Pushing towards lighter fermions in $SU(3)$ with 8 flavors

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Outline

1. Many-flavor physics, pheno, and the lattice
2. Preliminary 8 flavor results
3. Conclusions

Why are more flavors exciting?

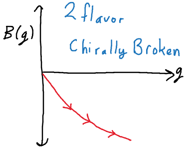
- The excitement is all hinted in the gauge-fermion beta function!

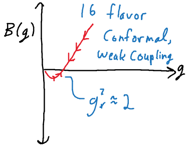
$$\beta(g) = -\beta_0 g^3 - \beta_1 g^5 + \mathcal{O}(g^7)$$

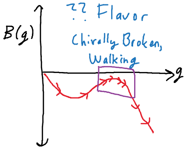
$$\beta_0 = \left[\frac{11}{3} N_c - \frac{2}{3} N_f\right] / (4\pi)^2$$

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

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







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

Phenomenological consequences

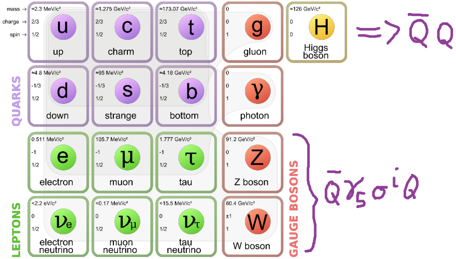
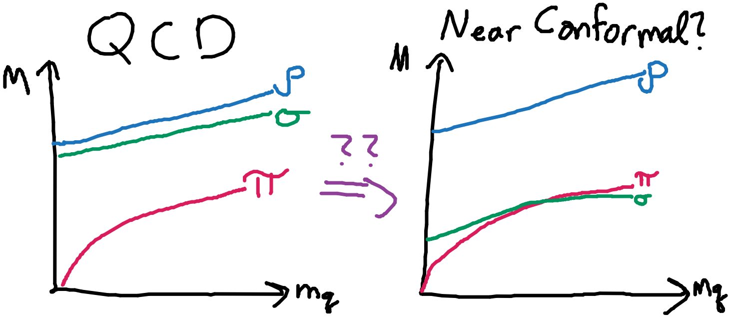


Figure : Modified from Wikipedia: "Standard Model"

- Higgs could be $\bar{Q}Q$ scalar composite of *strong dynamics.*
- Even before the Higgs, many composite BSM theories were built on near-conformal dynamics.

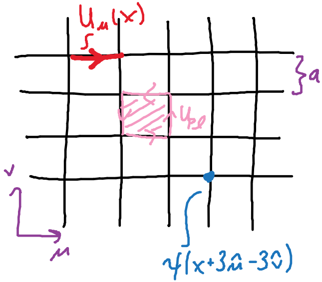
Not just your average confining theory

This can't just be scaled up QCD: the scalar Higgs candidate is heavy.



More fermions, such as $SU(3)$ 8 flavor, might give different, interesting behavior.

The Lattice



- Studies are done on 4-dimensional $L \times L \times L \times T$ lattices.
- Common values are $L = 24, 32 \rightarrow \mathcal{O}(1 \text{ million})$ sites.

$$\mathcal{Z} = \int [dU d\bar{\psi} d\psi] e^{-\frac{1}{g^2}F^2 - \bar{\psi}_i \not{D} \psi_i - m_q \bar{\psi}_i \psi_i}$$

$$= \int [dU] \det(D^\dagger D + m_q^2)^{N/2} \; e^{-\frac{1}{g^2}F^2}$$

- Non-perturbative method to do a strongly-coupled calculation.
- Having multiple flavors is just adding more fermion determinants.

Pushing 8 flavors with finite temperature studies

- We base our 8 flavor runs on existing results.

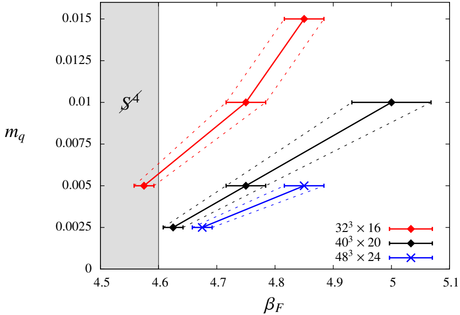


Figure : Finite T studies by Boulder / LSD, in preparation

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

8 flavor ensembles

Volume	am_q	MDTU
24^3x48	0.00889	25k
24^3x48	0.0075	10k
32^3x64	0.0075	25k
32^3x64	0.0050	22k
48^3x96	0.00222	12k
64^3x128	0.00125	3k

Gauge Action: Fundamental-Adjoint at $\beta = 4.8$, $\beta_r = -0.25$.

Fermion Action: nHYP Smeared Kogut-Susskind ("staggered")

Software: FUEL by James Osborn.

- How does the spectrum look as the fermion mass drops?
- How does the gauge coupling run?
- How does the lightest 0^{++} state behave?

We acknowledge computing time through the Grand Challenge program at LLNL and USQCD at Fermilab

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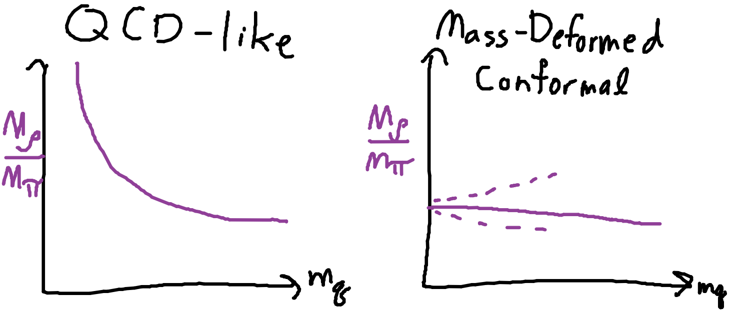
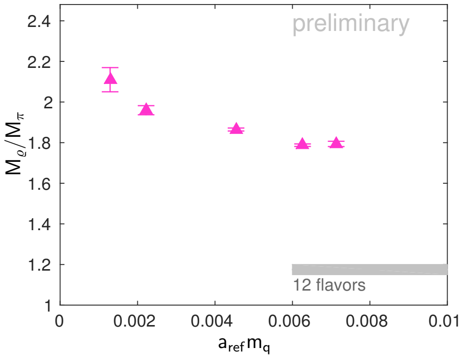
The vector-pseudoscalar mass ratio



- Chirally broken: $\frac{M_\rho}{M_\pi} \approx \frac{1}{\sqrt{m_q}}$.
- Mass-deformed conformal: $\frac{M_\rho}{M_\pi} \approx$ constant.
    - Dashed lines correspond to scaling corrections: finite volume artifact from irrelevant operators.

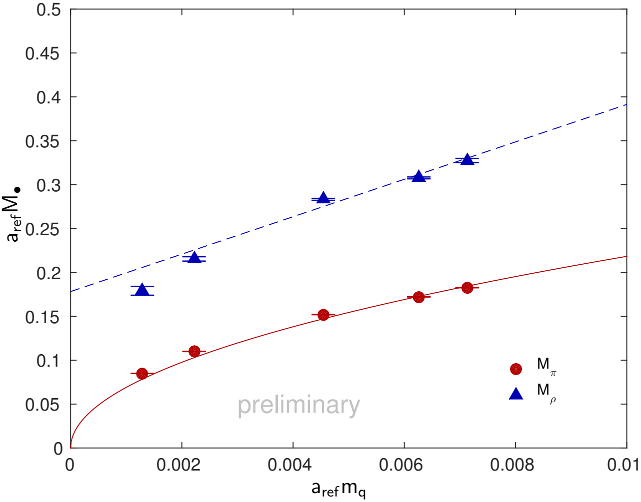
The 8 flavor vector-pseudoscalar mass ratio



Note: 12 flavor data: `arXiv:1401.0195`

- Current data doesn't favor chirally broken or conformal: we are not sufficiently chiral.
  - Could be diverging as $m_q \to 0$: chiral symmetry breaking.
  - Could be constant with hyperscaling corrections as $m_q \to 0$: conformal.

The non-scalar spectrum



Fit lines purely to guide the eyes.

Setting and varying a scale

- Along the gradient flow... `[arXiv:1006.4518]`

$$t = \text{gradient flow time}$$

- ...look at a quantity...

$$g^2_{WF}\left(\mu = \frac{1}{\sqrt{8t}}\right) = \frac{1}{\mathcal{N}}\left\langle t^2 E(t)\right\rangle$$

- ...relative to a consistent IR scale.

$$g^2_{WF}(\mu_0 = \frac{1}{\sqrt{8t_0}}) = \frac{0.3}{\mathcal{N}}$$

- μ_0 is an energy scale.
- $\sqrt{8t_0}$ is a length scale.

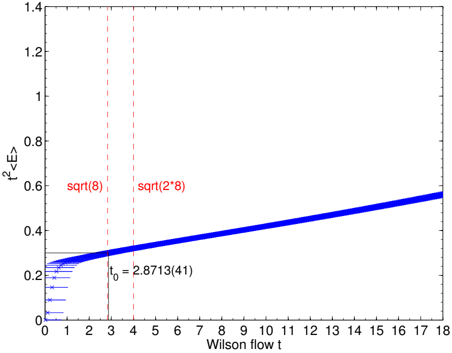
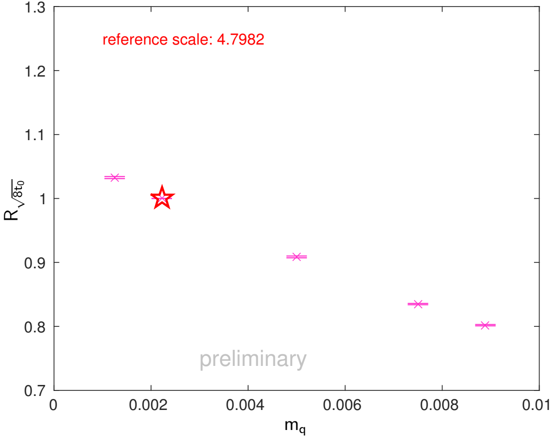


Figure : $48^3 \times 96$, $m_q = 0.00222$

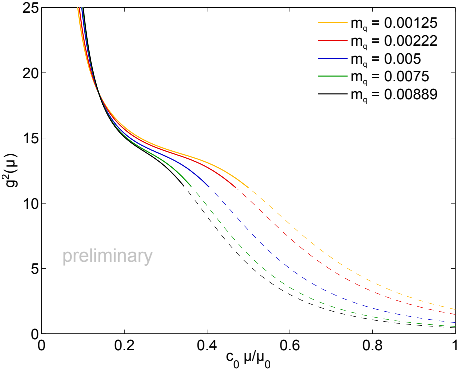
Ratio of gradient flow scale with the fermion mass



- Use $48^3 \times 96$, $m_q = 0.00222$ to set a reference scale.
- This ratio rescales massive quantities to common units, $a_{ref} M$.

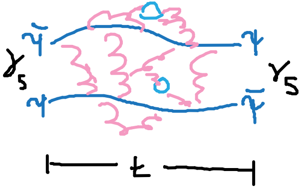
8 flavor gradient flow running coupling

- *Measured* gradient flow running coupling.
- Coupling is a function of $\mu \equiv \frac{1}{\sqrt{8t}}$.
- All curves made to agree in IR: scale setting.
- Dashed lines where cutoff effects may be relevant.



- Slow running tense with 8f beta function: see talk by A. Hasenfratz.
- Is the shoulder physics, or cutoff effects?

Euclidean correlation functions



$$\Rightarrow \sum_n f_n^2 e^{-m_n t}$$

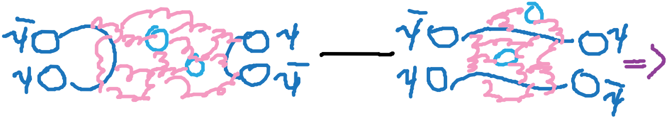
Extract masses from Euclidean correlation functions.
Example: Isomultiplet Pseudoscalar

$$\langle \bar{\psi}\gamma_5\lambda_i\psi(0)\ \bar{\psi}\gamma_5\lambda_i\psi(t)\rangle$$

$$= \frac{1}{\mathcal{Z}}\int [dUd\bar{\psi}d\psi]\ \bar{\psi}(0)\gamma_5\lambda_i\,\psi(0)\ \bar{\psi}(t)\gamma_5\lambda_i\psi(t) e^{-\frac{1}{g^2}F^2 - \bar{\psi}_i \not{D}\psi_i - m_q\bar{\psi}_i\psi_i}$$

$$= \frac{1}{\mathcal{Z}}\int [dU]\ (G_F(0,t))^2\ \det(D^\dagger D + m_q^2)^{N/2}\ e^{-\frac{1}{g^2}F^2}$$

0^{++} scalar correlation function



$$\Rightarrow f_\sigma^2 e^{-m_\sigma t} + \cdots$$

Example: Isosinglet Scalar (0^{++})

$$\langle \bar{\psi}\psi(0)\ \bar{\psi}\psi(t) \rangle$$

$$= \frac{1}{\mathcal{Z}} \int [dU d\bar{\psi} d\psi] \left\{ 2\, \bar{\psi}(0)\psi(0)\ \bar{\psi}(t)\psi(t) - \bar{\psi}(0)\ \psi(0)\ \bar{\psi}(t)\psi(t) \right\}\ e^{-\frac{1}{g^2}F^2 - \bar{\psi}_i \not{D}\psi_i - m_q \bar{\psi}_i \psi_i}$$

$$= \frac{1}{\mathcal{Z}} \int [dU]\ \left\{ 2 G_F(0,0) G_F(t,t) - (G_F(0,t)\gamma_5)^2 \right\}\ \det(D^\dagger D + m_q^2)^{N/2}\ e^{-\frac{1}{g^2}F^2}$$

- Factor $G_F(t,t)$ means we need *every* point to itself.

Strategy for disconnected diagrams

- Disconnected piece:
  - 6 $U(1)$ stochastic sources.
  - Dilution in time, color, even/odd space.
  - Improved estimator for disconnected piece.
  - Still need large statistics to suppress gauge noise.
- 0^{++} Vacuum Channel:
  - $\bar{\psi}\psi(t)$ has a **v**acuum **e**xpectation **v**alue.
  - Very expensive to measure **vev**.

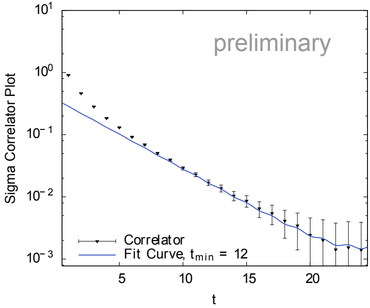


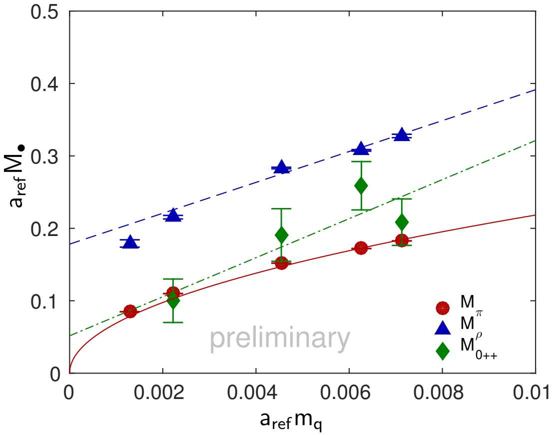
Figure : $24^3 \times 48, m_q = 0.00889$

- Ignore vacuum subtraction, fit extra constant:

$$\langle \bar{\psi}\psi(0)\ \bar{\psi}\psi(t)\rangle = A_\sigma \cosh\left(M_\sigma\left(T/2 - t\right)\right) + \mathbf{v}$$

0^{++} results

- The scalar appears to track the pseudoscalar closer than the vector.



Fit lines purely to guide the eyes.

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Recap and Conclusions

- Strong coupled multi-flavor theories are interesting...
- ...And could be composite Higgs models.
- The lattice is our non-perturbative tool.
- No strong preference in the parameter range we study towards chiral symmetry breaking or conformality...
  - ...in the isomultiplet spectrum.
  - ...from the gradient flow running coupling.
- The 0^{++} meson mass tracks the pseudoscalar over the range we study.

Thank you!