A light 0^{++} and other hadronic resonance from a new strongly interacting sector exhibiting large scale separation

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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. PLB 773C (2017) 86-90

Motivation

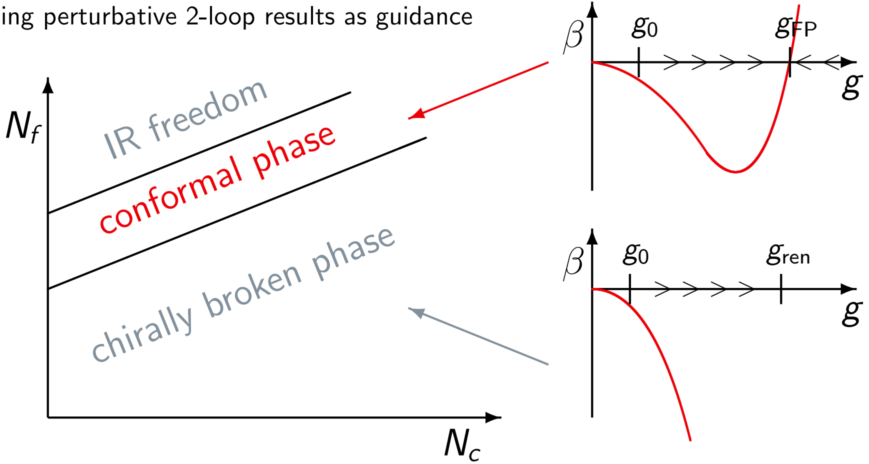
- Mass of the Higgs boson is 125 GeV
- Other states must be much heavier, likely > 1.5 TeV
- Standard Model not UV complete
- What is the origin of the electro-weak sector?

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

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

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 $\to$ "full" SM

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

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

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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_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]

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

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

→ One doublet plays the role of the Higgs doublet field

→ Other doublet and triplets are stable; could play role of dark matter

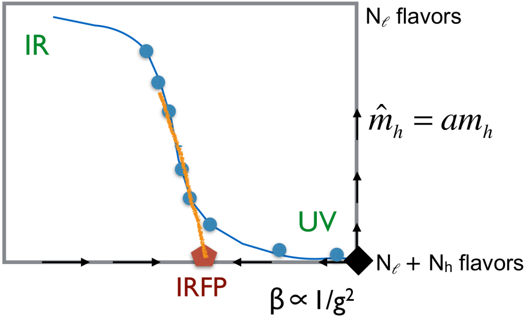
- Vecchi: "choose the right couplings to RH top" [Edinburgh talk]

$$\Rightarrow (2,2) + \cancel{(2,2)} + \cancel{(3,1)} + \cancel{(1,3)} + (1,1) \rightsquigarrow \text{effectively SU(4)/Sp(4)}$$

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 $m_\ell \to 0 \Rightarrow$ chirally broken
  - N_h flavors are massive, we will vary $m_h \to$ decouple in the IR

  $\to$ Choose m_h to feel the attraction of the IRFP of $N_f = 12$



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

Derivation of hyperscaling from Wilson RG

- Scale change: $\mu \to \mu' = \mu/b$, with $b > 1$
  - $\Rightarrow$ bare masses increase: $\widehat{m}(\mu) \to \widehat{m}(\mu') = b^{y_m}\widehat{m}(\mu)$
  - $\Rightarrow$ bare coupling approaches its fixed point: $g \to g^*$
  - $\Rightarrow$ 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 $C_H(t) \propto exp(-M_H t) \Rightarrow aM_H \propto (\widehat{m})^{1/y_m}$ (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]

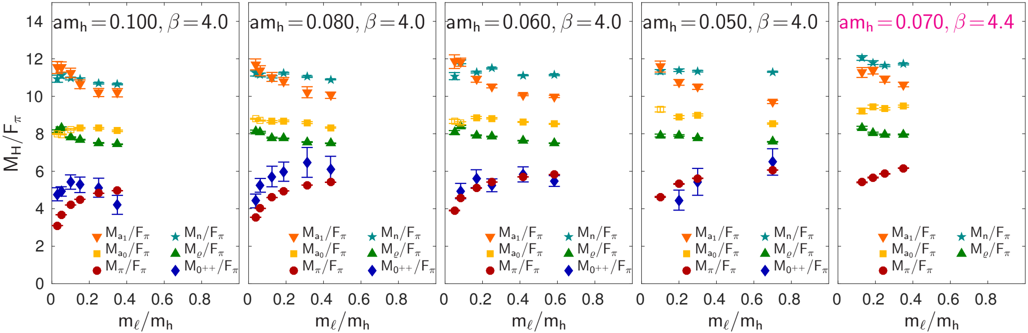
- Light flavors of mass $\widehat{m}_\ell$ and heavy flavors of mass $\widehat{m}_h$:

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

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

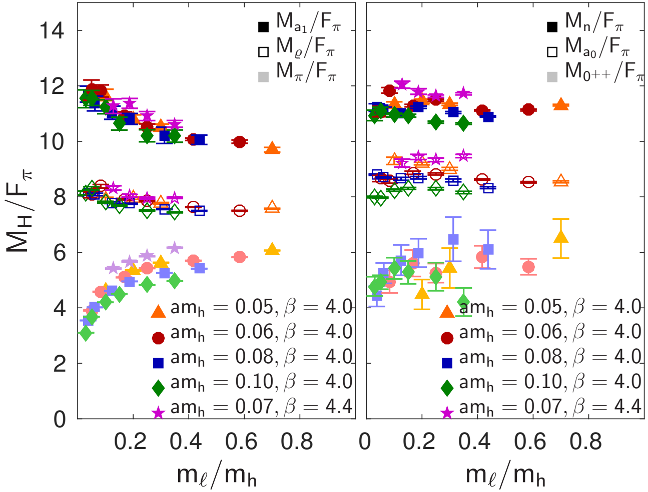
$\Rightarrow$ ratios depend only on m_ℓ/m_h

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

Hyperscaling at work

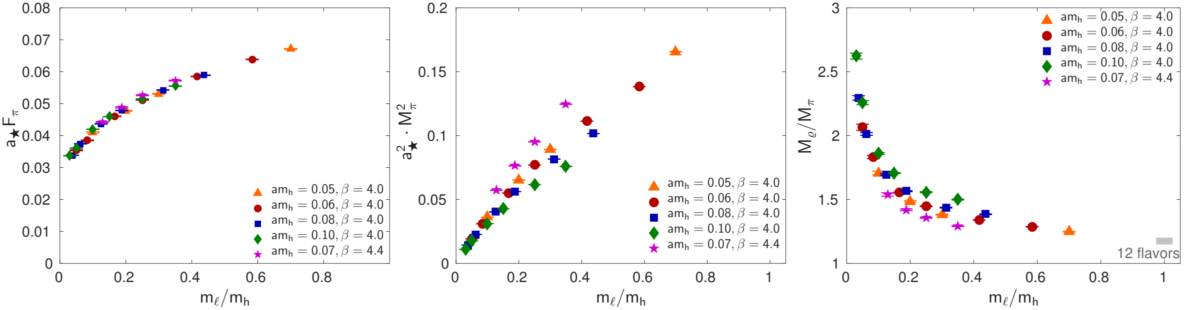


- $M_n/F_\pi \approx 11$
- $M_\varrho/F_\pi \approx 8$
- $M_{0^{++}}/F_\pi \approx 4 - 5$
  (taking the chiral limit is difficult but 0^{++} well separated from the ϱ)

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

- Gauge coupling is irrelevant

The system is chirally broken



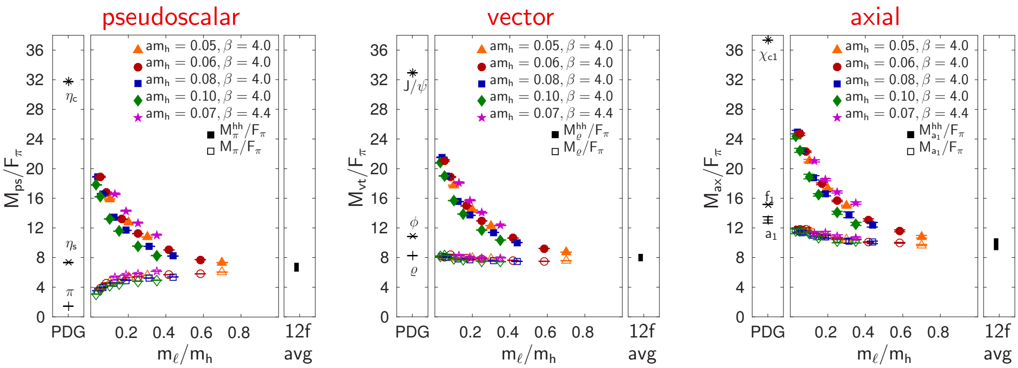
- All data points in $a_\star$ units
- $a_\star F_\pi$ is finite

- 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

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 existens of σ and $f_0(980)$ [PRL 107 (2011) 072001]

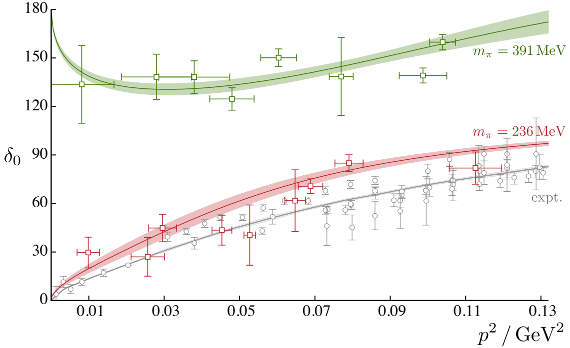
- Hadron spectrum calculation
  [Briceño et al., PRL 118 (2017) 022002]

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

  → Qualitatively different behavior

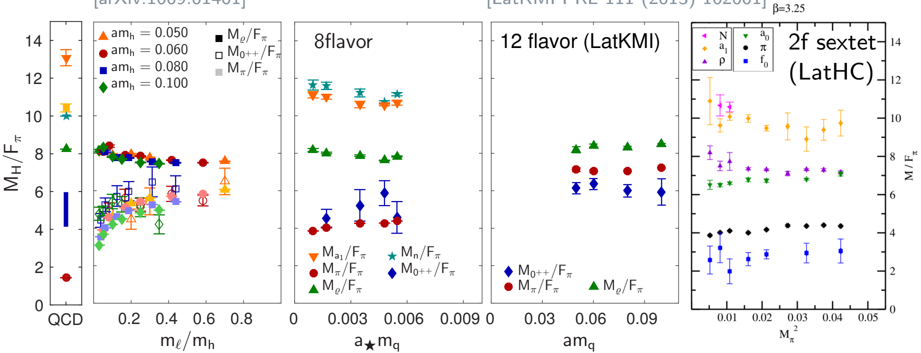
  ⇝ $M_\pi = 391$ MeV: bound state,
  $M_\sigma = 758(4)$ MeV

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



0^{++}

[PDG] [PRD 93 (2016) 075028] [arXiv:1609.01401] [LSD PRD 93 (2016) 114514] [LatKMI PRD86 (2012) 059903] [LatKMI PRL 111 (2013) 162001] [J. Kuti, Argonne 2016]



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

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

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

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

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

Magic 8

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

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

[LatKMI PRD86 (2012) 059903]
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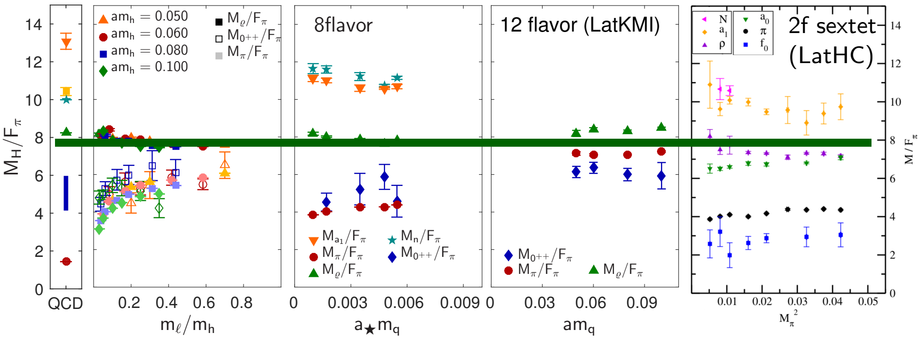


Concluding remarks

- Our model with four light and eight heavy flavors exhibits
  - → a large separation of scales
  - → walking gauge coupling (appendix)
  - → $M_\pi \sim M_{0^{++}} < M_\varrho$
  - → hyperscaling: ratios dependend 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 $M_{0^{++}} \sim M_\pi$

Outlook: four light and six heavy flavors

- → closer to boundary of the conformal window; larger anomalous dimension
- → theoretically clean, but expensive domain-wall fermions ⇒ 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)

QCD:

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

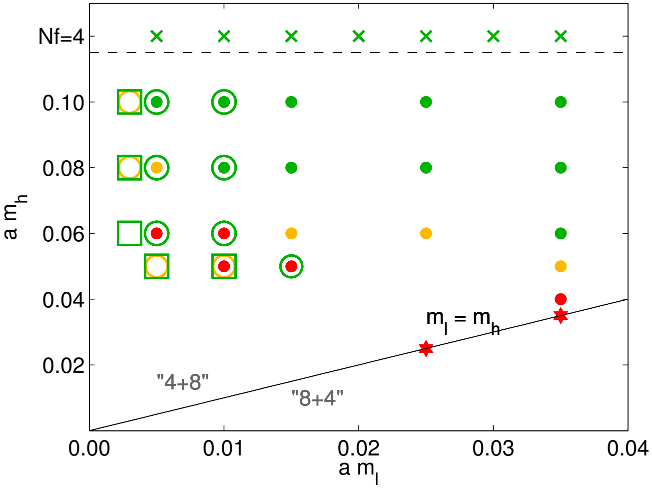
4+8:

- four flavors are massless ($m_\ell = 0$), eigth 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 $m_h \to 0$ for fixed m_ℓ / m_h
- ratios will be independent of m_h and β (hyperscaling)

$N_f = 12$:

- (it appears) theory is conformal and choose $\beta > \beta_{\rm cr}$
- 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

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

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]

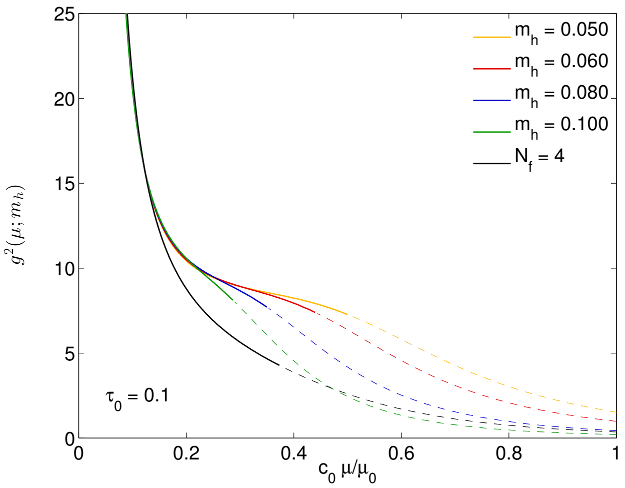
$$g^2_{GF}(\mu = 1/\sqrt{8t}) = t^2 \langle E(t) \rangle / \mathcal{N}$$

  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!

The 0^{++}

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 $\langle\overline{\psi}\psi\rangle$

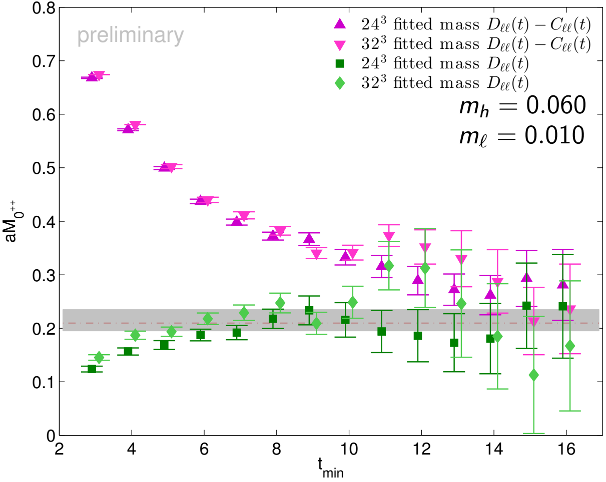
Analysis strategy

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

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!