Searching for new dynamics in strongly coupled lattice gauge theory

Simon Catterall

Syracuse University

Outline of talk

- Motivation: technicolor and walking technicolor
- Phase diagram non-supersymmetric gauge theory
- Lattice $SU(2)$ with 2 flavors of adjoint quark
- Simulation results
- Conclusions and outlook

Troubles with Higgs ...

Standard model Higgs has many problems:

- Quadratically unstable against radiative corrections.
- Triviality
- Symmetry breaking “put in by hand”. What sets scale ?

One attractive solution: dispense with elementary Higgs, invoke new strong dynamics to break EW symmetry: Technicolor

Basic idea

- Assume new strong dynamics at scale $\Lambda_{rmTC} = O(1)$ TeV causes condensation of new techni-quarks
- If electroweak symmetry embedded into chiral-flavor symmetries of techniquarks will precipitate EW breaking
- Massive EW bosons produced from would-be Goldstone's associated with broken chiral symmetries

Advantages

- Follows example of QCD: asymptotically free gauge theories naturally develop a scale $\Lambda << M_{\mathrm{GUT/Planck}}$ with chiral symmetry breaking.
- No quadratic fine tuning. No triviality problem.

Problems:

- Constraints: How many techni-quarks, how many colors, what representation ?
- Phenomena arise from strong dynamics: how to make predictions ?
- What about masses of quarks/leptons – need to couple techni-quarks to usual Standard Model particles – extended technicolor.
- Understand flavor hierarchy in terms of dynamics at Λ_{ETC} ?

Why QCD won't do

- Scaled up versions of QCD at odds with precision EW observables.
- In generic ETC theories – effective 4-quark operators yield FCNC – suppress by large Λ_{ETC}. But then fermion masses too small !

Solution: dynamics must be very different from QCD
One possibility: g_{TC} must walk in $\Lambda_{\mathrm{TC}} \rightarrow \Lambda_{\mathrm{ETC}}$

How can this arise ?

- Slow running requires theory lie near zero of the β-function. Theory near conformal.
- Can we find realistic walking gauge theories ?
- More generally: what types of dynamics are possible in 4d gauge theory ...?

Phases of gauge theory

Distinguish using long distance potential between static heavy sources.

- Coulomb $V(r) = \frac{1}{r}$. Conformally invariant.
- Free electric $V(r) = \frac{1}{r \ln r}$. Eg QED.
- Free magnetic $V(r) = \frac{\ln r}{r}$
- Higgs $V(r) = \mathrm{const}$
- Confining $V(r) = \sigma r$

All realized in supersymmetric GT. Non-supersymmetric ?
Can we find a region in (N_c, N_f, R) where theory develops I.R conformal fixed point ?

Phase diagram

Variety of approx analytical approaches used

Conformal window bounded below by chiral symmetry breaking and above by loss of asymptotic freedom.

Minimal theories

Notice: Using symmetric/adj reps significantly lowers the number of flavors needed for walking Minimal theory $SU(2)$ with 2 adjoint flavors is (near)conformal!

- Ladder: $N_f \sim, 2.1$
- Conjectured all order beta function – theory already in conformal window (Sannino)

Minimal walking technicolor MWT possible (Sannino).

Lattice approach - glue

Use lattice simulation to look for conformal phase.
Employ standard Wilson gauge action

$$S_G = -\frac{\beta}{2} \sum_x \sum_{\mu>\nu} \mathrm{ReTr} \Big(U_\mu(x) U_\nu(x+\hat{\mu}) U_\mu^\dagger(x+\hat{\nu}) U_\nu^\dagger(x) \Big) \ ,$$

where $U_m u(x) = e^{A_\mu(x)a}$ is in fundamental of $SU(2)$ and
$\beta = \frac{4}{g^2}$
Show $S_G \rightarrow \int d^4 x F_{\mu\nu}^2 + O(a)$

Lattice approach - quarks

Several choices. Use Wilson. Fast, no rooting problem.

$$S_F = -\frac{1}{2}\sum_x \sum_\mu \overline{\psi}(x)\Big(V_\mu(x)\,(I-\gamma_\mu)\,\psi(x+\mu) + V^T_\mu(x-\mu)\,(I+$$

$$+ \sum_x (m+4) \sum_x \overline{\psi}(x)\psi(x)\ .$$

with adjoint links

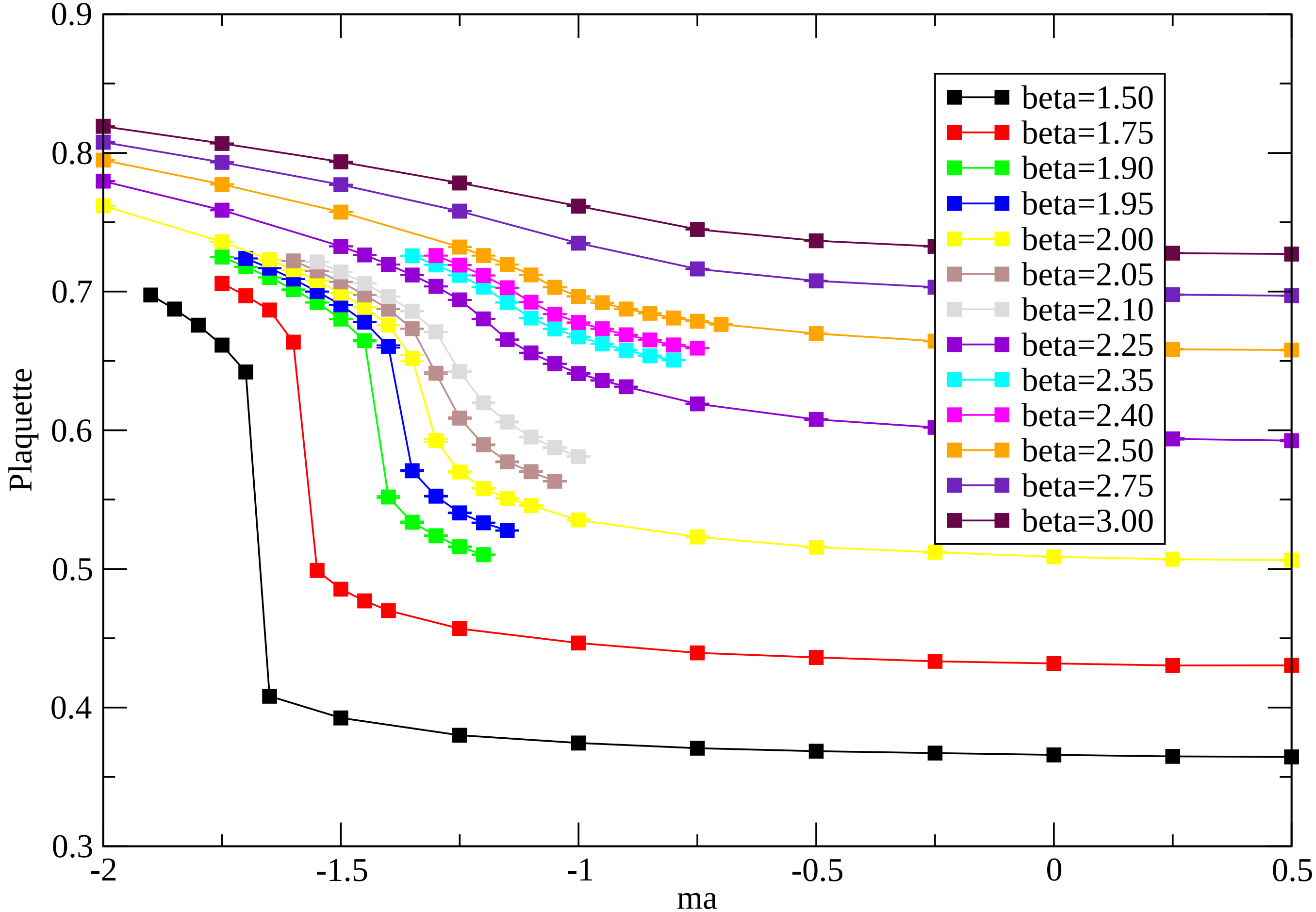
$$V^{ab}_\mu(x) = \mathrm{Tr}\left({}^a U_\mu(x)\,{}^b U^\dagger_\mu(x)\right)\ ,$$

Drawbacks: need to tune bare quark mass m with β to restore chiral symmetry.

Numerical details

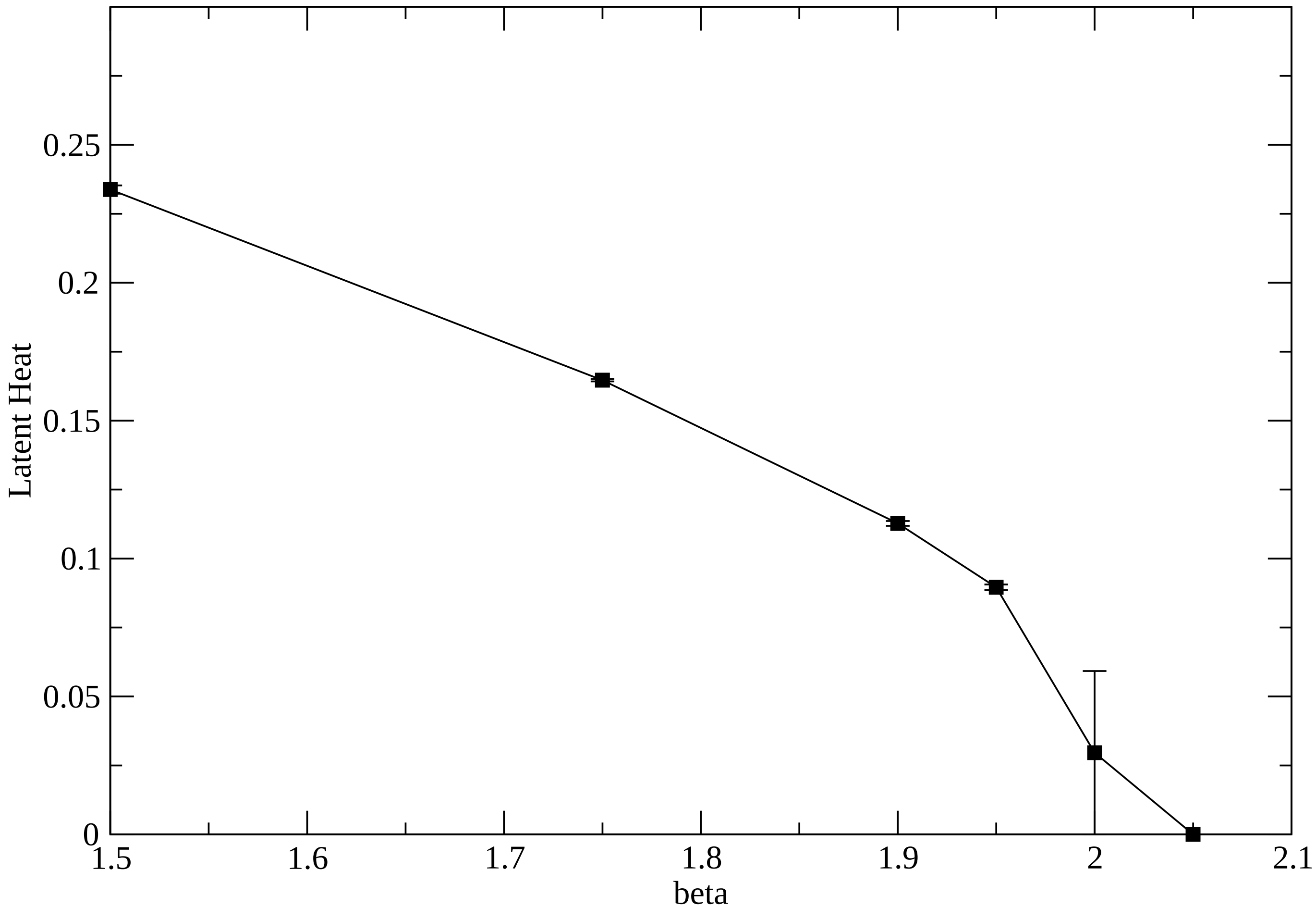
- Use HMC algorithm – efficient and exact way to handle dynamical fermions
- Implemented using a hack of CPS to allow for adjoints.
- Runs correspond to 4+ months on 128 node rack of IBM BlueGene L at RPI.
- Lattice sizes: $8^3 \times 16$ and $16^3 \times 32$.
- Initial work: find phase structure in (β, m) plane.
- Continuous phase transitions imply a massless state and allow a continuum limit. If chiral symmetry broken – massless state is pion.
- Scan in ma at fixed β for minimum pion(rho) mass and critical behavior of gluon action.

Mean gluon action



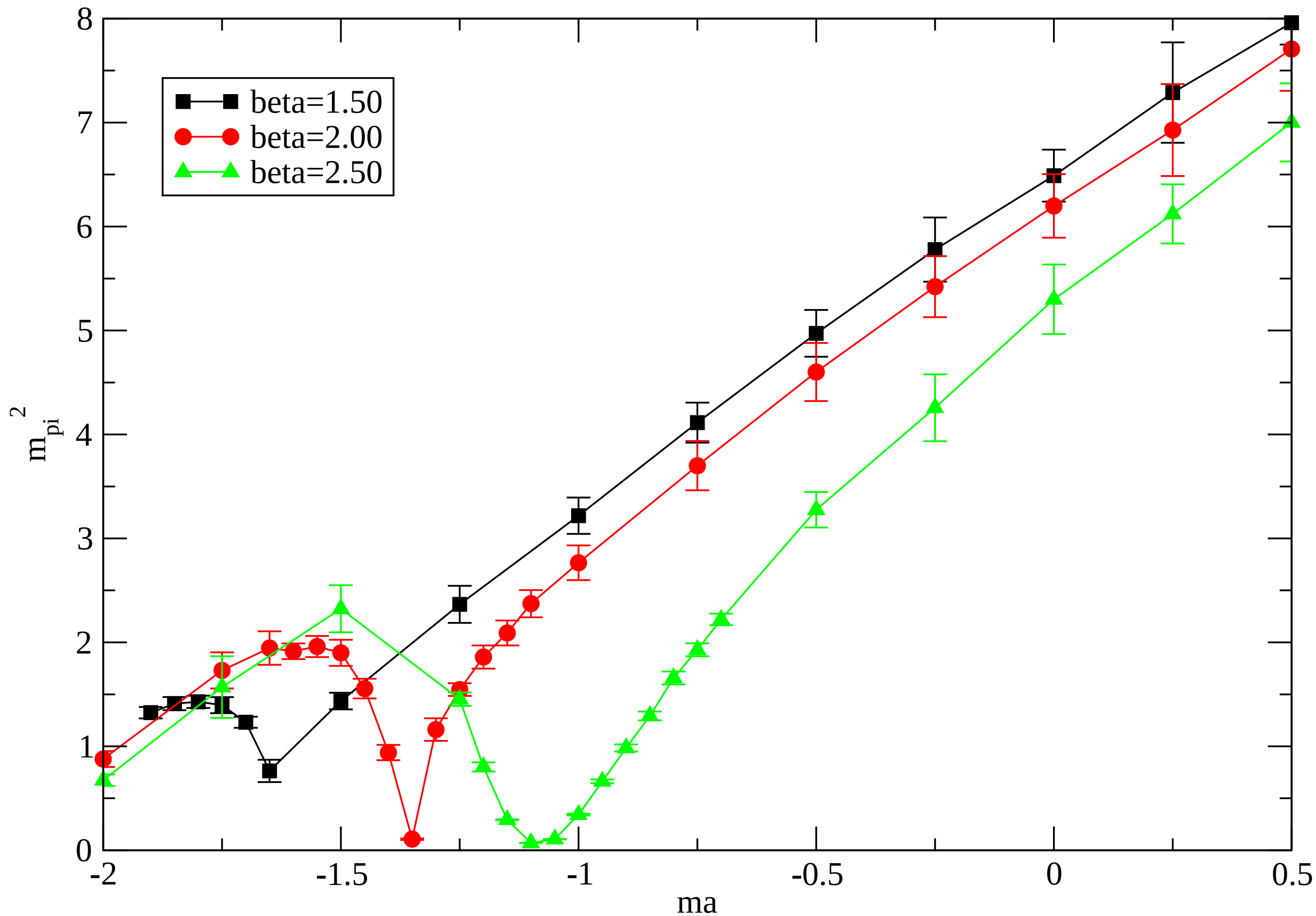
Discontinuity at small β: 1st order transition.

Latent Heat



Critical end point $\beta = \beta_c \sim 2.0$?

Pion mass squared

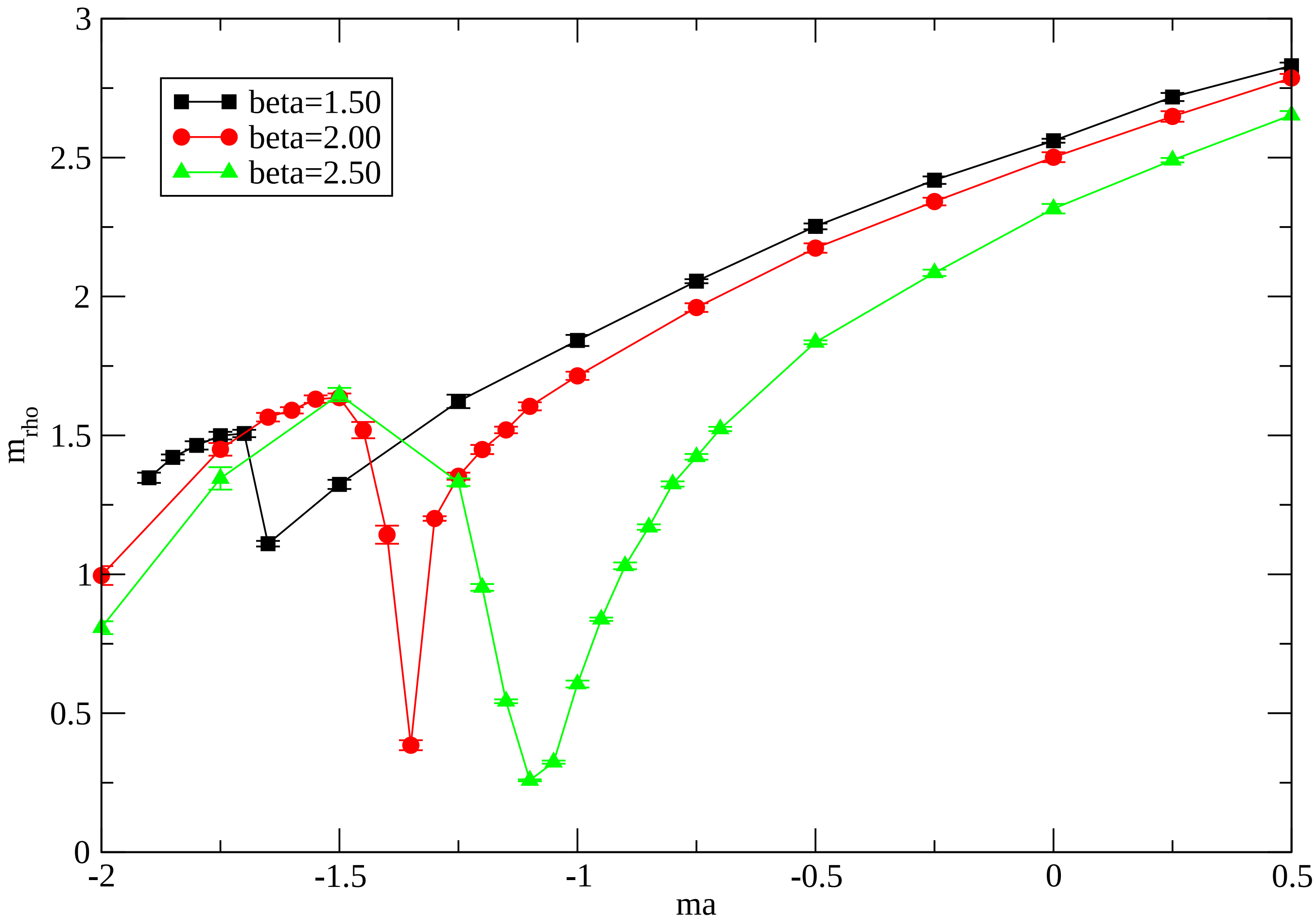


Two regimes:

$\beta < \beta_c$: Goldstone behavior. Coincides with jump in gluon action

$\beta > \beta_c$: Restoration of chiral symmetry (?). Gluon action smooth.

Rho mass

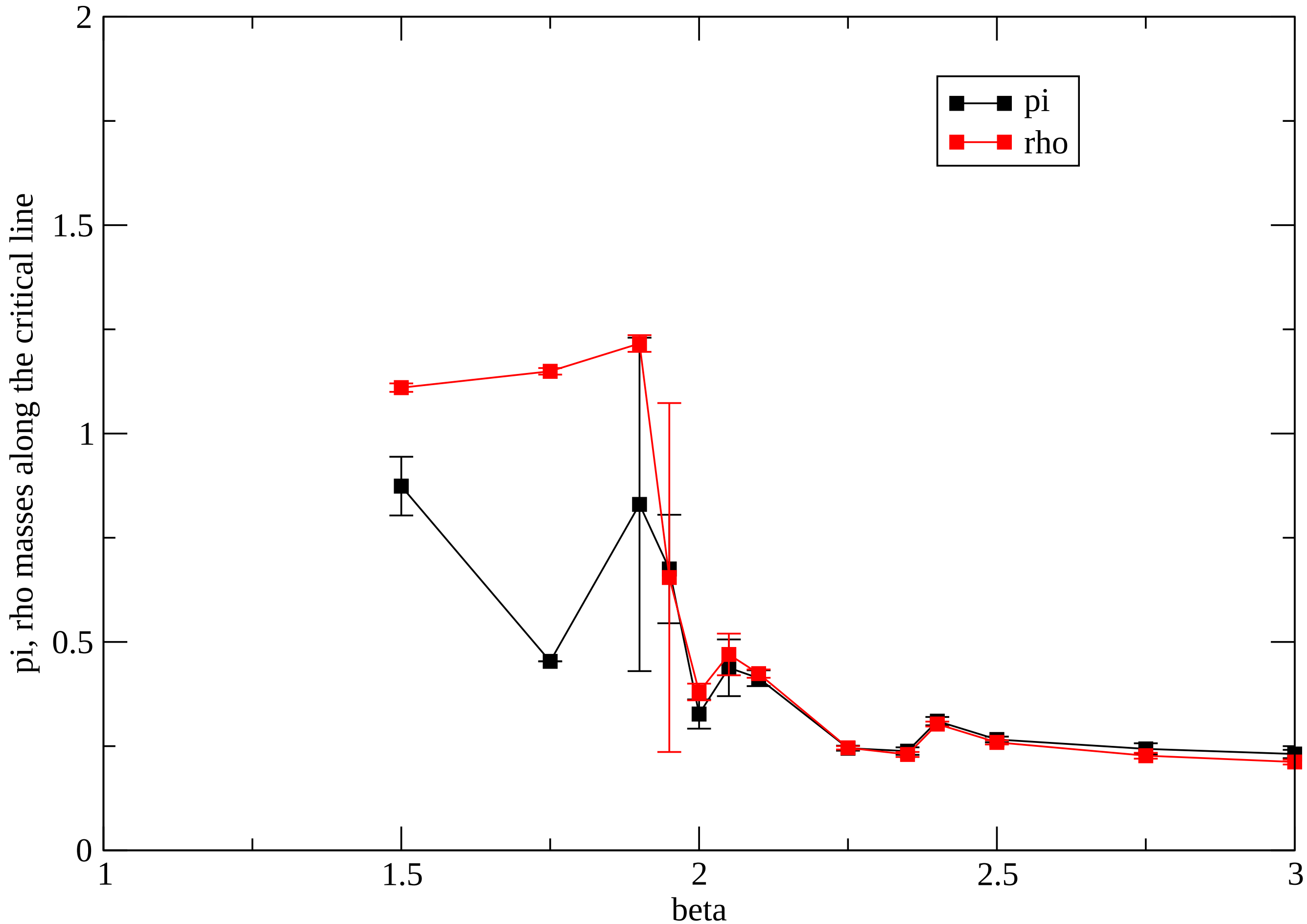


Two regimes:

$\beta < \beta_c$: Large mass. Coincides with jump in gluon action

$\beta > \beta_c$: m_ρ small and independent of bare coupling. Gluon action smooth.

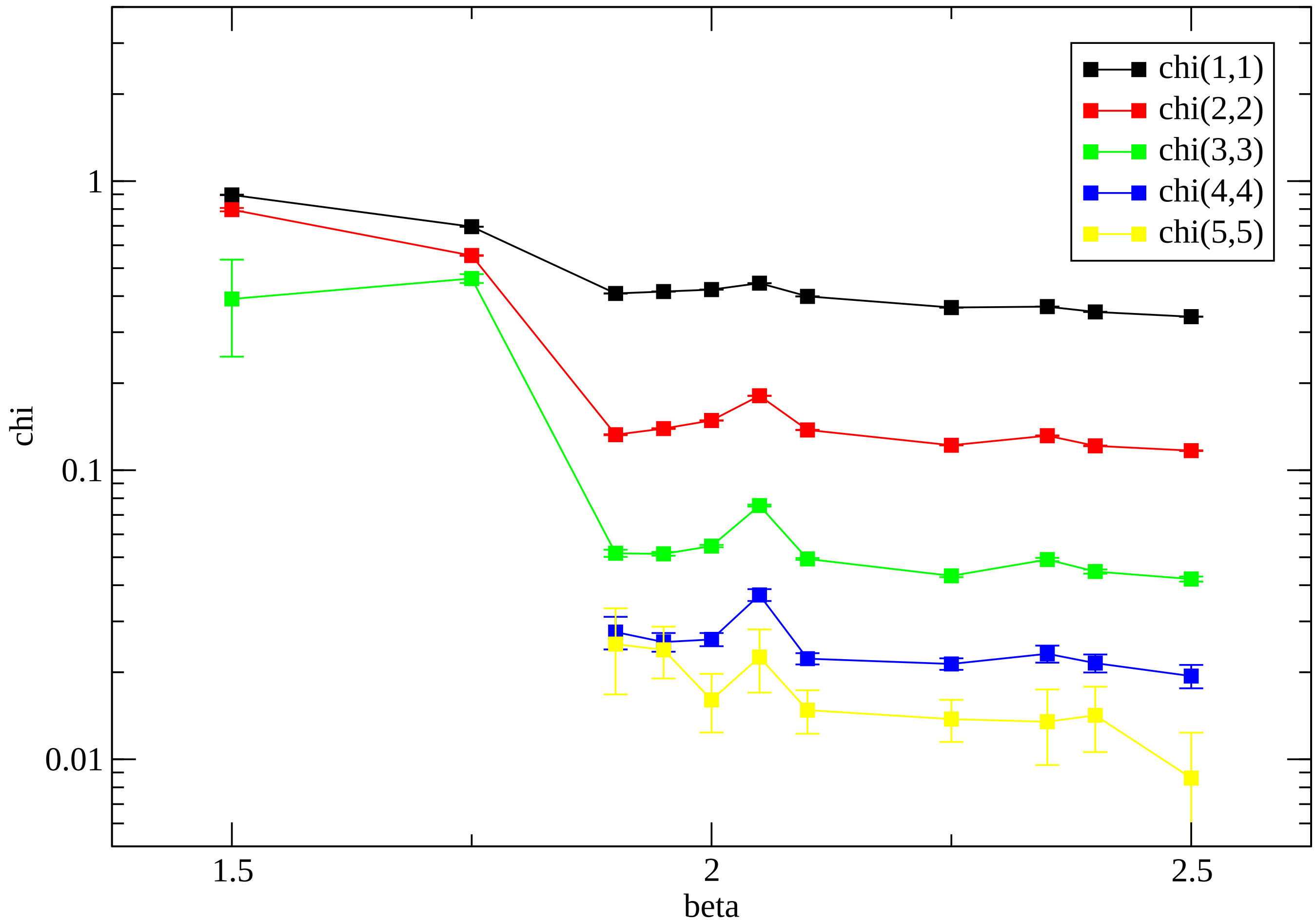
Masses along “critical” line



Notice: masses degenerate for $\beta > \beta_c$

Notice: $\beta > \beta_c$ $m_\pi = 0.2 \sim \frac{\pi}{T} \sim$ thermal mass.

String tension



Estimate from

Creutz ratio $\chi(R,R)$ (ratios of Wilson loops)

If $\frac{\chi(R,R)}{\chi(R+1,R+1)} \to 1$ $\sigma a^2 = \chi(R,R)$

Two regimes:

Conclusions

Along line where $m_q^r \sim 0$ see two phases.

- Confining, chirally broken phase with strong lattice artifacts $m_\rho a$,$\sigma a^2 \sim O(1)$.
- Chirally symmetric phase with $m_\pi \sim m_\rho \sim m_{\mathrm{thermal}}$ and $\sigma a^2 \leq 0.0015$. Deconfined ?
- Latter phase meson masses independent of bare coupling.

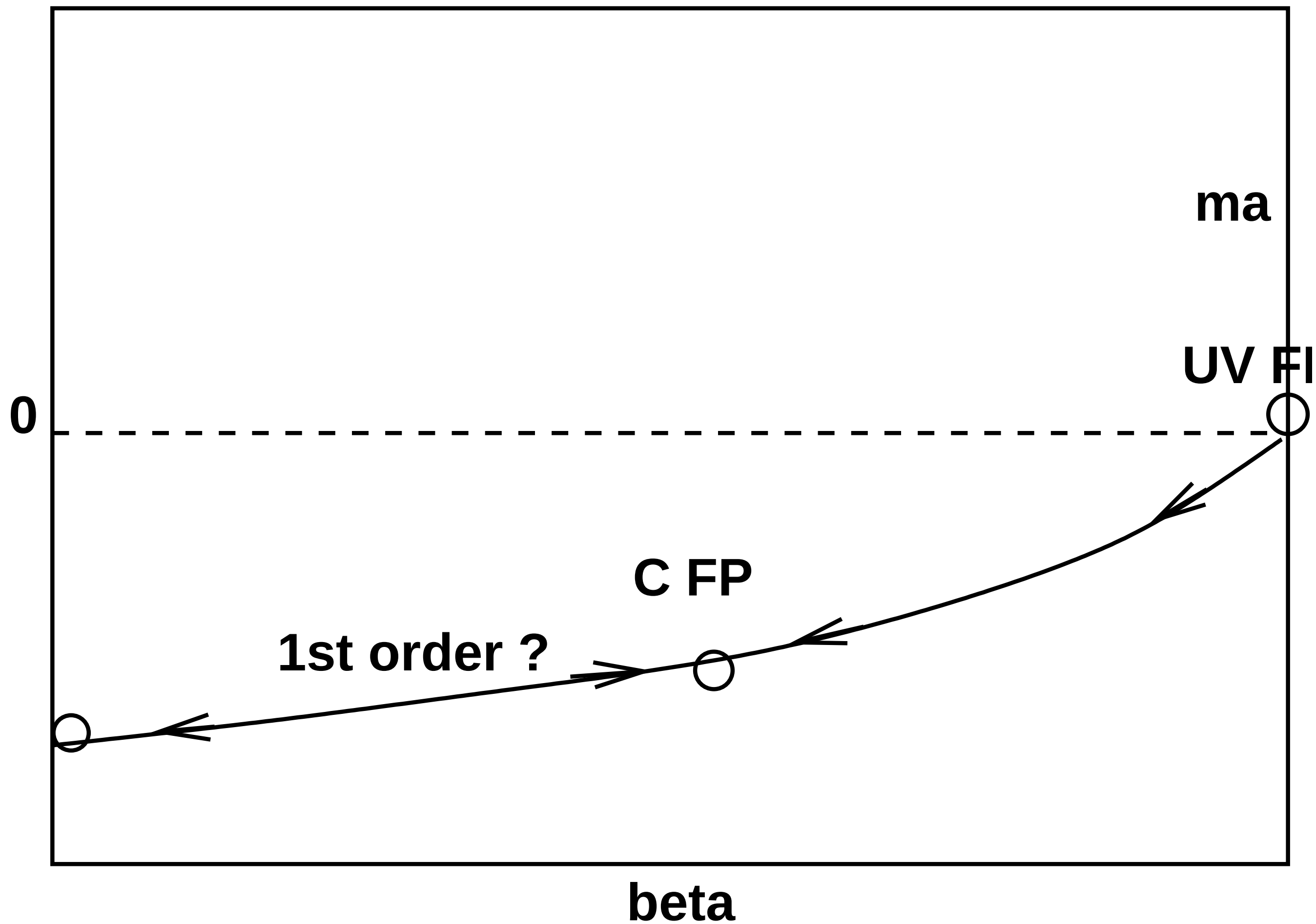
Observations consistent with existence of infrared stable fixed point

Caveats

- Continuum limit requires careful tuning of β with a taking care to avoid finite size effects
- If running $\beta(a)$ slow expect extreme sensitivity in inverse $a = a(\beta)$. Modest increases in β correspond to huge decreases in lattice spacing and for fixed lattice size large potential finite size effects.
- Eg. Physical box size so small system deconfines and looks quasi-free. Consistent with our data.
- Alternatively dynamical scale Λa will be small and require large lattices to see asymptotic confining behavior.
- Need large lattices to resolve between these scenarios

Possible scenario

Simplest picture for new CFP. Assume



Conclusions/Outlook

- Have performed high statistics, fine resolution survey of phase diagram of candidate (near)conformal gauge theory – $SU(2)$ with $N_f = 2$ adj quarks.
- Standard LGT methods used – HMC Wilson.
- Find theory exhibits either a very slow running of the gauge coupling or
- Contains an IR attractive conformal fixed point.
- Try to resolve using larger lattices and step scaling techniques (current)
- Either way. Theory looks very different from QCD and shows the growing utility of lattice GT techniques in exploring non-perturbative models of BSM physics.