Lattice QCD with 12 Quark Flavors — A Careful Scrutiny

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Many flavors on the lattice

Outdated List

Other groups w/ SU(3) fund. fermion

- 12 flavors
  - Aoki, *et al*
  - Appelquist, *et al*
  - Fodor, *et al*
  - Hasenfratz, *et al*
  - Pallante, *et al*
- Other number of flavors
  - Itou, *et al*
  - Yamada, *et al*
  - LSD

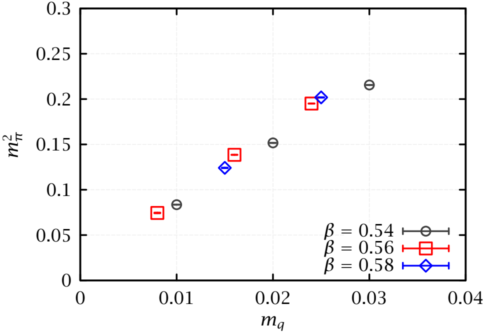
Our work w/ 8 and 12 flavors

- Naïve staggered fermion
- DBW2 gauge
- Low energy hadronic observables
- Zero and finite temperature
- Across a wide range of lattice scales
- Small finite volume effects (few percent)

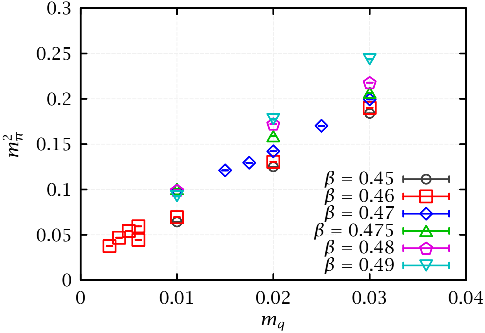
No consensus on whether the zero temperture continuum phase is conformal or chirally broken.

Behavior of m_π^2 vs. m_q

8 flavors

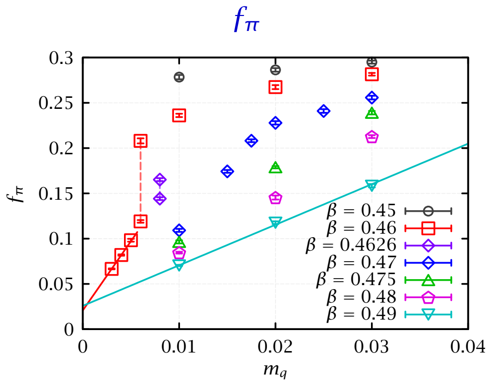


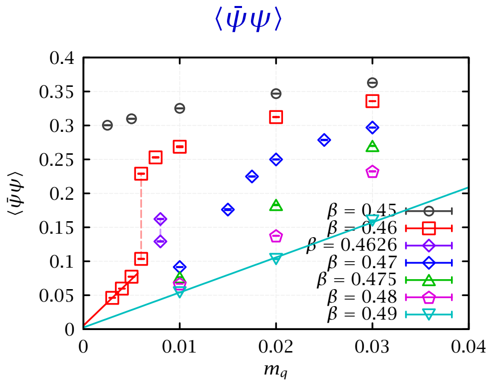
12 flavors



- Mostly linear in our parameter range $\Longrightarrow$ Gold stone behavior!?
- Slope, in lattice units, almost doesn't change for different β and N_f
- Bulk transition at $\beta = 0.46$, more about it later

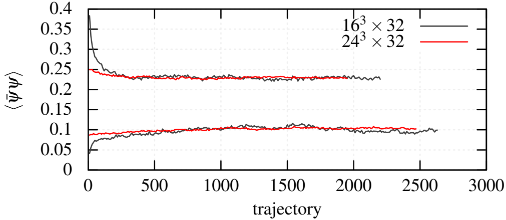
Large change of lattice scales at $N_f = 12$



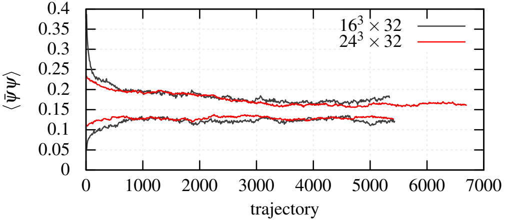


- Nonzero values at $m_q = 0$ with linear extrapolations
- Lattice scales change about $\times 10$ across the bulk transition

The 1 st order bulk transition & the critical end point



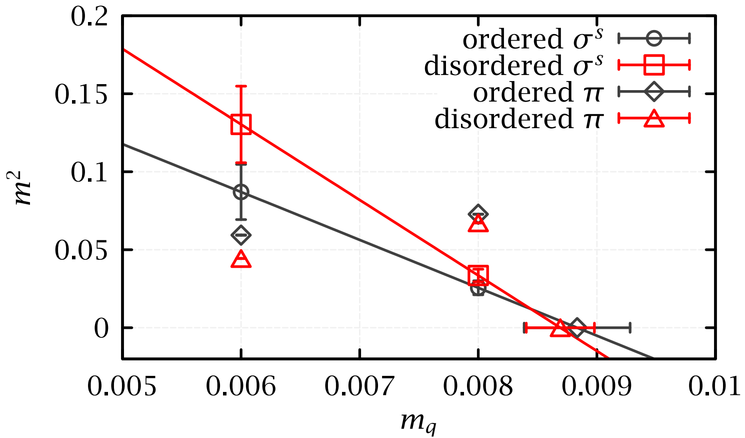
(a) $\beta = 0.46$, $m_q = 0.006$



(b) $\beta = 0.4626$, $m_q = 0.008$

- Volume independent $\Longrightarrow$ finite temperature effect less likely.
- For most channels, the difference in particle masses on the two sides of the bulk transition become smaller and vanish when quark mass is increased.
- The scalar singlet is found to be special.

Scalar singlet meson

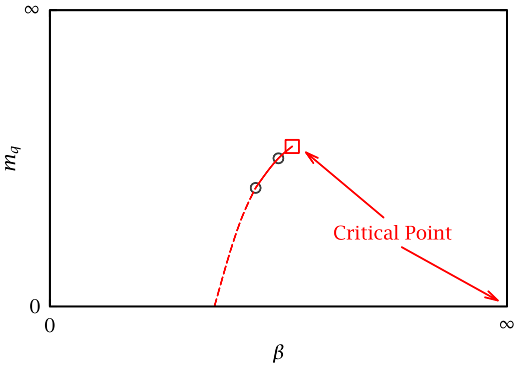


- The scalar singlet meson becomes lighter along the 1st order bulk transition line approaching the 2nd order critical end point.
- Continuum limit of the lattice theory at second order critical point is likely a free scalar field theory.

Lattice gauge theory & critical point

- Lattice theory represents the continuum theory only when correlation lengths diverge.
- Only then, the lattice system forgets about the underlying lattice.
- It only happens near some ultraviolet fixed points.
- $\beta \to \infty$ ($g \to 0$) for standard model QCD.
- The behavior of a continuum theory is only realized in the limit of UV fixed point on the lattice.
- The huge advantage of doing the standard model QCD:
  We know we are close to the continuum limit when our results conform to experiments.

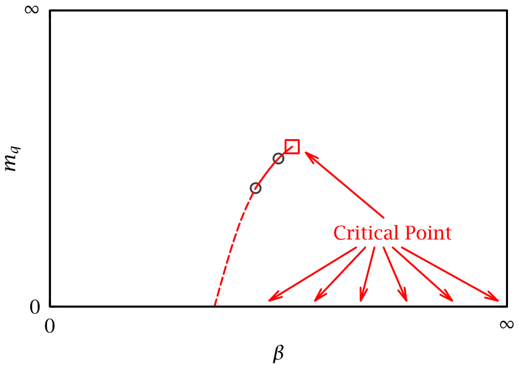
The lattice phase diagram



- Continuum approached by going to $\beta \to \infty$, where correlation length diverges.
- Certain correlation length (we found the scalar singlet meson) diverges at the second order critical point at finite quark mass.
- Now we have two fixed points on the lattice that have continuum limit.
- Not easy to tell if we are close to the $\beta \to \infty$ continumm limit.
- Decreasing quark mass $\Longrightarrow$ moving away from finite m_q continuum limit.

What about conformal behavior

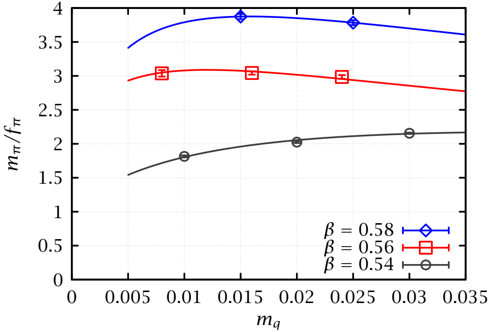
- Common finite size scaling hypothesis: $LM = f(Lm_q^\alpha)$
- $\lim_{L\to\infty} M \propto m_q^\alpha$, valid for all bare input β
- In the infinite volume limit, with vanishing quark masses, for every bare input β, there is a continuum limit!



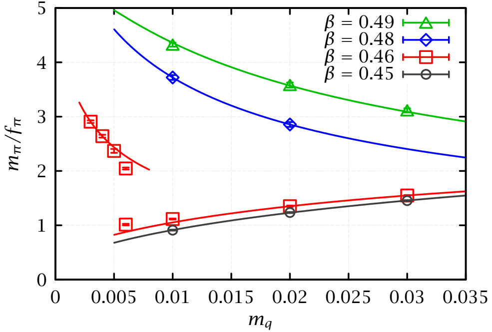
Question: With $L \to \infty$ and $m_q = 0$, do we have the same physics at different bare input β?

Constant physics by m_π/f_π

8 flavors



12 flavors

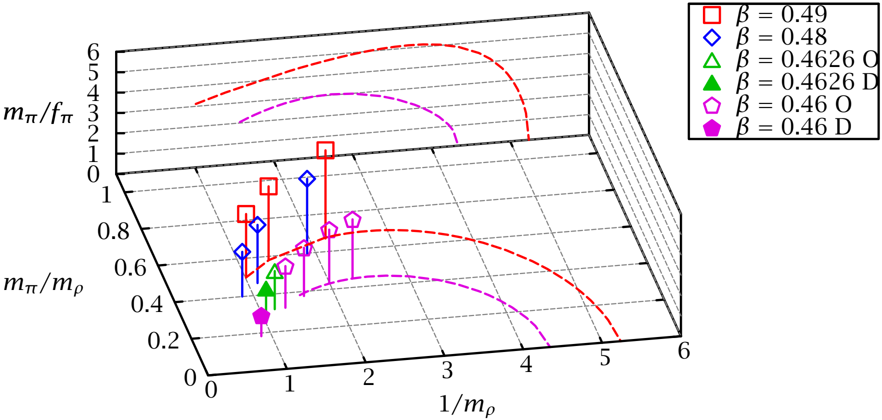


Hadronic scale (f_π) is decreasing so rapidly that m_π/f_π is increasing!

Warnings:

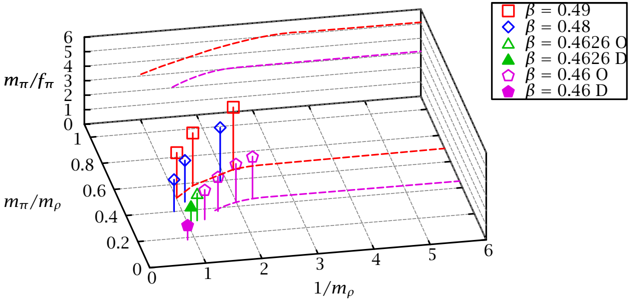
- Constant m_π/f_π requires increasing m_q while increasing β.
- Backward flow of constant m_π/f_π in weaker couplings.
- Misleading conclusions at large m_q.

More ratios using m_ρ as a scale

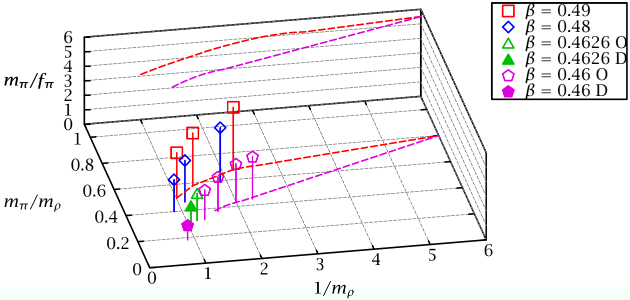


- Dashed lines are simple chirally broken extrapolations:
  $m_\pi^2 = c_0 m_q(1 + c_1 m_q)$, $m_\rho = b_0 + b_1 m_q + b_2 m_q^2$, and f_π similar to m_ρ
- Had conformal behavior assumed, each ratio be a constant as $1/m_\rho \to \infty$
- Question: Should a specific ratio be a same constant for different β?

Assuming conformal, which do we expect with $L \to \infty$

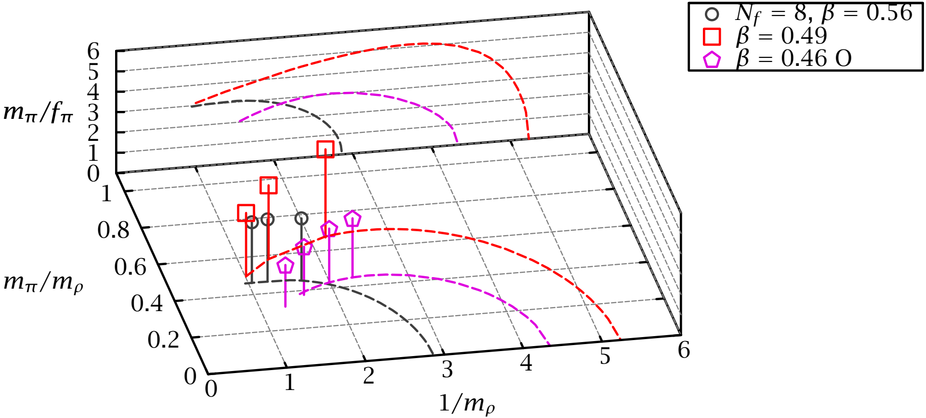


Different physics
for different β?



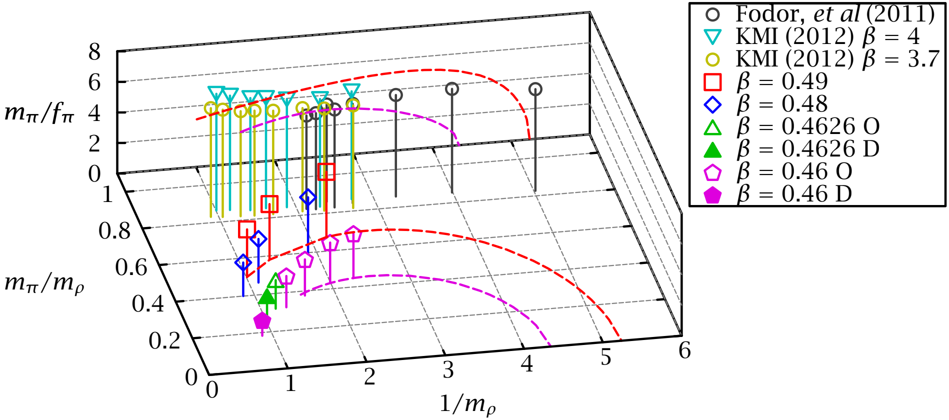
Same physics
for different β?

Is chiral symmetry breaking viable



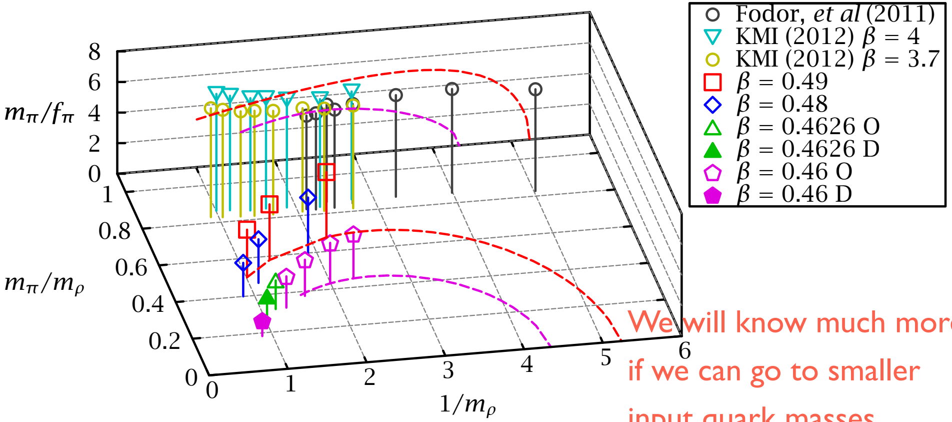
- Added 8-flavor $\beta = 0.56$ to 12-flavor picture
- Very similar behavior between 8-flavor and 12-flavor
- Hadronic scale (m_ρ, f_π) has much more profound dependence on input quark mass, m_q, in 12-flavor than 8-flavor. ChiPT ineligible for sim. points, 8f or 12f

Universality



- Picked the largest volume for each m_q, small finite volume effect
- Weakest couplings we can go are governed by computational resources
- Different lattice action, different lattice artifact, yet similar behavior
- Is each ratio going to a constant as $1/m_\rho \to \infty$?
- Are they showing any chirally broken behavior?

Universality



We will know much more if we can go to smaller input quark masses

- Picked the largest volume for each m_q, small finite volume effect
- Weakest couplings we can go are governed by computational resources
- Different lattice action, different lattice artifact, yet similar behavior
- Is each ratio going to a constant as $1/m_\rho \to \infty$?
- Are they showing any chirally broken behavior?

Summary

- We have located a lattice artifact, critical point where scalar correlation length diverges, with naïve staggered fermions and the DBW2 gauge action.
- Much lighter quark masses might be needed to actually differentiate between conformal and chirally broken scenarios.
- How to effectively scale towards the continuum limit within our current computational resources remains a question for both scenarios.