The adjoint version of QCD and the extension of the Standard Model of particle physics

Georg Bergner
Albert Einstein Center
ITP Bern

UNIVERSITÄT BERN

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In collaboration with I. Montvay, G. Münster, S. Ali, H. Gerber, S. Piemonte , P. Giudice, A. Athenodorou, E. Bennett, B. Lucini, T. Ryttov, F. Sannino

"Strong and weak interactions – from Hadrons to Dark matter"

- long time goal: extension of the SM
- motivations: dark matter, early universe, naturalness of the Higgs sector, ...

Several problems are of non-perturbative nature
$\rightarrow$ need lattice methods, e. g.

- strongly interacting supersymmetric theories
- technicolour models
- composite Higgs models
- higher dimensional compactified gauge theories
- SIMPs, unparticles, . . .

What lesson can we learn for QCD?

Technicolour

Higgs in the standard model:

- spontaneous symmetry breaking:
  Higgs vev, ew scale ≈ 250 GeV
- mass generation for W and Z
- mass generation for fermions
- ... but large quantum corrections, not "natural", strong dependence of δm_H on higher scales

Technicolour candidates (more "natural" EW sector):

- "strong" naturalness: dynamical scale generation like in QCD
- ... but requires theory much different from QCD

General theoretical question: exploration of different possible realisations of strong interactions.

Technicolour basics

- strong dynamics without Higgs: fermion condensation, equivalent of Higgs vev: F_π
- light fields (Goldstone modes of chiral symmetry breaking) generate W, Z mass

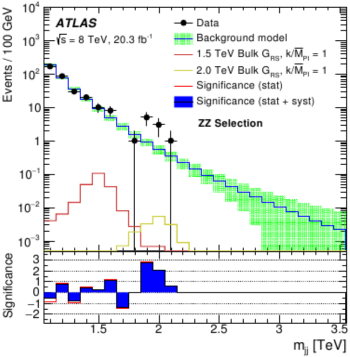
but . . . didn't we already see the Higgs?

$\Rightarrow$ Higgs as composite state generated by strong interactions (light scalar)

but . . . don't we already know the electroweak sector?

$\Rightarrow$ strong interactions without visible impact on electroweak precision measurements

New hints for technicolour?



[ATLAS, arXiv:1506.00962]

- $M_v/F_\pi \sim 8$, generic for several TC theories

Requirements for a technicolour candidate

Difficult conditions for a technicolour theory (TC) ...

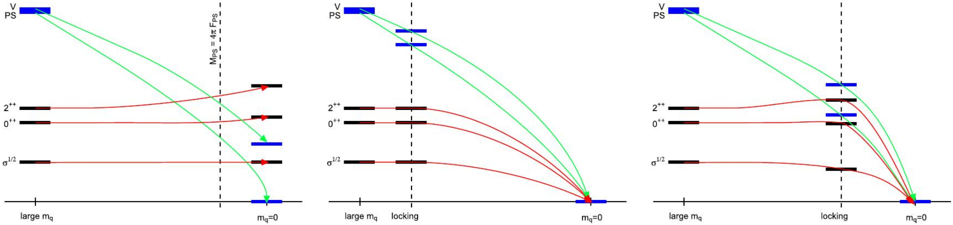
- electroweak symmetry breaking and mass generation of the W and Z bosons
- mass generation for the fermions without generation of FCNC
- extended technicolour (ETC)
- electroweak precision data ...

... here we focus on

1. light scalar to explain the Higgs boson
2. (near) conformal (walking behaviour)
3. $\gamma_m^* \sim 1$ (large)

$\Rightarrow$ Strong interactions, but much different from QCD!

Mass spectrum of near conformal theory



[Lucini, arXiv:1503.00371]

- QCD like: light Goldstone bosons from chiral symmetry breaking at $m \to 0$
- (near) conformal: m only scale setting parameter, no mass scale at $m \to 0$
- $M \sim m^{1/(1+\gamma_m)}$

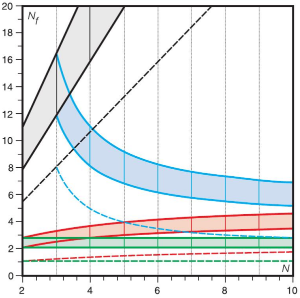
Conformal window

Perturbative picture:

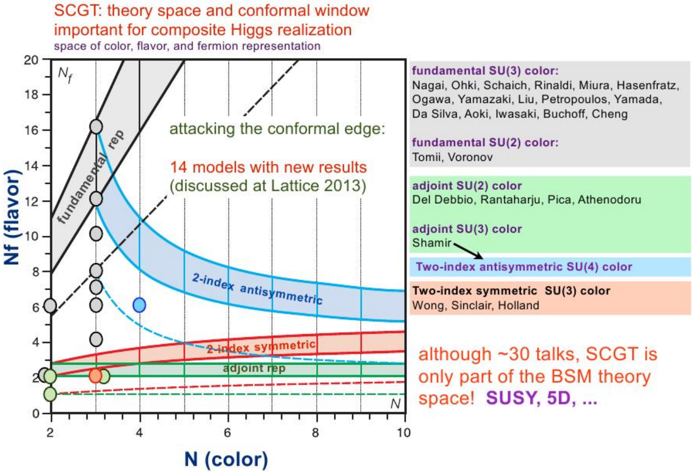
- fundamental representation: large N_f needed
- alternative: adjoint, sextett rep.
- nonperturbative methods needed to confirm conformal window
- large number of studies consider fund. representation

Adjoint QCD ($\mathrm{SU}(2)$):

- perturbative: conformal window starts above $N_f = 2$
- minimal walking technicolour (MWT)



[Dietrich, Sannino, hep-ph/0611341]



[Kuti, PoS LATTICE2013 (2014) 004]

Adjoint QCD

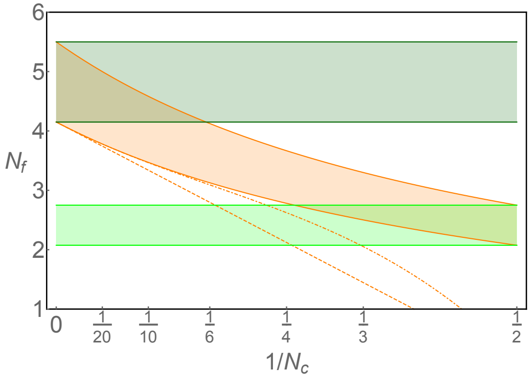
adjoint N_f flavour QCD:

$$\mathcal{L} = \mathrm{Tr}\left[-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \sum_i^{N_f} \bar{\psi}_i(\not{D} + m)\psi_i\right]$$

$$D_\mu\psi = \partial_\mu\psi + ig[A_\mu, \psi]$$

- ψ Dirac-Fermion in the adjoint representation
- adjoint representation allows Majorana condition $\psi = C\bar{\psi}^T$

$\Rightarrow$ half integer values of N_f: $2N_f$ Majorana flavours



[Bergner, Ryttov, Sannino]

- adjoint QCD constrains other theories, in particular symmetric rep.

SYM and the investigation of the conformal window

SYM simulation provides benchmark of lattice methods

- confining (i. e. below conformal window)
- formation of SUSY multiplets (benchmark for deviation from continuum limit)
- other possible benchmarks: all order beta-function, condensate

MWT benchmark for SYM methods: expect large difference between $N_f = 2$ and $N_f = 1/2$

Chiral symmetry breaking in adjoint QCD

N_f Dirac $= 2N_f$ Majorana spinors in Weyl representation
Symmetry breaking by condensate:

$$\mathrm{SU}(2N_f) \rightarrow \mathrm{SO}(2N_f)$$

$N_f(2N_f - 1)$ unbroken generators, $N_f(2N_f + 1) - 1$ Goldstone bosons (pNGb)
Different names for the same thing:
SYM: "adjoint pion", $N_f = 1$ adjoint QCD: "scalar baryon", $N_f = 2$ adjoint QCD: "pseudoscalar meson"

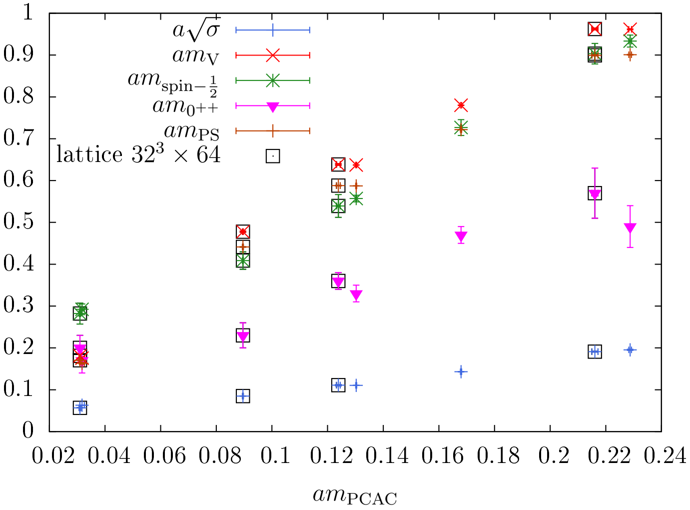
Spin-1/2 state

Specific feature of adjoint representation: Colourless mixed fermion-glue states are possible. One example:

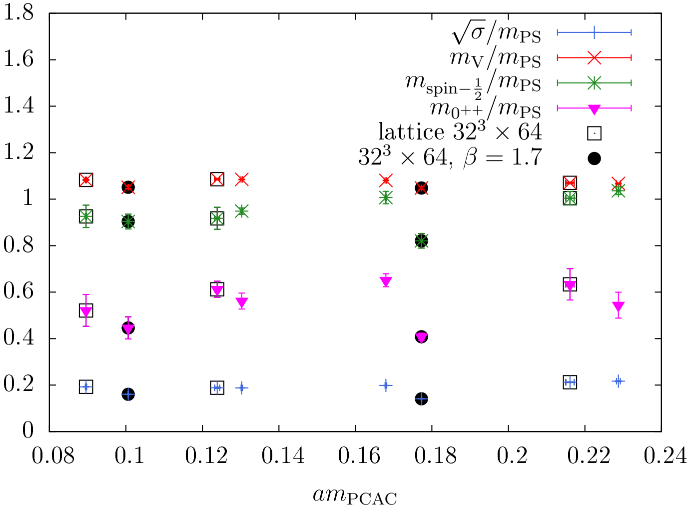
$$\sum_{\mu,\nu} \sigma_{\mu\nu} \mathrm{tr}\left[F^{\mu\nu}\lambda\right]$$

- spin-1/2 state
- in SYM: fermion state in SUSY multiplet
- in TC: might lead to fractionally charged particles

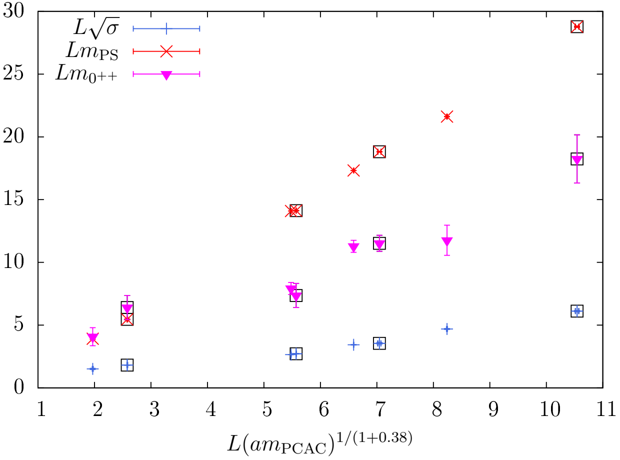
Lattice MWT: Mass spectrum



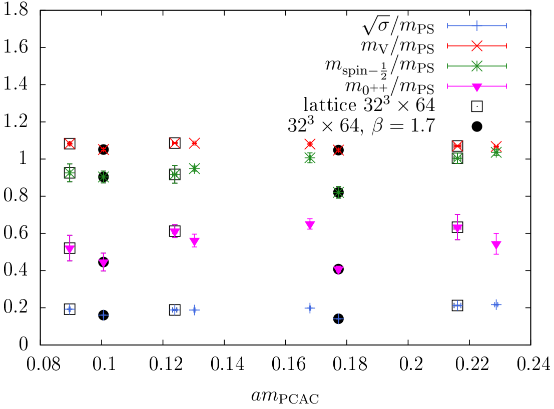
Mass spectrum of MWT at different β



Scaling of the Masses



Spin-1/2 state



- consistent in all measurements: Spin-1/2 state is above scalar glueball, close to, but below V (PS) $\Rightarrow$ light particle

Results for MWT

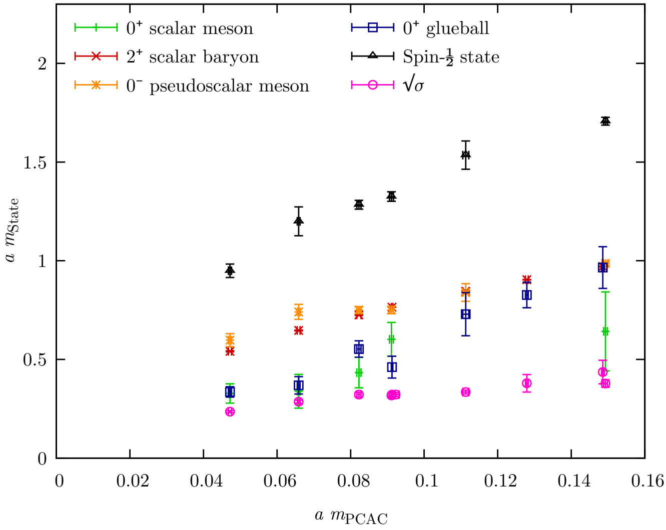
Challenges:

- limitation by bulk transition / lattice artefacts
- large finite size effects:
  QCD: $m_{\mathrm{PS}} L \sim 5$
  SYM: $m_{\mathrm{PS}} L \sim 3.5$
  MWT: $m_{\mathrm{PS}} L \sim > 15$

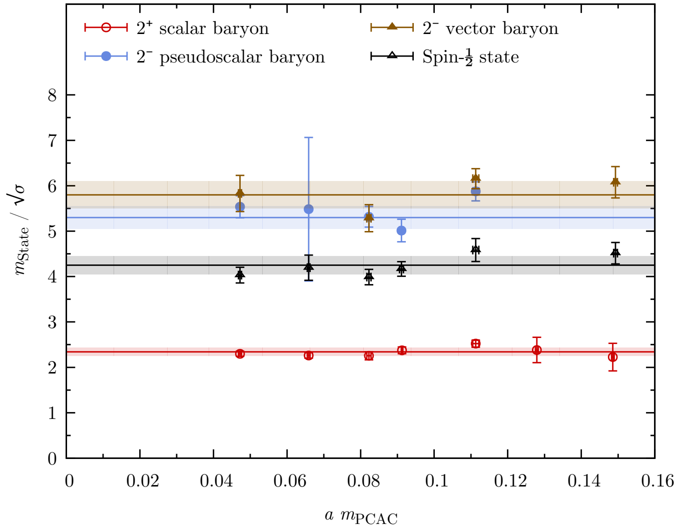
Results:

- large difference between SYM and MWT ☑
- light scalar ☑
- (near) conformal ☑
- from the spectrum $\gamma_m \sim 0.11 - 0.52 \Rightarrow$ might be too small
- seems to be more conformal than expected from perturbative arguments

Lattice $N_f = 1$ adjoint QCD: Mass spectrum



Results for $N_f = 1$ adjoint QCD



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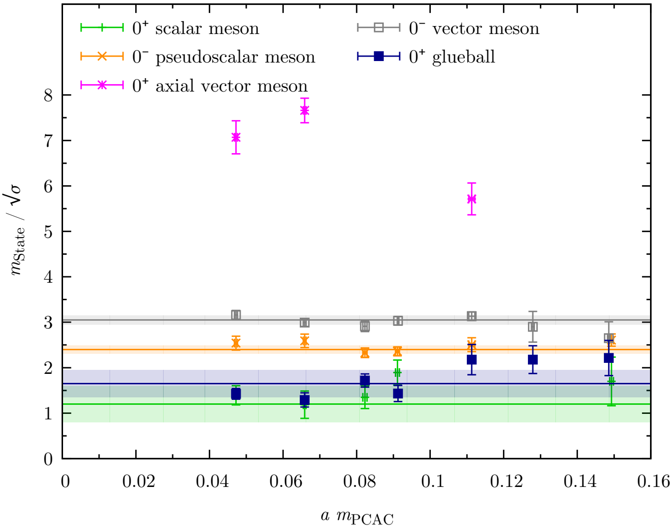

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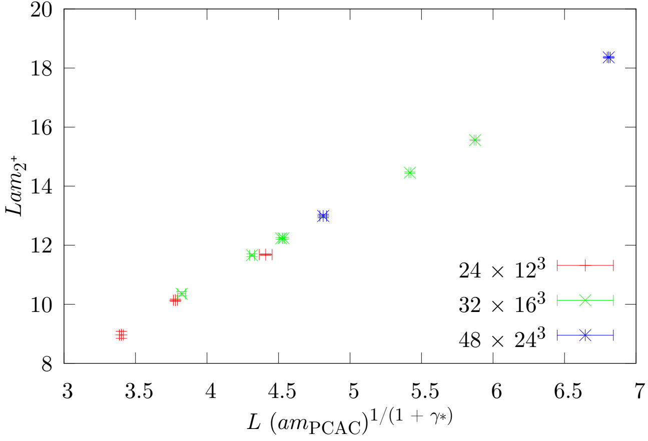

$\gamma_m^* = 0.9$

Results for $N_f = 1$ adjoint QCD

Challenges:

- precise determination of difference conformal/non-conformal

Results:

- light scalar ☑
- (near) conformal ☑
- $\gamma_m^* \sim 0.9$ ☑
- smaller lattice spacing: $\gamma_m^* \sim 0.7$ (preliminary)

Conclusions: Walking scenario

- $N_f = 1$ (near) conformal
- lower end of adjoint QCD conformal window might be at smaller N_f than expected
- $N_f = 2$ small γ_m, $N_f = 1$ rather large γ_m

Phenomenology:

- $N_f = 1/2$ or 1 might be combined with fundamental $\rightarrow$ UMWT
- $N_f = 1$ adjoint QCD conformal
  $\rightarrow N_f = 2$ symmetric QCD conformal
  (in contradiction with LH collaboration)

Conclusions: Spin-1/2 state

- SYM: Spin-1/2 part of multiplet
- $N_f = 1$ adjoint QCD: Spin-1/2 rather heavy
- $N_f = 2$ adjoint QCD: Spin-1/2 rather light

Phenomenology:

- problematic: fractionally charged particles
  $\rightarrow$ motivated investigations of $\mathrm{SO}(4)$ [A. Hietanen, C. Pica, F. Sannino, U. I. Sondergaard: arXiv:1211.5021]
- feature: dark matter Majorana with small cross section compared to baryons [C. Kouvaris: arXiv:hep-ph/0703266]

Conclusions

- lattice simulations resolve large difference of SYM and MWT
- MWT exotic theory: glueballs, fermion-glue particles below meson spectrum
- $N_f = 1$ adjoint QCD on the (near) conformal side and includes light scalar and large γ_m
- There is an interesting landscape of strongly interacting theories much different from QCD.
- interesting starting point for "Strong and weak interactions – from Hadrons to Dark matter"