\sqrt{8t}) = t^2 \langle E(t) \rangle / \mathcal{N}$$

  t: flow time; $E(t)$ energy density
- g^2_{GF} is used for scale setting

$$g^2_{GF}(t = t_0) = 0.3/\mathcal{N} \qquad (\text{“}t_0\text{-scale”})$$

- 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!

Conformal systems: Wilson RG predicts hyperscaling

- Scale change: $\mu \to \mu' = \mu/b$, with $b > 1$
- Transforms the bare masses $\widehat{m} = am$:

$$\widehat{m}(\mu) \to \widehat{m}(\mu') = b^{y_m} \widehat{m}(\mu) \text{ (increase)}$$

- The bare coupling approaches its fixed point: $g \to g^*$

- Any 2-point correlator:

$$C_H(t; g, \widehat{m}, \mu) \to b^{-2y_H} C_H(t/b; g_i^*, b^{y_m} \widehat{m}, \mu)$$

- Now $C_H(t) \propto exp(-M_H t)$

$$\Rightarrow aM_H \propto (\widehat{m})^{1/y_m} \quad \text{(hyperscaling)}$$

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

Hyperscaling in mass-split systems

- Light flavors of mass $\widehat{m}_\ell$ and heavy flavors of mass $\widehat{m}_h$:

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

Since $C_H(t) \propto \exp(-M_H t)$

$$aM_H \propto (\widehat{m})^{1/y_m} f_H(m_\ell/m_h)$$

with $f_H(m_\ell/m_h)$ a universal function

- M_H can be build up of only light, light and heavy, or only heavy flavors
- Does not follow a system with only N_ℓ (large m_h) or N_f degenerate (conformal) flavors

Hyperscaling in mass-split systems

- Masses / amplitudes scale as

$$aM_H \propto (\widehat{m})^{1/y_m} f_H(m_\ell/m_h)$$

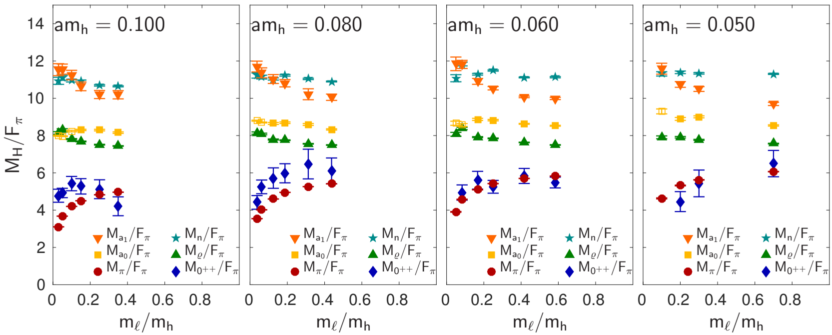
- Ratios are universal functions of m_ℓ/m_h

$$M_{H_1}/M_{H_2} = \Phi_H(m_\ell/m_h)$$
$$M_H/F_\pi = \tilde{\Phi}_H(m_\ell/m_h)$$

→ Chiral limit ($m_\ell = 0$): dimensionless ratios are independent of m_h
→ Known F_π: rest of the spectrum is predicted – no free parameters
⇝ There however corrections to scaling

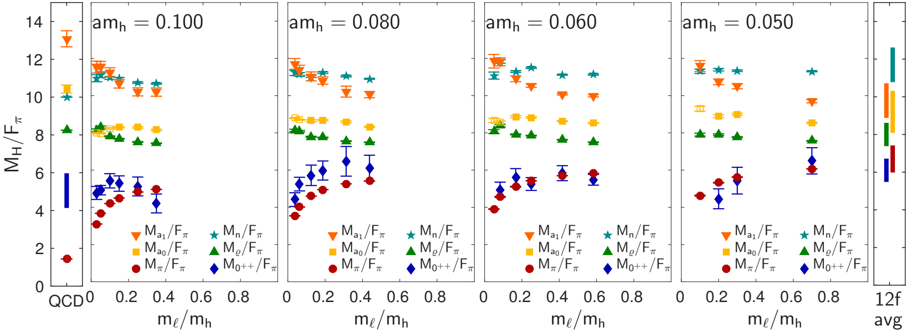
⇒ Very different form QCD!

Light-light spectrum: ratios of M_H/F_π



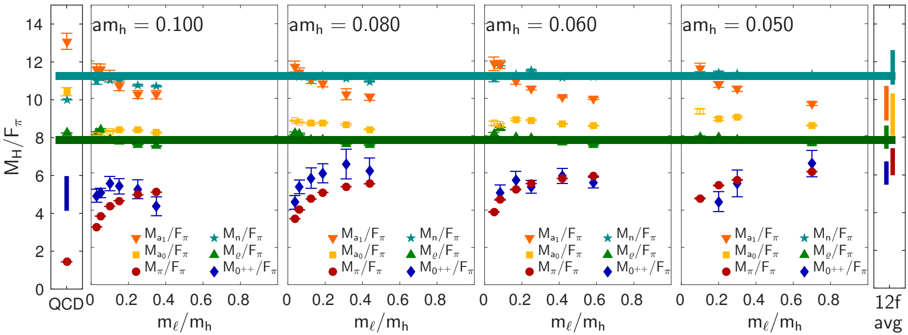
- Pion, rho, a_0, a_1, nucleon, and 0^{++} scalar
- 0^{++} is light ($M_{0^{++}} < M_\rho$), it tracks the pion. Chiral limit?
- M_π/F_π bends down $\Rightarrow$ indicates system is chirally broken

Light-light spectrum: ratios of M_H/F_π



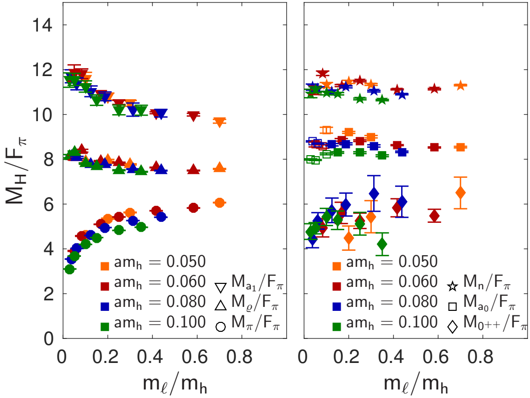
- For growing m_h and $m_\ell \to 0$ we approach QCD [PDG values]
- For decreasing m_h and $m_\ell \sim m_h$ we approach degenerate 12 flavors
  [LatHC PLB 703(2011) 348] [LatKMI PRD86 (2012) 059903][LatKMI PRL 111 (2013) 162001]
  [Cheng et al. PRD 90 (2014) 014509]

Light-light spectrum: ratios of M_H/F_π



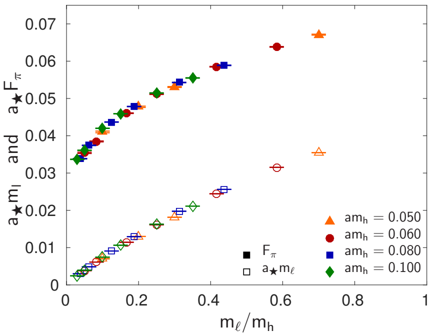
- Ratios appear largely independent of m_h!
- M_ϱ/F_π and M_n/F_π also show very little dependence on m_ℓ

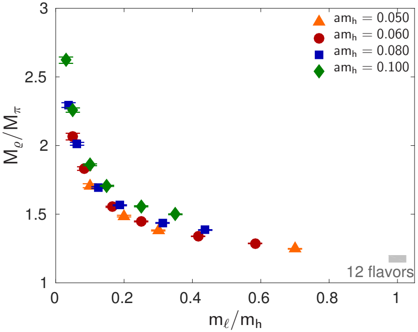
Hyperscaling at work



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

The system is chirally broken



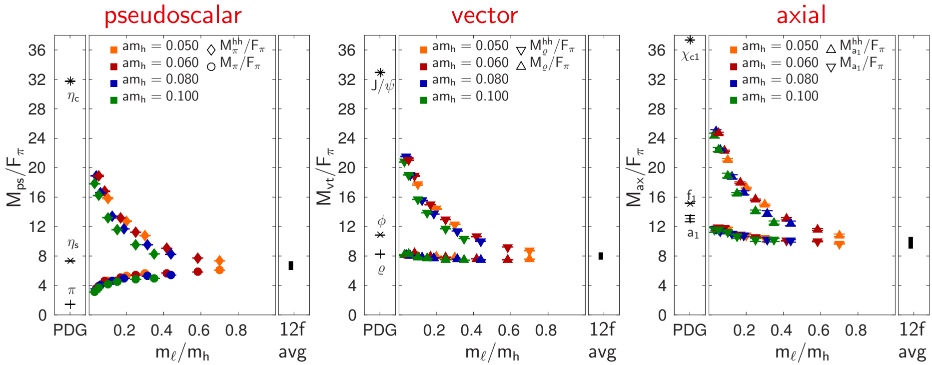


- $a_\star F_\pi$ is finite

- 4-flavors (QCD-like): ratio diverges
- 12-flavors: almost constant ratio

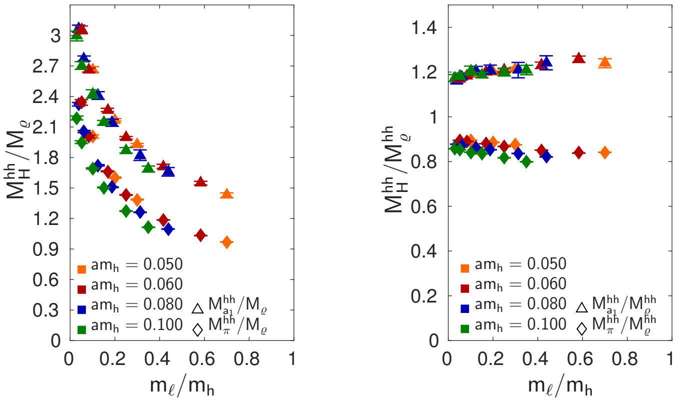
  [Cheng at al. 2014]

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

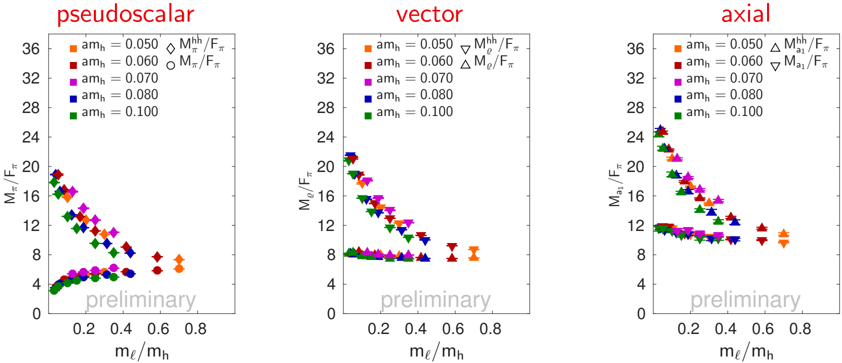
Other choices for forming ratios



- Heavy-heavy states increase mostly due to light-light quantity in denominator

Irrelevance of coupling g

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



The 0^{++}

Computationally challenging

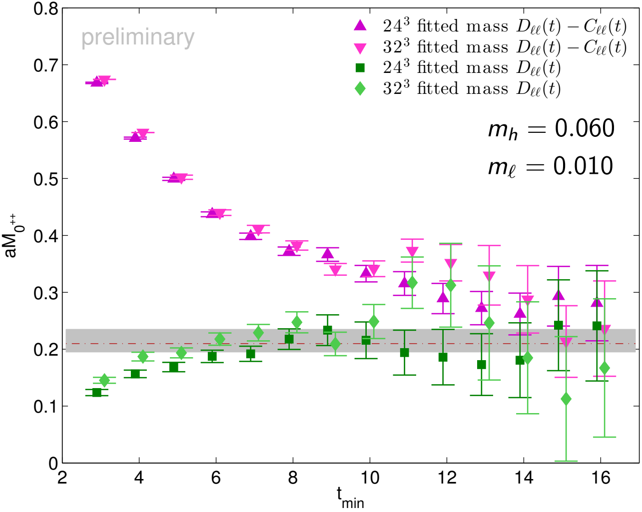
- Same quantum numbers as the vacuum (large background)

- 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

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 results!

"Light" 0^{++} in SU(3) gauge theories

- 2-flavor sextet model (LatHC)
  $\rightarrow aM_{0^{++}} < aM_\pi$, is the theory conformal?

- 12 degenerate flavors (LatKMI)
  $\rightarrow aM_{0^{++}} < aM_\pi$, theory is conformal

- 8 degenerate flavors (LatKMI, LSD)
  $\rightarrow aM_{0^{++}} \sim aM_\pi$, conformal? chirally broken?

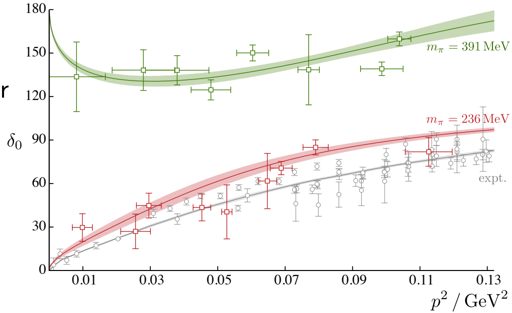
- 4+8 flavor model
  $\rightarrow aM_{0^{++}} \gtrsim aM_\pi$, is the 0^{++} "peeling off"?

- QCD [PDG]
  $\rightarrow M_{f_0(500)} = M_\sigma = 400 - 550 \text{ MeV} > 2M_\pi = 276 \text{ MeV}$

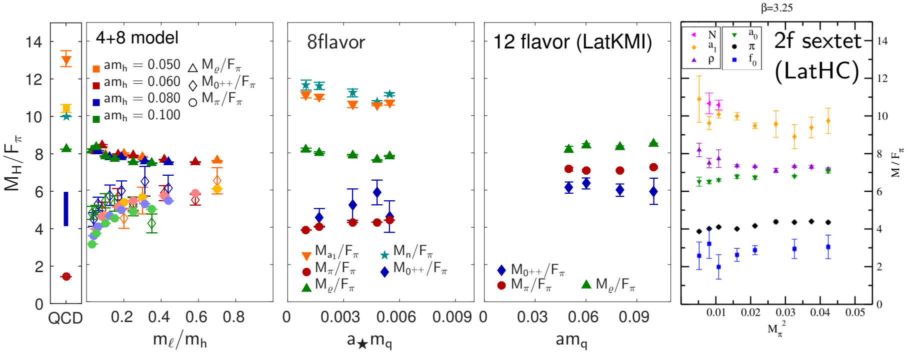
σ in QCD

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

- Hadron spectrum calculation [Briceño et al., arXiv:1607.05900]
  - → $\pi - \pi$ 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^{++}

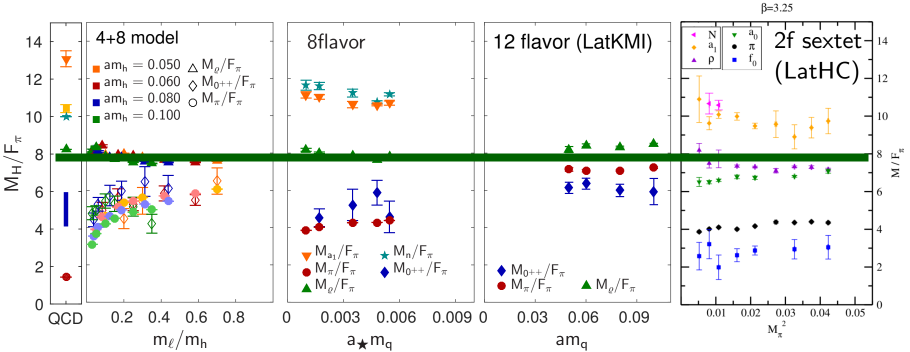


[PDG] [LSD PRD 93 (2016) 114514] [J. Kuti, Argonne 2016]

[PRD 93 (2016) 075028]
[arXiv:1609.01401]

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

Magic 8



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

[PRD 93 (2016) 075028]
[arXiv:1609.01401]

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

summary

Concluding remarks

- Mass-split models are great to explore near conformal dynamics
- Allow to investigate pNGB and dilaton-like Higgs scenarios
- Limiting cases of 4 and 12 flavors help to understand what is happening
- 4+8 is chosen for convenience of unrooted staggered fermions
  $\rightarrow N_f = 12$ is above the conformal window
  its anomalous dimension is however small $\gamma_m \approx 0.25$

- Walking gauge coupling (controlled by m_h)
- Hyperscaling $\Rightarrow$ predictive
- Heavy-heavy (and heavy-light) spectrum accessible but not QCD-like

- Future: decay constants, $\pi - \pi$ scattering, etc.

Resources and Acknowledgments

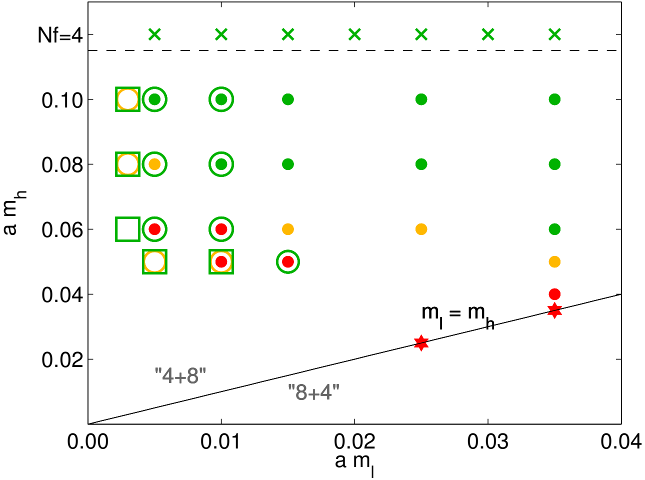
USQCD: Ds, Bc, and pi0 cluster (Fermilab)
BU: engaging (MGHPCC)
XSEDE: Stampede (TACC) and SuperMic (LSU)

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

Disconnected spectrum: the 0^{++} scalar

Numerical measurement on the lattice

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

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: $C(t+1) - C(t)$