Minimal Technicolor on the lattice

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Background:

- **Higgs field is special:**
  - it has not been found
  - it is scalar
  - ...hierarchy problem, vacuum stability, unitarity bound ...
- **Can we live without a scalar?**
- Consider the EW symmetry breaking and χSB in QCD:

	EWSB	χSB
condensate:	Higgs vev v	$\bar{\psi}\psi$ chiral condensate
goldstones:	eaten by W,Z (gauged)	π-mesons
radial excitation:	Higgs particle	scalar meson

Technicolor

Technicolor (TC): Electroweak symmetry breaking $\longrightarrow$ chiral symmetry breaking of "Techni-QCD", (technigauge + techniquarks Q), with $\Lambda_{\rm TC} \approx \Lambda_{\rm EW}$.

- Quarks have technicolor and EW charge
- After chiral symmetry breaking:
  - $\Rightarrow$ scalar $\bar{Q}Q$ -meson: Higgs
  - $\Rightarrow$ Pseudoscalars $\rightarrow$ W,Z -longitudinal modes
  - $\Rightarrow$ exotic technihadrons

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It's both Strong and Electroweak

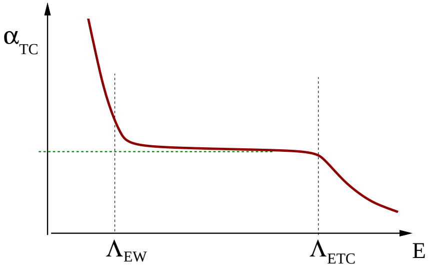
What about Yukawa couplings to SM quarks?

$\Rightarrow$ **Extended technicolor (ETC):** new gauge interaction coupling normal quarks and techniquarks.

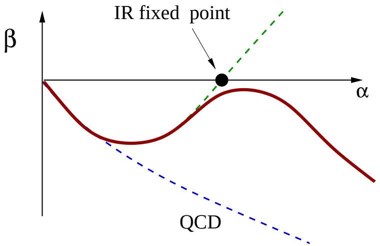
- At low energy, $\mathcal{L}_{\rm Yukawa} \sim \langle \bar{Q} Q \rangle \, \bar{q} \, q$
- **Experimental constraint:** $\Lambda_{\rm ETC} \gg \Lambda_{\rm EW} = \Lambda_{TC}$, due to FCNC's.
- Typically $\Lambda_{ETC} \sim 100$–$1000 \times \Lambda_{EW}$

Walking coupling

To make this work, the theory has to be (almost) conformal in a wide range of energy:



β-function is almost zero at moderately strong coupling

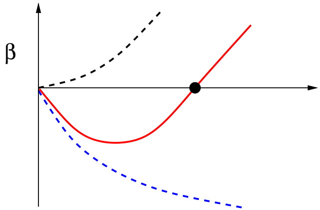


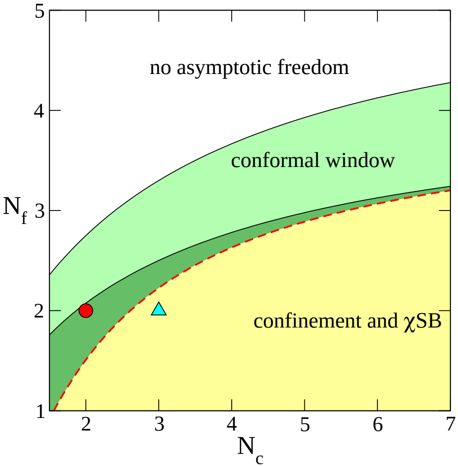
Symmetric representation

- The required behaviour is difficult to satisfy using fundamental rep. quarks. (Need large $N_f \rightarrow$ difficult to avoid FCNC's.)
- However, for SU(N) with 2-index symmetric representation quarks ($\square\square$) $N_f \leq 5$ is sufficient to reach conformal behaviour for any N_c (at least in perturbative analysis).
- There $\exists$ "conformal window" with IR fixed point
  [Dietrich, Sannino, Tuominen; Dietrich, Sannino]

Conformal window

Within the conformal window
there ∃ IR fixed point





Lattice simulations have been done at $N_c = 2$, $N_f = 2$ and $N_c = 3$, $N_f = 2$

Why lattice simulations?

- χSB is essentially non-perturbative: lattice simulations are needed to check whether the scenario works.
- We study here $N_c = 2$, $N_f = 2$ -case; the simplest model in this class: "Minimal technicolor".
- Also studied by [Catterall, Sannino; Del Debbio, Patella, Pica].
- $N_c = 3$, $N_f = 2$ has been studied by [DeGrand, Shamir, Svetitsky].

How to observe the "walking"/conformal behaviour?

- Measure the running coupling directly using "Schrödinger functional" (not yet done!)
- Particle spectrum: all modes become massless as $m_q \to 0$.

On the lattice:

- SU(2) Wilson gauge action in fundamental rep.
- SU(2) Wilson fermions in symmetric ($\equiv$ adjoint for SU(2)) rep.
- volumes $20^4 - 32^4$, 5 different lattice couplings $\beta \equiv 4/g^2$.

Phase diagram

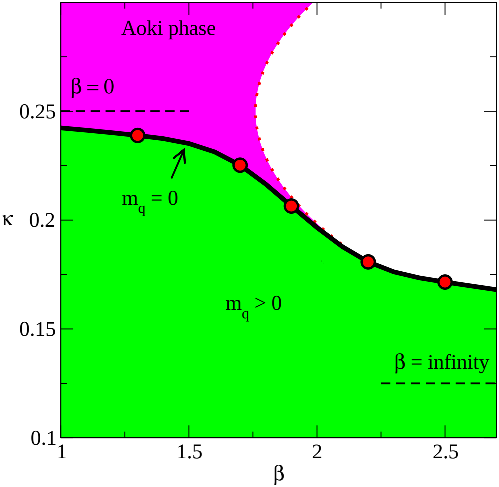
Lattice parameters:

$$\beta = \frac{4}{g^2} \qquad \kappa = \frac{1}{8 + 2m_{q,\mathrm{bare}}}$$

We determine physical quark mass from the axial Ward identity

$$m_q = \lim_{t\to\infty} \frac{1}{2} \frac{\partial_t V_{\mathrm{PS}}(t)}{V_{\mathrm{PP}}(t)}$$

$m_q(\beta, \kappa) = 0$ determines the critical line $\kappa_c(\beta)$



States

SU(2) + fundamental quarks:

- 2-quark states $\bar{q}q$, qq (degenerate except in isoscalar channel)
- glueballs

SU(2) + adjoint quarks:

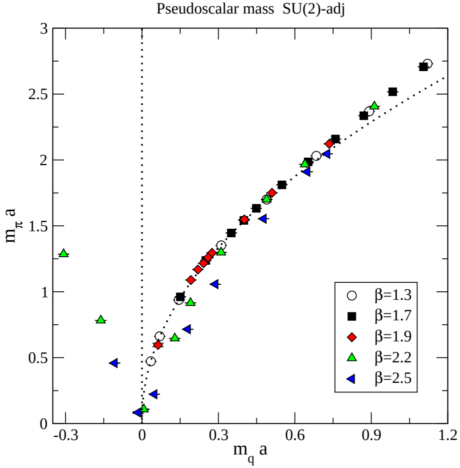
- QQ "mesons" – π, ρ ...
- QQQ "baryons" – "proton"
- Qg quark-gluon state
- glueballs

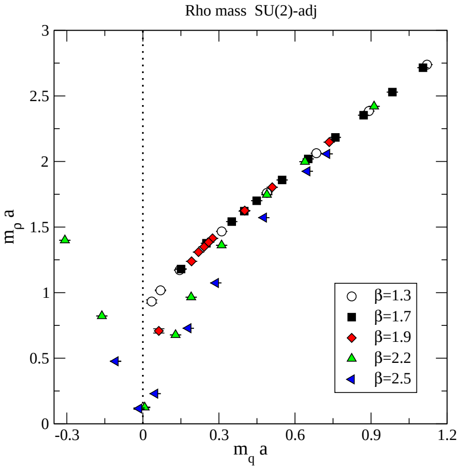
What to expect:

- If QCD-like χSB: as $m_Q a \to 0$,
  - $m_\pi \propto m_Q^{1/2}$
  - other states have finite mass.
- If IR fixed conformal point: $m_Q a \to 0$, all states become massless. $\sim$free quarks?
- If walking behaviour
  - There $\exists$ $\beta_{\rm conf.}$, where system appears almost conformal.
  - When $\beta < \beta_{\rm conf.}$, there is χSB as in QCD.
  - When $\beta > \beta_{\rm conf.}$, theory looks non-$\chi$SB except in humongous volumes.
- On the lattice extrapolation $m_Q a \to 0$ is required. Too large m_Q or too small V can lead to misleading results.

Results

Pseudoscalar ("π") and vector ("ρ") masses

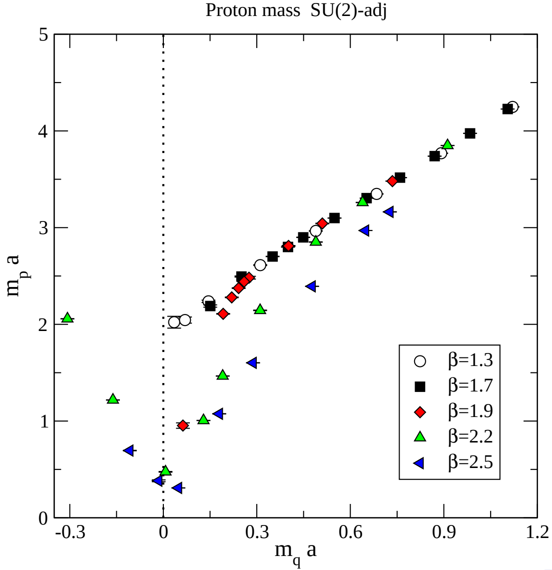




At small β, looks like χSB. At large β?

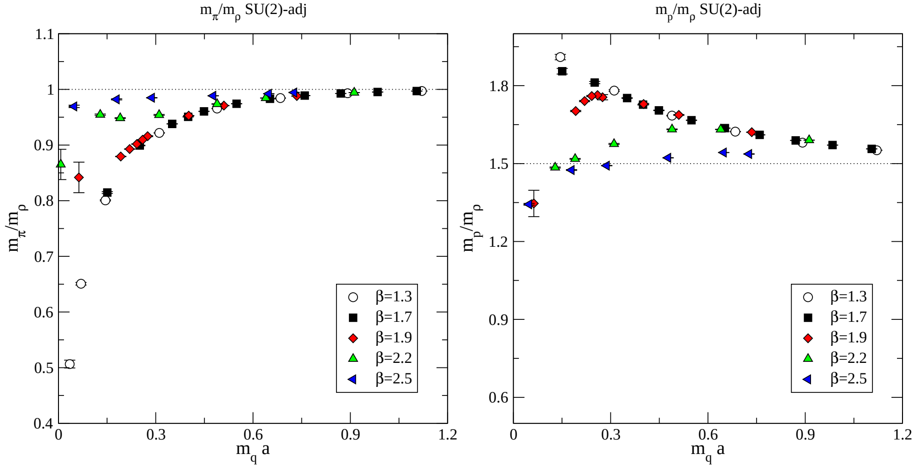
Results

3-quark state (“proton”) mass

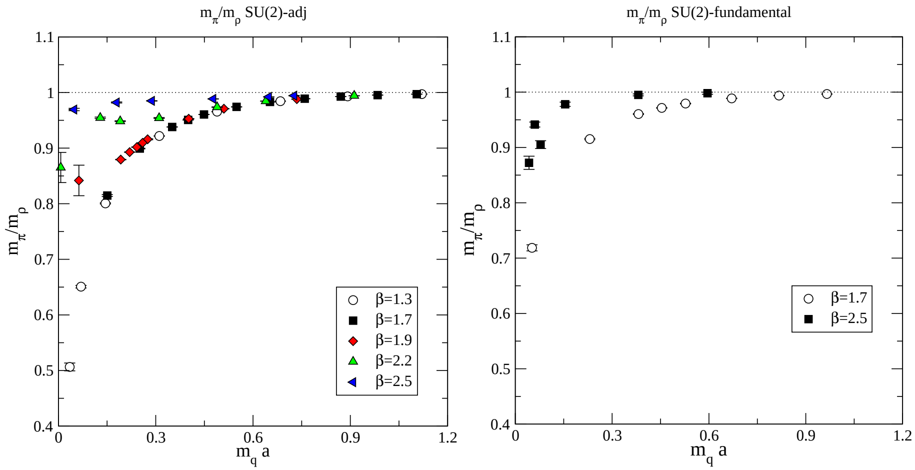


Results

Mass ratios m_π / m_ρ and $m_{\text{Proton}} / m_\rho$



Compare with fundamental rep.



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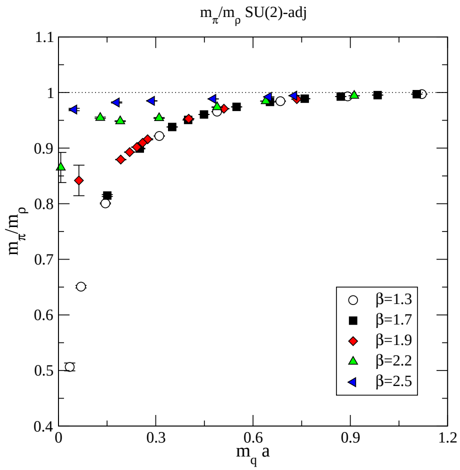

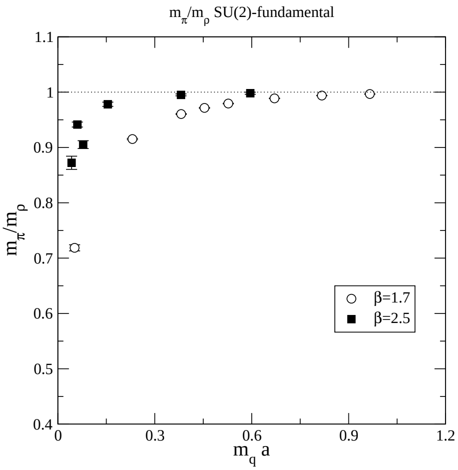

Conclusions (preliminary!)

- There is χSB at small β
- Theory appears to be more "walking" (i.e. slower) than fundamental quark theory, but how much?
- It may be possible that there exists almost–fixed–point near $\beta \sim 2 \Rightarrow g^2_{\mathrm{Lat.}} \sim 2$?
- There is also room for a genuine IR fixed point. In that case small-β χSB phase is a lattice artifact, and is separated by a phase transition at some β from the continuum (large β) behaviour.
- Direct evaluation of β-function required (in progress).

- Predictions obtainable from this TC model:
  - Measure $\langle \bar{Q} Q \rangle$, set to v_{Higgs}
  - Measure QQ scalar mass $\rightarrow$ Higgs mass
  - ρ: lightest exotic particle
  - Modified by ETC corrections