Probing near conformal dynamics with 4+8 and 8 flavors: running coupling and the spectrum

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8 and 4+8 flavors: Two projects

- With a common action...
  - $SU(3)$ gauge group
  - Gauge action: fundamental-adjoint with $\beta_a = -\beta/4$ [Cheng et al. 2013][Cheng et al. 2014]
  - Fermion action: nHYP smeared staggered [Hasenfratz et al. 2007]
  - Software: HMC and most measurements in FUEL [J. Osborn]
- ...common goals...
  - Explore near conformal or conformal dynamics
  - Study the iso-singlet 0^{++}
- ...and common collaborators!
  - 8 flavor: LSD Collaboration + Anna Hasenfratz [SCGT proceedings 2015]
  - 4+8 flavor: Richard Brower, Claudio Rebbi, Anna Hasenfratz, ESW, Oliver Witzel [JETP 120 (2015) 3, 423] [PoS Lattice2014 254] [CCP proceedings 2014]

LSD Collaboration

in collaboration with Anna Hasenfratz

Lattice Strong Dynamics Collaboration

James Osborn
Xiao-Yong Jin
Rich Brower
Claudio Rebbi
Evan Weinberg

Ethan Neil

Ethan Neil
Sergey Syritsyn

Meifeng Lin

Graham Kribs

Evan Berkowitz
Mike Buchoff
Enrico Rinaldi
Chris Schroeder
Pavlos Vranas

Joe Kiskis

David Schaich

Tom Appelquist
George Fleming

Oliver Witzel

Motivation

Why are more flavors exciting?

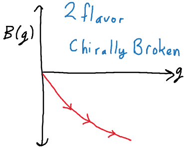
- The excitement is all hinted in the gauge-fermion beta function!

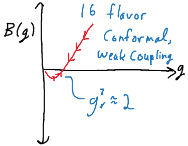
$$\beta(g) = -\beta_0 g^3 - \beta_1 g^5 + \mathcal{O}(g^7)$$

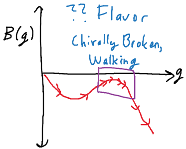
$$\beta_0 = \left[\frac{11}{3}N_c - \frac{2}{3}N_f\right] / (4\pi)^2$$

$$\beta_1 = \left[\frac{34}{3}N_c^2 - \left(\frac{13}{3}N_c - \frac{1}{N_c}\right)N_f\right] / (4\pi)^4$$

$\beta_1 = 0 \rightarrow N_f \approx 8.05$







- 2 flavor is clearly confining (nature), and 16 flavor is perturbative. What happens in between?

8 vs. 4+8

8 flavors

- Promising candidate for near conformal dynamics
  - $SU(3)$, fundamental rep.
  - Integer number of fermions
- Interesting and significant observations from LatKMI

  [Y. Aoki et al. 2014]
- Large scale resources required to explore chiral limit

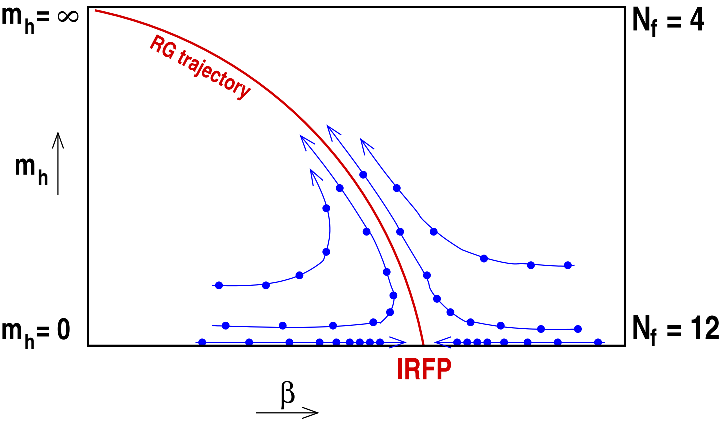
4+8 flavors

- *Specific* case of *general* model for near conformal dynamics
- 4 flavors chiral mass m_ℓ
  +8 flavors of *tunable* mass m_h
- $m_h \to \infty$: 4 flavor: QCD-like
- $m_h \to m_\ell$: 12 flavor:
  likely conformal

  [Cheng et al. 2013][Itou 2013]

  [Cheng et al. 2014][Lombardo et al. 2014]

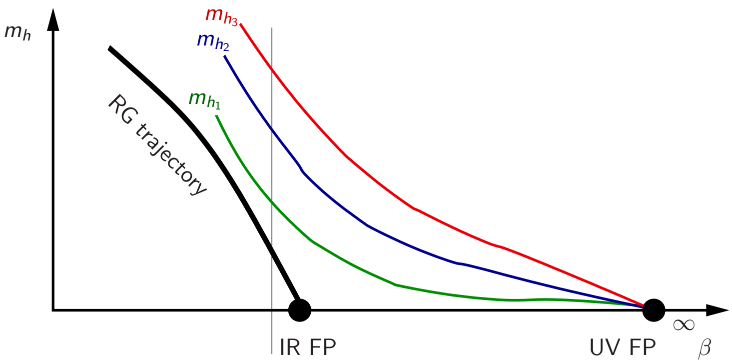
4+8 model: RG sketch



With a finite m_h, we can see walking behavior.

4+8 model: continuum limit

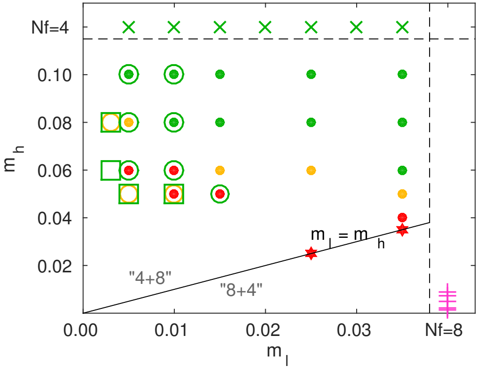
- We have 3 parameters: β, m_ℓ, m_h
- Chiral limit first: $m_\ell \to 0$. 2 parameters
- Continuum limit next: simultaneous $\beta \to \infty$ *and* $m_h \to 0$



- This is difficult but it can be done!

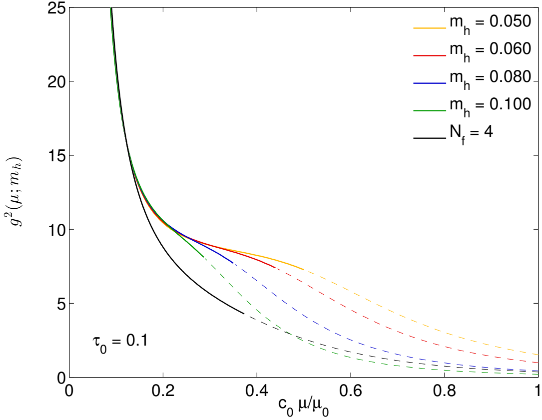
Simulations
$+$ Running Coupling

Performed simulations



- 8 flavor simulations at $\beta = 4.8$ focus on chiral masses and are very expensive
- 4+8 simulations at $\beta = 4.0$ are largely on $24^3 \times 48$ volumes
- Symbols indicate volumes, colors finite volume effects.

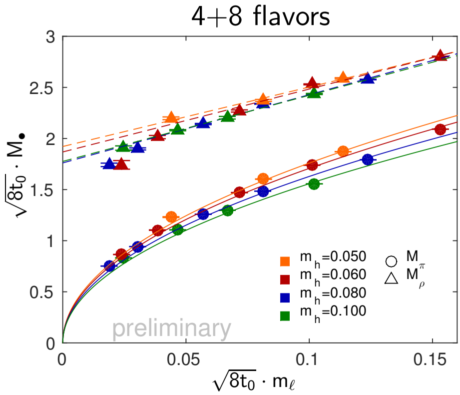
Gradient flow running coupling: 4+8

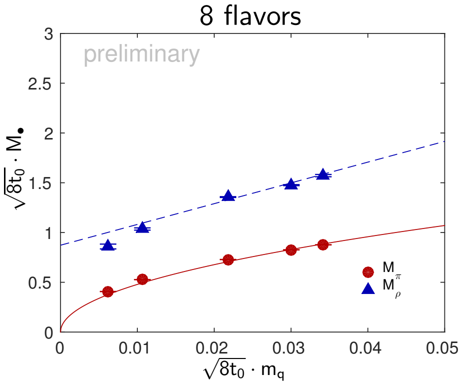


- Gradient flow coupling with τ-shift extrapolated to $m_\ell = 0$.
- $N_f = 4$ shows QCD-like running.
- Finite m_h: "shoulder" increases for smaller m_h.

Spectrum

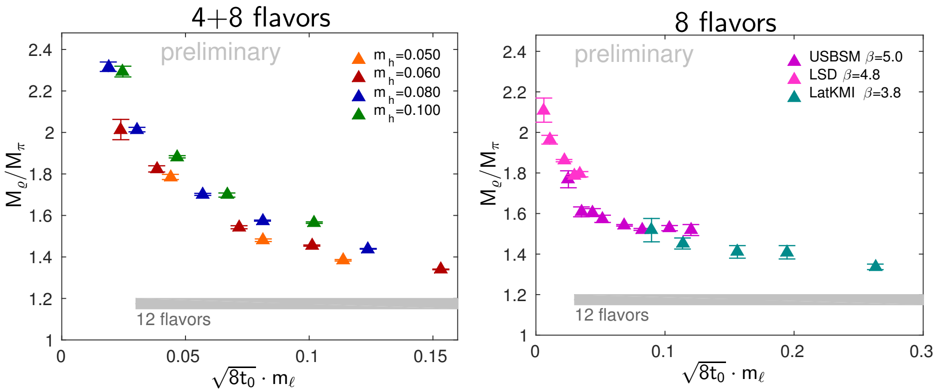
Connected spectrum





- Rescaled m_ℓ, m_q, M_π, and M_ρ by $\sqrt{8t_0}$: relative scales are significant
- 4+8 flavors: weak dependence on m_h
- Fit lines are meant to "guide the eye" based on ChPT.

Are we chirally broken?



- LatKMI data [Y. Aoki et al. 2014], USBSM data [Schaich, PoS Lattice2013 072]
- 4 flavors (QCD-like) has a divergent ratio.
- 12 flavors has a constant ratio [Cheng et al. 2014]: expected for a conformal system

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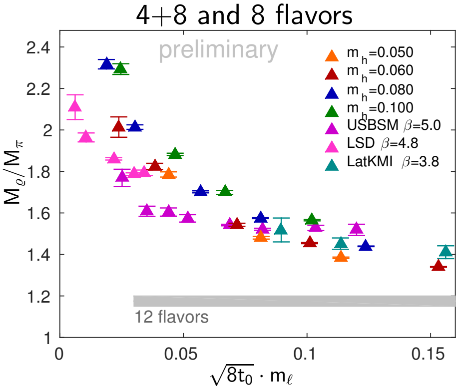

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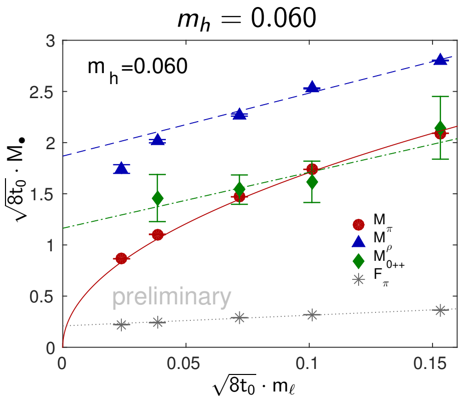
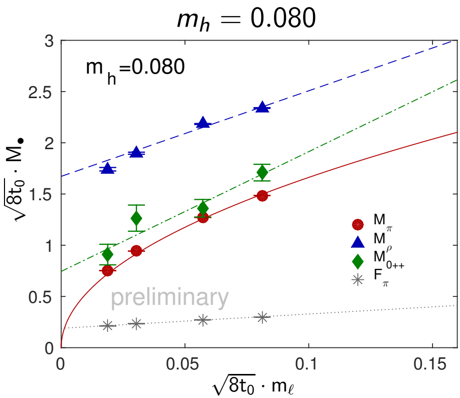
Strategy for disconnected diagrams

- 4+8 and 8 flavor projects have the same setup...
  - 6 $U(1)$ sources with dilution in time, color, and even/odd spatially
  - Improved estimator for $\langle\bar{\psi}\psi\rangle$
  - Dilution in time, color, even/odd space
  - Improved estimator for disconnected piece
  - Still need large statistics to suppress gauge noise
- ...and the same analysis strategy.
  - Correlated fit to both parity states
  - Vacuum subtraction introduces large uncertainties
  - Fit an additional constant
  - Equivalent to fitting the finite difference $C(t+1) - C(t)$

$$C(t) = c_{0^{++}} \cosh\left(M_{0^{++}}\left(T/2 - t\right)\right) + c_{\tilde{\pi}_{sc}}\left(-1\right)^{t} \cosh\left(M_{\tilde{\pi}_{sc}}\left(T/2 - t\right)\right) + v$$

4+8 flavors: F_π, M_π, M_ρ, and $M_{0^{++}}$ for $m_h = 0.060, 0.080$

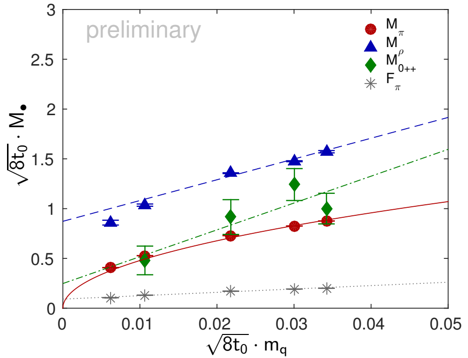


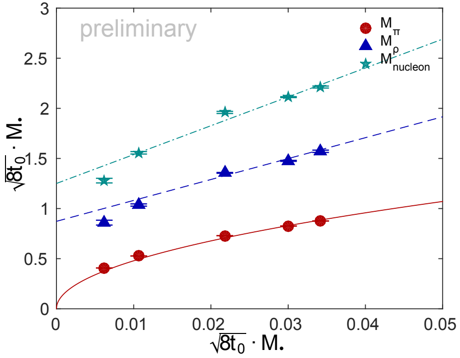


- $m_\ell = 0$: $\sqrt{8t_0} M_\rho = 1.87$
  $\sqrt{8t_0} M_{0^{++}} = 1.16?$, $\sqrt{8t_0} F_\pi = 0.21$
- $m_\ell = 0.003$: $F_\pi L = 0.027 \cdot 48 = 1.3$

- $m_\ell = 0$: $\sqrt{8t_0} M_\rho = 1.67$
  $\sqrt{8t_0} M_{0^{++}} = 0.74$, $\sqrt{8t_0} F_\pi = 0.19$
- $m_\ell = 0.003$: $F_\pi L = 0.034 \cdot 36 = 1.2$

8 flavors: F_π, M_π, M_ρ, $M_{nucleon}$, and $M_{0^{++}}$





- $m_\ell = 0$: $\sqrt{8t_0}M_\rho = 0.87$, $\sqrt{8t_0}M_{nucleon} = 1.25$, $\sqrt{8t_0}M_{0^{++}} = 0.25$, $\sqrt{8t_0}F_\pi = 0.09$
- $m_\ell = 0.00125$: $F_\pi L = 0.0213 \cdot 64 = 1.4$
- Connected spectrum not happy with “naive” fit form

Remarks

Concluding remarks

4+8 flavors

- A great model to explore near conformal dynamics by varying m_h *continuously*.
- Limiting cases of 4 and 12 flavors help us understand what is happening.

8 flavors

- A difficult system requiring very expensive, chiral simultations to study
- May be very close to the onset of the conformal window: further studies are needed

Non-QCD like features

- “Shoulder” in the running coupling
- Tunable chiral behavior with m_h
- Chiral behavior visible only for small bare fermion masses

The 0^{++} is light: $M_{0^{++}} < M_\rho, 2M_\pi$
Does a dynamical mechanism give this?

Thank you!

Backup

Backup: 8 flavors finite temperature studies

- We base our 8 flavor runs on existing results.

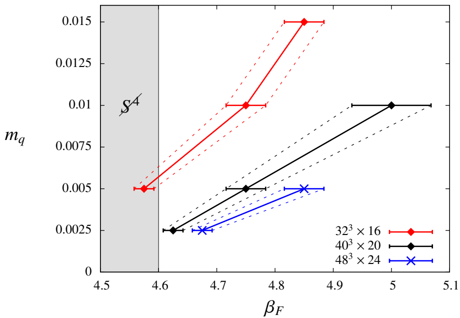
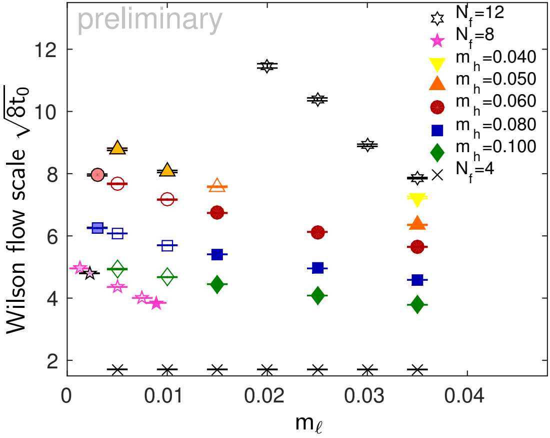


Figure: Finite T studies by Boulder / LSD, in preparation

- Run at strong couplings safe from deconfinement and lattice phases.

Backup: Gradient flow running coupling



- Wilson flow scale $\sqrt{8t_0}$ [Narayanan and Neuberger 2006] [Lüscher 2010]
- 4, 4+8, 12 flavor at $\beta = 4.0$
- 8 flavor at $\beta = 4.8$